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José Vicente Ruiz Arredondo

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Université Paris 1 - Panthéon Sorbonne

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soutenue publiquement par

**José Vicente RUIZ**

17 mai 2016

**Analysis and evaluation of economic policy instruments  
for environmental control in Mexico**

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## Notice

Except for the general introduction, all chapters of this thesis are self-contained research articles. Thus, the term *paper* is frequently used. Moreover, some contents such as literature, maps, and certain statistics are repeated in different sections of the thesis.



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## Résumé des chapitres en français

# Chapitre 1 - Surexploitation de l'eau souterraine, électricité, et mauvaises incitations : le cas du Mexique

## Introduction

De nombreuses inefficacités dans la conception interne des concessions empêchent l'allocation adéquate des ressources en eau au Mexique. Le déficit le plus important dans la conception des concessions est probablement liée à la méthode établissant la limite maximale pour l'extraction de l'eau. La limite maximale fixée par les concessions est basée sur les caractéristiques techniques du système de pompage (Shah et al., 2004; Cob and Romero, 2011) et non pas sur un régime favorisant la conservation des ressources. Celui-ci implique que les contraintes imposées par les concessions sont rarement contraignantes. En outre, même lorsqu'elles le sont, le prix payé pour tout mètre cube supplémentaire est très faible. En fait, les activités agricoles paient le prix le plus bas dans le pays. Ce prix est le même pour toutes les régions du pays, indépendamment de la disponibilité en eau dans la région.

Les activités d'irrigation bénéficient de tarifs d'électricité fortement subventionnés. Depuis 2003, les autorités mexicaines ont favorisé la compétitivité du secteur agricole en subventionnant les tarifs de l'électricité pour les activités d'irrigation. Selon les estimations, les tarifs d'électricité ont reçu des subventions allant jusqu'à 83% des coûts de production d'énergie (Cob and Romero, 2011).

L'inefficacité des mécanismes de régulation a conduit à l'augmentation au Mexique du nombre de nappes phréatiques classées comme surexploitées au cours des dernières décennies. Fin 2010, il y avait 101 (sur 653) nappes phréatiques classées comme surexploitées dans le pays, contre 32 nappes

phréatiques surexploitées en 1975 (CONAGUA, 2010).

Ce chapitre s'intéresse aux irrigants basés dans les nappes phréatiques surexploitées au Mexique. Les différents effets d'un changement dans le prix de l'eau souterraine sur l'allocation des facteurs de production sont analysés. À cette fin, une combinaison de sources de données est utilisée pour estimer une fonction de coût qui permet en outre de calculer différents types d'élasticités. Ces différentes sources d'information incluent un ensemble de données uniques contenant des micro-données sur les caractéristiques les plus pertinentes des entreprises basées dans les nappes phréatiques souffrant de taux élevés d'extraction, les statistiques officielles, ainsi que des informations sur les caractéristiques environnementales construites grâce à des systèmes d'information géographique (SIG).

### **Analyse empirique**

La modélisation des techniques de production des irrigants mexicains est basée sur une fonction de coût Translog. En raison de la disponibilité limitée des données sur les activités d'irrigation (à un niveau désagrégé), il n'est pas possible d'analyser les changements dans la répartition des cultures sur le long terme comme cela est le cas avec des études récentes portant sur la demande d'eau d'irrigation (Schoengold et al., 2006; Hendricks and Peterson, 2012; Pfeiffer and Lin, 2014; Hornbeck and Keskin, 2014). A la place, l'étude se concentre sur les changements à court terme. Par construction, l'analyse à court terme des changements suppose que les immobilisations et les technologies d'irrigation restent constantes. Ces dernières ont été identifiées dans la littérature comme réagissant aux changements dans le prix de l'eau et de l'énergie à long terme (Caswell and Zilberman, 1985; Zilberman et al., 2008). Le principal avantage de l'utilisation d'une forme flexible telle



que la fonction de coût Translog est la possibilité de l'existence d'effets prix-croisés entre l'eau souterraine et d'autres facteurs de production ([Chambers, 1988](#)).

La fonction Translog considère le coût variable de production en fonction des prix des facteurs de production, des quantités de biens produits et des facteurs quasi fixes. L'eau souterraine, le travail, et l'engrais sont considérés comme des facteurs variables de production. Le rendement de production est regroupé dans quatre types de produits agricoles : luzerne et fourrages, fruits, céréales et légumes. Sont utilisés comme contrôles supplémentaires : le volume total de pluie et la température moyenne au cours de l'année ; la pente du terrain ; les caractéristiques du sol (argile, sable, ou limoneux) ; la disponibilité de l'eau dans la municipalité ; le montant total des hectares utilisant une technologie d'économie d'eau ; le nombre de puits utilisés par chaque producteur ; la distance au centre de population le plus proche de plus de 25.000 habitants ; si les producteurs ont déjà été condamnés à une amende ou non ; le nombre d'années d'études ; et le nombre d'années dans la réalisation d'activités agricoles.

Les élasticités de la demande ainsi que celles des prix-croisés de la fonction de coût Translog sont estimées en ne considérant que le système des coûts décrit dans l'Équation 1.7. Ceci correspond à la spécification du modèle utilisé par [Fuss \(1977\)](#), [Nieswiadomy \(1988\)](#), et [Dalton et al. \(1997\)](#). Les paramètres de la fonction de coût sont estimés en exploitant la variation des prix des facteurs de production, des quantités de biens produits, et du facteur semi-fixe dans l'espace. Pour ce dernier, la méthode de régression des équations apparemment sans liens (SURE) est estimée par la procédure de maximum de vraisemblance.

$$\begin{aligned}
S_1 &= \alpha_1 + \sum_{j=1}^3 \alpha_{1,j} \ln(P_j) + \sum_{j=1}^4 \beta_{1,j} \ln(Q_j) + \sum_{j=1}^{10} \gamma_{1,j} \ln(Z_j) + \sum_{j=1}^4 \delta_{1,j} D_j + \epsilon_1 \\
S_2 &= \alpha_2 + \sum_{j=1}^3 \alpha_{2,j} \ln(P_j) + \sum_{j=1}^4 \beta_{2,j} \ln(Q_j) + \sum_{j=1}^{10} \gamma_{2,j} \ln(Z_j) + \sum_{j=1}^4 \delta_{2,j} D_j + \epsilon_2 \quad (1) \\
S_3 &= \alpha_3 + \sum_{j=1}^3 \alpha_{3,j} \ln(P_j) + \sum_{j=1}^4 \beta_{3,j} \ln(Q_j) + \sum_{j=1}^{10} \gamma_{3,j} \ln(Z_j) + \sum_{j=1}^4 \delta_{3,j} D_j + \epsilon_2
\end{aligned}$$

Le système est composé de trois équations correspondant aux parts des coûts de l'eau souterraine  $S_1$ , du travail  $S_2$ . et des engrais  $S_3$ . Chaque équation comprend : les prix de l'eau souterraine  $P_1$ , du travail  $P_2$ , et des engrais  $P_3$ ; les quantités pour chacun des quatre groupes différents de biens produits  $Q_j$ ; des variables supplémentaires en lien avec la production et l'environnement comprises dans  $Z_j$ ; et les trois variables muettes - dont deux représentent les types de sol et indiquent si le producteur a déjà été condamné à une amende avant - représenté par  $D_j$ .

## Données

La principale source de données pour l'analyse est une enquête menée par l'Institut national d'écologie et des changements climatiques (*Instituto Nacional de Ecología y Cambio Climático*, INECC). Cette enquête fournit des micro-données sur les producteurs dans des régions caractérisées par la sur-exploitation de l'eau souterraine. Les informations recueillies se réfèrent aux activités productives menées en 2009. Le questionnaire a permis de collecter des données sur les caractéristiques générales des unités de production et des producteurs, des différents modes de culture, des technologies utilisées, de la consommation en eau souterraine et d'électricité, et de la perception des

producteurs en matière de régulation de l'eau. Le questionnaire comprenait également un module sur l'intérêt potentiel des producteurs à recevoir la subvention de l'électricité comme une somme forfaitaire plutôt que couplée aux frais d'électricité. Le sondage a été appliqué dans sept États mexicains, à partir duquel un échantillon de 499 observations a pu être recueilli. En raison du manque d'information sur la consommation d'eau ou d'autres variables clés, seulement 432 observations sont prises en compte dans l'analyse <sup>1</sup>.

Les résultats basés sur cet échantillon ne peuvent pas être extrapolés à l'échelle nationale, mais s'appliquent uniquement aux nappes phréatiques surexploitées. La sélection des États et des nappes phréatiques n'est pas le fruit du hasard, au contraire elle se concentre sur les zones caractérisées par des nappes phréatiques surexploitées. Les États mexicains analysés ont été choisis par les autorités en fonction du nombre de nappes phréatiques surexploitées. Dans les États sélectionnés, seules les nappes phréatiques surexploitées ont été considérées. Néanmoins, les producteurs de ces nappes phréatiques ont été choisis au hasard à partir d'une liste d'irrigants fournis par la Commission fédérale de l'électricité (CFE), la principale compagnie d'électricité du Mexique. Il est important de souligner que, dans le cadre de cet échantillon, tous les résultats d'analyse sont limités aux agriculteurs *légaux*, à savoir les agriculteurs ayant une concession (seuls les agriculteurs ayant une concession ont accès à des frais d'électricité subventionnés). Ainsi, la technologie utilisée par les agriculteurs *illégaux* ne peut pas être modélisée en utilisant cet ensemble de données.

Les informations concernant les prix de la main-d'œuvre et des engrais ont été recueillies à partir de sources officielles, car elles n'étaient pas incluses

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<sup>1</sup> Les informations manquantes ne montrent aucun motif spécifique, mais semblent être liées, de manière aléatoire, au manque de documentation au cours des entretiens.

dans le questionnaire. Les données sur les salaires proviennent d'une autre enquête menée par l'INECC qui recense les données sur les salaires pour un large éventail de cultures différentes. En outre, puisque les deux enquêtes comprennent pratiquement les mêmes municipalités, il a été possible de faire correspondre le prix journalier de chaque culture dans l'enquête. Les informations concernant le prix des engrais ont été obtenues à partir du système national d'information et de l'intégration des marchés (SNIIM) du Ministère mexicain de l'Economie.

Les variables capturant les précipitations, la température, la pente du terrain, et la distance aux centres de population ont été construites grâce à des systèmes d'information géographique (SIG). Les données sur les précipitations et la température ont été obtenues à partir du Centre de recherche climatique de l'Université du Delaware <sup>2</sup>. Les géodonnées sur la pente du terrain et la distance aux centres de population ont été obtenues auprès de l'Institut national de statistique et de géographie (INEGI).

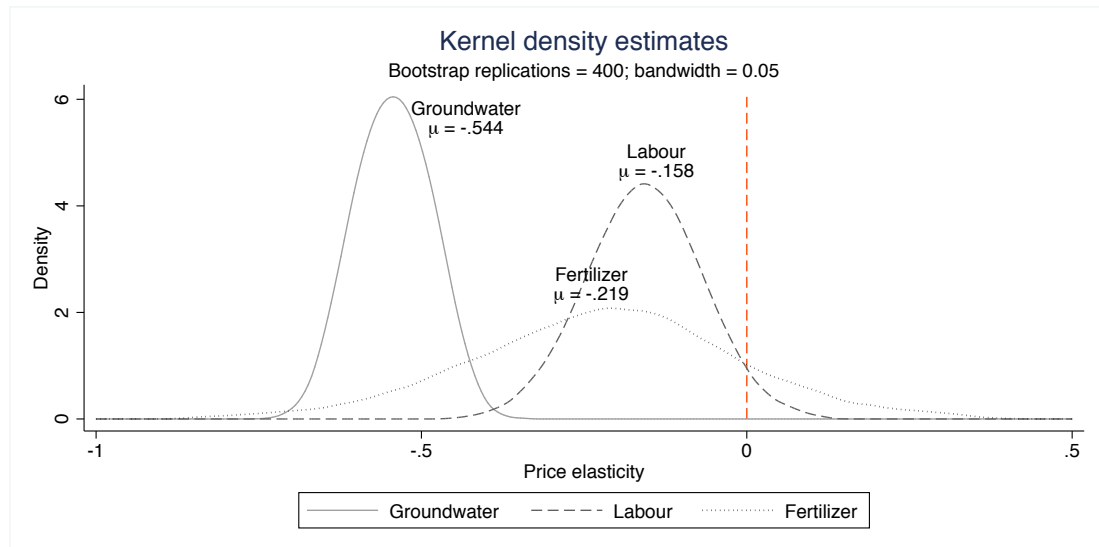
## Résultats

Les élasticités sont stochastiques, donc leur signification statistique (à savoir si elles sont différentes de zéro) doit être analysée avant de faire d'inférences basées sur leurs valeurs. Ainsi, les erreurs types et les intervalles de confiance pour les élasticités prix et prix-croisés sont calculés grâce à une technique de ré-échantillonnage bootstrap en utilisant la méthodologie proposée par [Eakin et al. \(1990\)](#). Conformément à cette méthode, les paramètres des équations des coûts partagés dans 400 échantillons bootstrap sont calculés ainsi que l'ensemble des élasticités correspondantes. Ce dernier fournit une distribution de probabilité pour chaque élasticité des prix et prix-croisés.

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<sup>2</sup> <http://climate.geog.udel.edu/climate/>

**Graphique 1** – Estimations des élasticités de l'eau souterraine, du travail, et de l'engrais selon la méthode du noyau.



Toutes les élasticités prix sont négatives, mais elles ne sont pas toutes statistiquement différentes de zéro. La distribution de probabilité pour chaque élasticité est représentée par une densité de noyau dans le Graphique 1.2<sup>3</sup>. La masse de probabilité des trois distributions se concentre sur le côté négatif de l'échelle. La valeur moyenne de la distribution de densité de l'eau souterraine est atteinte à  $-0.54$ , tandis que pour la main-d'œuvre et l'engrais ce point est atteint à  $-0.15$  et  $-0.21$ , respectivement. Néanmoins, l'estimation pour les engrais n'est pas statistiquement significativement différente de 0.

Les résultats des estimations des élasticités prix-croisés montrent que les élasticités Morishima et de demande de facteur sont toutes deux positives, ce qui implique que la main-d'œuvre et les engrais peuvent agir comme un substitut à l'eau souterraine. En d'autres termes, une augmentation du prix de l'eau

<sup>3</sup> Pour des raisons pratiques, toutes les distributions de ce graphique ont été calculées en utilisant la même bande passante, ce qui à son tour peut conduire à un sur-lissage. La densité du noyau de chaque élasticité est indiquée dans l'annexe en utilisant une bande passante optimisée.

**Tableau 1** – Estimations ponctuelles pour les élasticités prix-croisés

|          | Cross-price Elasticities | Morishima Elasticities |
|----------|--------------------------|------------------------|
| WL       | 0.365***<br>(10.89)      | 0.710***<br>(17.19)    |
| LW       | 0.165***<br>(9.97)       | 0.519***<br>(6.29)     |
| FW       | 0.240***<br>(6.58)       | 0.385**<br>(2.06)      |
| WF       | 0.179***<br>(7.01)       | 0.784***<br>(14.75)    |
| FL       | -0.0341<br>(-0.17)       | 0.194<br>(0.76)        |
| LF       | -0.0115<br>(-0.17)       | 0.119<br>(0.45)        |
| <i>N</i> | 432                      | 432                    |

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

**Note:** Les résultats montrent l'estimation des élasticités prix-croisés et Morishima pour l'eau souterraine (W), le travail (L), et les engrais (F) ; statistiques t entre parenthèses.

souterraine augmente la quantité de travail. Par exemple, une augmentation de 1% du prix de l'eau souterraine augmenterait la quantité de travail de 0,16% (LW, élasticité prix-croisé) et le rapport de la quantité de l'eau souterraine au travail de 0,51% (LW, élasticité Morishima). Dans le cas des engrais, une augmentation de 1% du prix de l'eau souterraine augmenterait la quantité d'engrais de 0,24% (FW, élasticité prix-croisé) et le rapport de la quantité de l'eau souterraine aux engrais de 0,38% (FW, Morishima élasticité). Ces résultats suggèrent en outre que l'engrais est un substitut plus sensible à l'eau souterraine que la main-d'œuvre. Des tests de fiabilité utilisant différentes spécifications du modèle soutiennent ces résultats.

## **Le découplage des subventions de l'électricité représente-t-il une alternative de politique viable?**

La mise en œuvre de futures réformes visant à découpler la subvention de l'électricité pourrait bénéficier d'une meilleure compréhension des intérêts des producteurs pour ce type de programme. En effet, seuls 11% des producteurs inclus dans l'échantillon analysé accepteraient un découplage de la subvention en contrepartie de l'attribution d'un transfert direct forfaitaire. Pour alimenter et contribuer aux discussions sur les réformes hydriques, les informations fournies dans l'enquête INECC ont été utilisées pour analyser les caractéristiques des producteurs qui seraient intéressés à participer au programme. Ainsi, un modèle de choix binaire a été utilisé pour analyser l'intérêt *hypothétique* à participer à ce programme sur la base d'un ensemble de covariables, incluant le montant de la subvention que les producteurs recevraient, ainsi que sur les caractéristiques des producteurs et des nappes phréatiques.

Les résultats de cet exercice montrent que le montant de la subvention ne semble pas influencer sur le souhait de participer, même en contrôlant pour le revenu net des producteurs. Les producteurs les plus âgés seraient plus susceptibles de participer à un tel programme, tandis que ceux ayant l'expérience la plus longue dans les activités agricoles, quel que soit leur âge, sont moins intéressés. Un autre résultat important de cette analyse est le fait que les producteurs confrontés à des niveaux plus élevés de surexploitation de l'eau souterraine, et en conséquence à un prix plus élevé pour l'eau souterraine, sont plus susceptibles de participer à un tel programme. Enfin, les producteurs dans le centre du pays sont plus intéressés à participer que les producteurs dans les États du Nord.

## Conclusion

Ce chapitre contribue à la littérature existante en fournissant des estimations sur les élasticités prix-croisés liées à la demande d'eau d'irrigation au Mexique. En effet, les résultats montrent que les changements dans le prix de l'eau souterraine affectent la répartition du travail et des engrais. Les estimations des élasticités prix-croisés montrent que le travail et les engrais agissent comme un substitut pour l'eau souterraine. Selon mes estimations, une augmentation de 10% du prix de l'eau souterraine dans les nappes phréatiques surexploitées pourrait réduire la consommation moyenne d'eau de 5%.

Les résultats de cette étude visent à fournir aux décideurs politiques mexicains des données pouvant contribuer aux réformes hydriques en cours. Les résultats suggèrent en outre que la mise en œuvre de programmes visant à découpler les subventions de l'électricité ainsi que toute hausse des frais d'électricité devront faire face à des défis importants. La faible volonté à accepter le découplage potentiel des subventions à l'électricité impose des défis réels et majeurs pour les autorités mexicaines. En outre, cette réticence cache d'importantes variations régionales. Ceci implique que les stratégies politiques existantes ne doivent pas seulement tenir compte de la différence territoriale, mais aussi reconnaître et intégrer l'hétérogénéité spatiale des effets des politiques mises en œuvre.



## Chapitre 2 - La géographie de l'extraction illégale de l'eau souterraine au Mexique

### Introduction

Bien que les autorités mexicaines aient tenté de contrôler l'extraction illégale de l'eau, une série de contraintes ont entravé ces efforts.

Imposer le cadre légal et les dispositions juridiques régissant le secteur hydrique représente l'un des défis les plus importants auxquels les autorités mexicaines se sont confrontées ces dernières décennies. Bien qu'obligatoire pour tous les utilisateurs d'eau dans les secteurs agricole, industriel et municipal, un nombre important de ces utilisateurs fonctionne sans concession. L'extraction illégale de l'eau est un phénomène particulièrement fréquent parmi les utilisateurs agricoles. Considérant que les irrigants sont les plus gros consommateurs d'eau souterraine dans le pays, la réduction de l'extraction illégale de l'eau dans le secteur agricole est un facteur clé pour limiter la surexploitation des nappes phréatiques.

Les efforts de réglementation sont aussi remis en cause par le fait qu'un grand nombre d'utilisateurs d'eau est dispersé sur de grandes étendues de terre. Ainsi, la vérification de la conformité des utilisateurs peut être très coûteuse. En conséquence, un certain nombre de producteurs ne respecte pas les limites d'extraction ou ne possède pas de concession (permis) pour extraire l'eau souterraine. Ce type de producteurs est présent dans tout le pays et représente une configuration spatiale complexe : ils sont présents dans des régions dont les niveaux de disponibilité en eau et de revenu sont différents; ont tendance à se regrouper sans respecter les limites administratives ; et peuvent être proches ou éloignés des principaux centres de population.

Les organismes de bassins régionaux sont chargés de mettre en œuvre des inspections, en fonction de leurs capacités et priorités financières. Certains des principaux défis auxquels CONAGUA a été confrontée sont liés à la capacité limitée des conseils de bassins et des bureaux régionaux à effectuer des inspections. Cette capacité limitée comprend un personnel non-qualifié et le manque d'équipement adéquat (CONAGUA, 2012b).

Se dégage donc la question de savoir si ces efforts d'application des lois ont un effet sur le respect de l'environnement. L'objectif de ce chapitre est donc de faire la lumière sur cette question.

### **Analyse empirique**

L'objectif principal de l'analyse est d'examiner les effets des mesures d'exécution sur l'extraction illégale de l'eau au Mexique. En particulier, l'analyse se concentre sur les effets des inspections environnementales - comme mécanisme de dissuasion - sur le nombre d'utilisateurs illégaux d'eau (IWU) dans le secteur agricole. Mon unité d'analyse est la municipalité, le troisième niveau de gouvernement au Mexique.

Le nombre d'utilisateurs illégaux d'eau dans chaque municipalité est considéré comme un événement de comptage. Bien que l'utilisation du taux de IWU eut été la façon la plus directe pour analyser cette question, dans certaines municipalités au Mexique le nombre total d'irrigants peut être aussi petit que un, tandis que dans d'autres, il peut représenter plus de cinq cents. Ainsi, dans les municipalités où le nombre d'irrigants est faible, un petit nombre d'utilisateurs illégaux d'eau peut se traduire par des taux IWU très élevés. Les taux basés sur un petit nombre d'irrigants sont susceptibles d'être augmentés artificiellement, ce qui reflète un manque de données plus qu'il ne

capture les processus qui conduisent à des taux élevés d'extraction illégale de l'eau. Pour cette raison, IWU a été modélisé à travers un modèle de comptage dans lequel le nombre total d'irrigants est considéré comme *exposure term*.

Les inspections environnementales sont généralement endogènes. Dans la pratique, les inspections ont tendance à se concentrer sur les zones où la probabilité d'infractions est la plus élevée, ou dans les zones où le non-respect a des effets importants sur l'environnement.

La stratégie d'identification utilisée repose sur une approche des variables instrumentales qui contrôle l'endogénéité des inspections. En raison des caractéristiques géographiques et des processus historiques, certaines municipalités sont plus accessibles aux autorités environnementales que d'autres. Ceci n'est pas nécessairement capturé par des mesures basées sur la distance euclidienne, mais grâce à des indicateurs reflétant l'accessibilité. Un exemple simple est le temps de conduite. Pour cette raison, le temps de conduite entre chaque municipalité et le bureau régional CONAGUA le plus proche a donc été utilisé.

Le cadre d'analyse fourni par [Becker \(1968\)](#) concernant les mesures publiques d'application, et leur adaptation à la réglementation environnementale proposée par [Heyes \(2000\)](#), ont été utilisés pour modéliser le nombre d'utilisateurs illégaux d'eau. Dans ce cadre analytique, les producteurs respectent la réglementation environnementale que si le coût de son respect est inférieur à l'amende estimée en cas de non-conformité. En outre, l'augmentation de la probabilité des inspections ou du montant des amendes augmente le niveau de respect dans la population.

L'équation suivante représente la spécification économétrique pour le mod-

èle de base. Cette spécification ne considère pas seulement les variables de dissuasion, mais aussi des covariables institutionnelles, socio-économiques et géographiques afin de contrôler les facteurs qui influent sur l'extraction illégale mais qui ne sont pas directement liés à des actions de politiques publiques. Dans ce modèle, les variables de dissuasion sont considérées comme exogènes.

$$IWU_{i,t} = f(deterrence_{i,t}, policy_i, production_{i,t}, social_{i,t}, weather_{i,t}, N_{i,t}, C) \quad (2)$$

Où  $i$  représente une municipalité dans laquelle les irrigants ont utilisé l'eau pour la production dans le temps  $t$ ;  $deterrence_{i,t}$  représente un ensemble de variables de dissuasion ;  $policy_i$  représente des outils de politique territoriale qui réglementent les extractions d'eau en spécifiant les limites au nombre de concessions accordées, et ne changent pas dans le temps ;  $social_{i,t}$  représente les caractéristiques socio-économiques ;  $production_{i,t}$  sont les caractéristiques de production des irrigants ;  $weather_{i,t}$  sont des variables liées aux conditions climatiques ;  $N_{i,t}$  est le nombre total d'irrigants ; et  $C$  est un groupe de contrôles, incluant des effets fixes.

L'ensemble des variables de dissuasion est composé par le nombre d'inspections et le nombre de procédures juridiques mises en œuvre par CONAGUA contre les utilisateurs d'eau.

La LAN, la loi hydrique nationale (*Ley de Aguas Nacionales*), stipule qu'aucune concession supplémentaire ne peut être accordée dans les nappes phréatiques fermées à l'extraction ni dans les zones d'interdiction de type I. Ainsi, la présence de zones d'interdiction et de nappes phréatiques fermées à l'extraction sont considérées dans l'ensemble de variables  $policy_i$ .

Comme les variables représentant les caractéristiques socio-économiques ont tendance à être fortement corrélées, l'analyse se concentre uniquement sur deux variables. Ces variables sont un indice de privation et la densité de population.

En ce qui concerne le groupe de variables liées à la production, l'analyse se concentre sur le rendement par hectare et sur la zone d'agriculture mécanisée dans chaque municipalité.

Enfin, le groupe de covariables climatiques est composé par les précipitations et la température.

Les contrôles comprennent deux types d'effets fixes et une variable prenant en compte la taille de chaque municipalité. Les effets fixes concernent à la fois le temps et les régions administratives hydriques.

Comme indiqué précédemment, un problème récurrent de l'analyse des effets de dissuasion est lié à l'endogénéité des mesures d'application. Afin de prendre cet élément en compte, les variables de dissuasion sont considérées, dans un deuxième temps, comme étant endogènes et le coefficient des inspections environnementales est identifié grâce à un instrument de capture de l'accessibilité des autorités environnementales.

L'intuition derrière cet instrument est simple : en raison du nombre limité d'inspecteurs et des frais de transport (coûts non seulement monétaires, mais aussi en termes de temps), les inspections sont plus fréquentes dans les zones qui sont plus proches des bureaux régionaux de CONAGUA. Cette relation est exprimée par l'équation 2.4.

$$deterrence_{i,t} = f(access_i, policy_i, production_{i,t}, social_{i,t}, weather_{i,t}, N_{i,t}, C)$$

(3)

Où  $access_i$  représente les variables d'accessibilité. L'accessibilité est principalement abordée à travers le temps de conduite entre chaque municipalité et le bureau régional de CONAGUA le plus proche dans la région administrative hydrique correspondante. En plus de cette variable, la densité du réseau routier est utilisée comme un instrument supplémentaire pour les tests de fiabilité.

Différentes méthodes d'estimation sont utilisées selon que les inspections sont considérées comme exogènes ou non. Dans le premier cas, les paramètres de la spécification de base sont estimés grâce à un modèle de régression binomiale négative (NBRM).

Dans le deuxième cas, deux méthodes de comptage différentes sont utilisées pour permettre notamment de prendre en compte les covariables endogènes. La première méthode est un modèle de comptage basé sur un estimateur de GMM qui permet de considérer que le résidu est additif ou multiplicatif. La deuxième méthode de comptage des covariables endogènes est basée sur une procédure d'estimation en deux étapes. Cet estimateur est connu comme une fonction de contrôle et est également basé sur GMM.

## **Données**

La principale variable d'intérêt pour l'analyse est le nombre d'irrigants qui ne possèdent pas de concession valide pour extraire de l'eau. Comme on pouvait s'y attendre, les informations concernant les activités illégales sont rares et

leur accès au grand public limité. Néanmoins, le contexte institutionnel régissant la gestion de l'eau au Mexique fournit un cadre particulier pour l'identification des irrigants ne possédant pas de concession.

Les utilisateurs illégaux d'eau peuvent être identifiés par leurs contrats avec la compagnie d'électricité. L'accès aux tarifs d'électricité subventionnés (9CU et 9N) est étroitement lié à la possession d'une concession ; sans concession valide les irrigants ne peuvent accéder qu'à des tarifs d'électricité qui sont presque cinq fois plus élevés que ceux subventionnés (même si dans le secteur agricole ces derniers demeurent largement inférieurs à ceux pratiqués dans d'autres secteurs d'activité). Par conséquent, il est très probable que les irrigants bénéficiant de tarifs non subventionnés ne possèdent pas de concession valide. La variable dépendante est alors construite en comptant, dans chaque municipalité, le nombre d'irrigants ayant des contrats d'électricité basés sur des tarifs non subventionnés : 9 ou 9-M.

Les informations sur les tarifs d'électricité ont été obtenus auprès de la Commission fédérale de l'électricité (CFE)<sup>4</sup>. Cet ensemble de données couvre pour l'univers des irrigants qui ont un contrat avec la compagnie d'électricité.

Les deux principales variables représentant la réglementation environnementale sont le nombre d'inspections (au niveau municipal) et le nombre de procédures judiciaires contre les utilisateurs d'eau en raison de l'absence soit d'une concession soit d'un permis pour les rejets d'eaux usées (au niveau des États). Les données sur le nombre d'inspections ont été obtenues à partir du registre public des inspections de CONAGUA<sup>5</sup>. En ce qui concerne les procédures juridiques, les informations proviennent du compendium statistique de

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<sup>4</sup> Cette agence est la principale compagnie d'électricité dans le pays ; elle est rattachée au Ministère de l'Énergie.

<sup>5</sup> <http://www.conagua.gob.mx/>

gestion de l'eau de CONAGUA ([CONAGUA, 2012a](#)).

Les variables de politiques publiques se réfèrent aux zones géographiques où l'extraction de l'eau est limitée par la loi. Les deux types de zones considérées sont a) les nappes phréatiques fermées à l'extraction ; et b) les zones d'interdiction. Ces deux variables ont été construites à l'aide de SIG. Ensuite, les cartes des nappes phréatiques fermées à l'extraction et des zones d'interdiction ont été superposées avec celle des municipalités. Cela permet de rendre compte pour chaque municipalité des zones, exprimées en kilomètres carrés, où ces deux instruments de politiques sont en place.

Les variables sociales ont été obtenues auprès du Comité national d'évaluation des politiques de développement social (CONEVAL) et de l'INEGI. CONEVAL produit une série de statistiques liées à la pauvreté, dont un indice de privation multidimensionnelle. Cet indice prend en compte différentes variables liées à l'éducation, à l'accès aux services de santé, aux moyens de subsistance, et à la richesse dans toutes les municipalités du pays. La densité de population a été calculée en utilisant les informations sur la population totale et sur la superficie de chaque municipalité. Ces données ont été obtenues à partir de la base de données SIMBAD de l'INEGI <sup>6</sup>.

Les variables de production ont également été obtenues à partir de la base de données SIMBAD. La production totale est exprimée en MEX\$ par hectare et se réfère aux principales cultures produites dans le pays : la luzerne verte, l'avoine fourragère, le piment vert, les haricots, le maïs, l'herbe, le sorgho, les tomates rouges, les tomates vertes et le blé ; les zones agricoles mécanisées se réfèrent aux surfaces utilisées pour la production agricole et travaillées avec des machines, ce qui nécessite une source d'énergie différente de celle

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<sup>6</sup> <http://sc.inegi.org.mx/cobdem/>



des hommes.

Les mesures sur les précipitations et la température ont été calculées pour chaque municipalité en utilisant le SIG. La principale source de calcul de ces variables est [Willmott and Matsuura \(2001\)](#), qui fournit des estimations mensuelles et annuelles pour la température de l'air terrestre et pour les précipitations dans le monde entier entre 1900 et 2010. Cette base de données est elle-même alimentée par les mesures de station des précipitations mensuelles et des températures interpolées sur une grille de latitude/longitude de 0,5 degré par 0,5 degré, où les noeuds du réseau sont centrés sur le degré 0,25.

L'accessibilité du régulateur est utilisé comme le principal instrument pour identifier l'effet des inspections sur IWU. L'accessibilité est mesurée en calculant le temps de conduite entre les agences régionales de CONAGUA et les municipalités. Cette variable est construite grâce au SIG, en utilisant des cartes SIG renseignant sur la localisation des agences régionales de l'eau, les principaux centres de population de chaque municipalité, le réseau routier, et les limites des régions administratives hydriques. En effet, le Network Analyst de Arcinfo est utilisé pour calculer le temps de conduite. L'algorithme utilisé par Arcinfo indique la route la moins coûteuse entre deux points sur le réseau. Le temps de conduite est calculé pour chaque segment du réseau en utilisant la formule  $temps = \frac{longueur}{vitesse}$ . Le deuxième instrument, la densité du réseau, est également construit en utilisant le SIG. La densité du réseau est définie comme le rapport entre le montant total de kilomètres des routes (incluant les routes simples comme les autoroutes) et la taille de chaque municipalité. Le calcul des kilomètres de route est basé sur le même ensemble de données du réseau que celui utilisé pour le calcul du temps de conduite. Tous ces ensembles de données géographiques ont été obtenus auprès de l'INEGI.

## Résultats

L'analyse débute en considérant les variables de dissuasion comme étant exogènes. Dans tous les modèles, les inspections sont toujours positives et significatives à 95%. Le signe positif de ces coefficients va à l'encontre du cadre théorique de la dissuasion décrit dans le cadre analytique. Ce dernier pointe vers un problème potentiel d'endogénéité.

Ces variables sont donc ensuite considérées comme endogènes et le coefficient du nombre d'inspections est estimé à l'aide d'une approche des variables instrumentales. Trois types de modèles de comptage qui reposent tous sur des estimateurs GMM différents sont utilisés. Le premier modèle considère que le résidu est additif (GMM-S), le second estime qu'il est multiplicatif (GMM-M) et le troisième est une estimation en deux étapes communément appelée fonction de contrôle (GMM-CF).

L'estimateur GMM-M et l'estimateur GMM-CF semblent corriger le biais d'endogénéité. Le Tableau 2.13 montre les résultats de l'estimation après contrôle de l'endogénéité des inspections. Deux spécifications sont testées pour chacun des trois modèles de comptage qui prennent en compte l'endogénéité. La première spécification considère les inspections et les actions légales, tandis que la seconde se concentre uniquement sur les inspections. Les résultats montrent que les estimateurs de GMM-M et de GMM-FC fournissent tous deux un coefficient négatif et significatif pour les inspections de l'année antérieure. De plus, la présence de *LEG LAG* n'a pas d'influence sur le coefficient de *INSP LAG*. Bien que les coefficients pour *LEG LAG* donnés par GMM-M et GMM-CF sont pratiquement identiques à celui de NBRM, aucun d'entre eux n'est statistiquement significatif. Entre ces deux modèles, GMM-CF fournit un meilleur ajustement avec un Pseudo-R carré égal à 0,88.

**Tableau 2** – Les résultats des modèles de comptage basé sur GMM et prenant en compte l'endogénéité potentielle du nombre d'inspections

|                     | GMM-S                  | GMM-S                  | GMM-M                   | GMM-M                   | GMM-CF                 | GMM-CF                 |
|---------------------|------------------------|------------------------|-------------------------|-------------------------|------------------------|------------------------|
| INSP LAG            | 0.00190<br>(0.24)      | 0.00191<br>(0.24)      | -0.0188**<br>(-2.34)    | -0.0184**<br>(-2.30)    | -0.0304*<br>(-1.95)    | -0.0301*<br>(-1.93)    |
| LEG LAG             | -0.000226<br>(-0.15)   |                        | -0.00204<br>(-1.30)     |                         | -0.00161<br>(-0.98)    |                        |
| AQUIFER             | -0.0000577*<br>(-1.66) | -0.0000578*<br>(-1.66) | -0.000116***<br>(-2.88) | -0.000119***<br>(-3.00) | -0.000109**<br>(-2.50) | -0.000110**<br>(-2.54) |
| VEDA I              | 0.000123<br>(1.25)     | 0.000122<br>(1.24)     | 0.000315***<br>(2.78)   | 0.000306***<br>(2.74)   | 0.000432**<br>(2.40)   | 0.000428**<br>(2.38)   |
| VEDA II             | 0.0000126<br>(0.48)    | 0.0000123<br>(0.47)    | 0.000119**<br>(2.34)    | 0.000112**<br>(2.24)    | 0.000110**<br>(2.08)   | 0.000105**<br>(2.00)   |
| VEDA III            | 0.00000127<br>(0.05)   | 0.00000108<br>(0.04)   | -0.0000338<br>(-1.33)   | -0.0000364<br>(-1.44)   | -0.0000191<br>(-0.62)  | -0.0000209<br>(-0.69)  |
| OUTPUT              | -0.000314<br>(-0.17)   | -0.000316<br>(-0.17)   | -0.000471<br>(-0.43)    | -0.000501<br>(-0.46)    | -0.000657<br>(-0.61)   | -0.000667<br>(-0.62)   |
| MECHA               | -4.107***<br>(-3.16)   | -4.127***<br>(-3.21)   | -3.030**<br>(-2.32)     | -3.169**<br>(-2.45)     | -2.626*<br>(-1.79)     | -2.736*<br>(-1.88)     |
| POP                 | 0.000161**<br>(2.01)   | 0.000161**<br>(2.02)   | 0.000207***<br>(3.22)   | 0.000203***<br>(3.19)   | 0.000207***<br>(3.08)  | 0.000205***<br>(3.06)  |
| DEPRIV              | 0.00180<br>(0.03)      | 0.00143<br>(0.02)      | -0.00558<br>(-0.13)     | -0.00870<br>(-0.20)     | -0.00788<br>(-0.18)    | -0.0106<br>(-0.24)     |
| TEMP                | 0.0558***<br>(4.72)    | 0.0559***<br>(4.74)    | 0.0308***<br>(4.31)     | 0.0308***<br>(4.30)     | 0.0318***<br>(4.40)    | 0.0318***<br>(4.39)    |
| RAIN                | 0.000883<br>(0.91)     | 0.000890<br>(0.91)     | 0.000417<br>(0.50)      | 0.000458<br>(0.55)      | 0.000629<br>(0.74)     | 0.000660<br>(0.77)     |
| Constant            | -2.412***<br>(-5.31)   | -2.415***<br>(-5.32)   | -1.784***<br>(-7.31)    | -1.792***<br>(-7.35)    | -1.799***<br>(-7.28)   | -1.806***<br>(-7.31)   |
| Pseudo-R Square     | 0.916                  | 0.916                  | 0.808                   | 0.816                   | 0.885                  | 0.886                  |
| HAR Fixed effects:  | Yes                    | Yes                    | Yes                     | Yes                     | Yes                    | Yes                    |
| Year Fixed effects: | Yes                    | Yes                    | Yes                     | Yes                     | Yes                    | Yes                    |
| Observations        | 2958                   | 2958                   | 2958                    | 2958                    | 2958                   | 2958                   |

*t* statistics in parentheses

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

<sup>1</sup> La variable dépendante est le nombre de IWU ; la variable endogène est LAG INSP ; et l'instrument est le logarithme du temps de conduite.

<sup>2</sup> Des écarts-types robustes regroupés par municipalité.

<sup>3</sup> Tableau 2.19 dans l'annexe présente les résultats de l'estimation de la première étape de la procédure de fonction de contrôle.

Pour tester la validité des résultats, trois modèles de comptage prenant en compte l'endogénéité ont ensuite été réalisés en utilisant le temps de conduite exprimé en variables muettes. En dehors de la perte de qualité de l'ajustement, et d'une petite augmentation des erreurs standard, le coefficient du nombre d'inspections est négatif et significatif.

En outre, la validité du temps de conduite comme variable instrumentale est ensuite corroborée par le biais d'un test de sur-identification. Ce test utilise la densité du réseau comme deuxième instrument. Sur la base de ces résultats, l'hypothèse de sur-identification n'est pas rejetée. Bien que ce test n'évalue pas la qualité de l'instrument, ces résultats fournissent des informations supplémentaires qui viennent appuyer l'utilisation du temps de conduite comme instrument valable pour le nombre d'inspections.

## **Conclusion**

Ce chapitre analyse l'effet de dissuasion des inspections environnementales sur le nombre d'utilisateurs illégaux d'eau. À cette fin, les caractéristiques socio-économiques, ainsi que les politiques territoriales telles que les zones d'interdiction et les nappes phréatiques fermées à l'extraction sont contrôlées. Pour ce faire, une série d'indicateurs a été construite à l'aide de sources de données officielles et des systèmes d'information géographique (SIG). En ce qui concerne la stratégie empirique, l'effet des inspections environnementales est estimé en utilisant une approche des variables instrumentales.

Les résultats montrent qu'une inspection supplémentaire au cours de l'année précédente peut réduire le nombre moyen d'usagers illégaux de l'eau dans chaque municipalité entre 1% et 3%. Bien que cet effet semble important, l'efficacité des inspections environnementales en tant que mécanisme pour

assurer durablement la viabilité de l'eau au Mexique est entravée par la faible fréquence des inspections dans tout le pays. En effet, le nombre moyen d'inspections par an au Mexique était de 2 dans la période utilisée pour les analyses (2007-2009).

Ce chapitre présente la première analyse économétrique concernant l'extraction illégale de l'eau au Mexique. De plus, à ma connaissance, il est également le premier à analyser au Mexique les effets des inspections environnementales en dehors des activités industrielles et de manufacture. Ce chapitre contribue à la littérature économique en améliorant notre compréhension de l'efficacité des mécanismes d'application dans un contexte caractérisé par la faiblesse des institutions. En outre, il fournit également des conseils sur la façon d'améliorer les stratégies de développement visant à limiter à la fois le nombre d'utilisateurs illégaux d'eau et la surexploitation des nappes phréatiques.

## Chapitre 3 - Les événements climatiques influencent-ils la migration interne? Le cas du Mexique

### Introduction

La pression sur les ressources en eau n'est pas seulement induite par des défaillances institutionnelles, elle peut également être provoquée par des chocs externes associés aux changements climatiques. De plus, ces changements influencent un certain nombre de processus socio-économiques, dont les migrations.

Bien que l'attention des universitaires et des organisations internationales s'est essentiellement concentrée sur les migrations internationales - le Mexique étant l'un des couloirs de migration les plus importants au monde - la migration interne représente aujourd'hui un flux beaucoup plus important de population. Sur la période 2005-2010, les flux migratoires entre les États mexicains ont représenté 3,3% de la population totale du pays, contre des taux de 1,1% de la population totale pour les flux migratoires impliquant le passage à un autre pays (INEGI, 2010b).

Le changement climatique aura des répercussions importantes et négatives sur le Mexique, mais l'ampleur de ces impacts sera différente selon les régions. Des projections récentes suggèrent que d'ici la fin du siècle, les températures pourraient augmenter entre 1 et 4 degrés celsius, alors que les précipitations pourraient diminuer de 11%. De plus, ces projections suggèrent en outre que les effets seront plus forts dans les régions du Nord et du Nord-Ouest du Mexique, régions caractérisées par des climats arides (Estrada et al., 2013).

La migration fait partie des nombreuses stratégies possibles que les individus

peuvent adopter suite à des changements environnementaux ([Millock, 2015](#)). Par exemple, les activités économiques dans les zones rurales ont tendance à dépendre de l'environnement comme facteur de production, ce qui fait que la population dans ces régions est particulièrement exposée aux changements environnementaux.

Les caractéristiques géographiques du Mexique rendent certaines régions plus susceptibles d'être touchées par la sécheresse. [Ortega-Gaucin and Velasco \(2013\)](#) ont passé en revue les dernières sécheresses qui ont touché le Mexique depuis les années 1990 en soulignant la fréquence et l'ampleur importantes qui ont caractérisé les récents épisodes de sécheresse. Par exemple, le bassin de la rivière Bravo a connu l'une des plus longues périodes de sécheresse dans l'histoire moderne du Mexique : elle a duré de 1993 à 2005 et a eu d'importants effets secondaires hydriques dans les États de Nuevo Leon, Chihuahua, Coahuila et Tamaulipas. En outre, entre 2009 et 2011, le Mexique a connu les plus fortes périodes de sécheresse des 70 dernières années.

Les inondations sont également fréquentes dans certains États du pays, causant d'importantes pertes matérielles. En 2010, les précipitations et les inondations dans les États de Michoacan, Distrito Federal, Mexico, Oaxaca et Chiapas ont causé des pertes pour plus de MEX\$ 15,000 millions, soit environ US\$1,200 millions ([García Arróliga et al., 2011](#)).

### **Analyse empirique**

L'objectif principal de ce chapitre est de tester empiriquement l'influence des événements climatiques sur les migrations internes au Mexique. Un modèle économétrique est utilisé pour analyser les flux migratoires entre les États mexicains pour les périodes 2000-2005 et 2005-2010. Pour exploiter les infor-

mations fournies par les flux migratoires bilatéraux, l'analyse empirique est basée sur un modèle axé sur la gravité.

La spécification empirique de ce modèle repose sur le cadre analytique fourni par le modèle d'utilité aléatoire (RUM). Dans la littérature, le modèle d'utilité aléatoire a été adapté et développé pour analyser les migrations internationales par [Grogger and Hanson \(2011\)](#) et [Beine et al. \(2016\)](#).

Selon le modèle RUM, les individus décident ou non de migrer afin de maximiser leur utilité. Ce modèle suppose que les individus sont homogènes et capables de choisir parmi l'ensemble des destinations potentielles (dans le cas présent, parmi tous les États mexicains), y compris leur propre lieu de résidence. Après avoir comparé l'utilité de chaque destination, un individu choisit la destination optimale qui maximise son utilité. Ce processus de décision tient compte des caractéristiques du lieu d'origine, celles d'une destination potentielle, ainsi que les coûts associés à la migration.

Cette spécification modélise les flux de migration en fonction des écarts de salaires et de différents ensembles de covariables représentant les caractéristiques, variables dans le temps, du pays d'origine et des coûts de migration. En effet, cette analyse se concentre sur les effets des phénomènes climatiques dans l'État d'origine, tout en tenant compte des caractéristiques des destinations à travers des effets-fixes temps-destination. Ceci permet également de prendre en compte les changements au niveau national qui peuvent avoir influencé tous les États mexicains à travers le temps. Les caractéristiques dans l'État d'origine qui restent constantes dans le temps sont aussi contrôlées par des effets d'origine fixe. La spécification principale du modèle économétrique est donnée par :



$$\begin{aligned}
\ln N_{ij,t} = & \alpha \ln \text{GDP DIFF}_{ji,t} & (4) \\
& + \omega_1 \ln \text{KM}_{i,j} + \omega_2 \text{CONTIGUITY}_{i,j} \\
& + \beta_1 \ln \text{EDUCATION}_{i,t} \\
& + \beta_3 \ln \text{MURDER}_{i,t} + \beta_4 \ln \text{MURDER CHNG}_{i,t} \\
& + \gamma_1 \text{EARTHQUAKE}_{i,t} + \gamma_k \text{HURRICANE}_{k,i,t} \\
& + \mu_k \text{CLIMATE}_{k,i,t} \\
& + \delta_i + \delta_{j,t} + \ln M_{ii,t} + \epsilon_{ij,t}
\end{aligned}$$

Où  $N_{ij,t}$  est le flux migratoire entre l'origine  $i$  et la destination  $j$ . Dans cette spécification, les écarts de salaire entre la destination et l'origine sont représentés par  $\ln \text{GDP DIFF}_{ji,t}$ ;  $\ln \text{KM}_{i,j}$  et  $\text{CONTIGUITY}_{i,j}$  représentent les coûts de migration ; la part de la population qui a atteint un certain niveau d'éducation (primaire, secondaire ou tertiaire) est représentée par  $\ln \text{EDUCATION}_{i,t}$ ; l'étendue des homicides dans la région  $i$  est capturée par  $\ln \text{MURDER}_{i,t}$  et  $\ln \text{MURDER CHNG}_{i,t}$ ;  $\text{EARTHQUAKE}_{i,t}$  représente le nombre de tremblements de terre en  $i$  ;  $\text{HURRICANE}_{k,i,t}$  se réfère à la variable  $k$ -ième considérée pour prendre en compte les différentes catégories d'ouragans dans  $i$  ; de manière similaire,  $\text{CLIMATE}_{k,i,t}$  se réfère aux variables  $k$ -ièmes pour prendre en compte la fréquence, l'ampleur, ou la durée des sécheresses ou des inondations dans l'État d'origine. En plus de l'ensemble des covariables décrites précédemment, cette spécification inclut le terme  $\ln M_{ii,t}$ , qui représente le logarithme de la population totale qui est restée dans la région d'origine ; tandis que  $\delta_i$  et  $\delta_{j,t}$  sont, respectivement, les effets-fixes d'origine et des effets-fixes destination-temps.

## Données

La principale variable d'intérêt est le flux migratoire entre les États mexicains au cours des périodes 2000-2005 et 2005-2010. Les informations pour la période 2005-2010 proviennent du recensement de 2010 ; et les informations couvrant la période 2000-2005 proviennent d'une enquête de population réalisée entre les recensements et effectuée en 2005. Les migrants inter-États sont identifiés par la question : *Dans quel État résidiez-vous il y à 5 ans?* Ces deux sources utilisent la même question pour quantifier la migration interne. Pour chaque période, les flux migratoires sont présentés comme une matrice de 32 par 32 qui représente tous les mouvements de population entre les États mexicains sur la période. Des informations supplémentaires sur la population totale qui est restée dans chaque État au cours de la période de migration sont également fournies dans chaque ensemble de données. La matrice de migration pour le recensement de 2010 a été obtenue auprès de la commission nationale de la population (CONAPO), tandis que les informations relatives à l'enquête de population de 2005 ont été obtenues auprès de l'INEGI.

Le PIB par habitant est utilisé comme proxy pour refléter les facteurs péculniaires de la migration interne. Sur la base du modèle analytique décrit dans la section précédente, les incitations péculniaires à la migration sont capturées par l'écart entre les salaires à destination et ceux des États d'origine. Le ratio du PIB par habitant de l'État de destination sur celui des États d'origine est utilisé comme proxy des écarts de salaire.

Le PIB par habitant des États est exprimé en pesos mexicains en termes réels (base = 1993), et se réfère à l'année précédent chaque période de migration, i.e 1999 et 2004. Cette information a été obtenue auprès de la banque

d'information économique de l'INEGI (BIE).

Les migrants internes ne représentent pas un échantillon aléatoire de la population, mais ont plutôt tendance à s'auto-sélectionner en fonction de certaines caractéristiques personnelles ou en étant exposé à certains contextes socio-économiques. Ces derniers comprennent le niveau de capital humain et l'ampleur de la violence dans l'État de résidence. Pour le capital humain, le proxy utilisé est le niveau éducatif atteint (primaire, secondaire ou tertiaire) ; pour la violence, sont utilisés comme proxies le taux d'homicides et l'augmentation des taux d'homicides au cours de la période de migration. La source de toutes ces variables est la base de données SIMBAD de l'INEGI.

La population mexicaine est exposée à un certain nombre de catastrophes naturelles qui peuvent déclencher ou augmenter certains flux migratoires internes. Basé sur le climat et la géographie du Mexique, les séismes et les ouragans sont considérés ici comme étant les deux phénomènes les plus importants.

Les informations sur les tremblements de terre ont été obtenues à partir de la base de données des catastrophes naturelles construite par le centre national pour la prévention des catastrophes (CENAPRED). Cette base de données comprend le nombre de tremblements de terre dans chaque État, y compris leur ampleur. Pour ne tenir compte que des tremblements de terre qui pourraient avoir déclenché une migration, l'analyse ne retient que les tremblements de terre d'une magnitude minimum de sept degrés sur l'échelle de Richter. En ce qui concerne les ouragans, les informations ont été obtenues auprès de la commission nationale de l'eau (CONAGUA). CONAGUA recueille des renseignements sur les tempêtes tropicales depuis les années 1970. Les tempêtes y sont classées en fonction de la vitesse du vent. Selon la

classification de CONAGUA, une tempête doit atteindre une vitesse de vent supérieure à 118 kmh pour être considérée comme un ouragan. Après avoir atteint ce seuil, les ouragans sont classés en quatre catégories. Sur la base de cette classification, deux variables ont été créées ; l'une tient compte du nombre d'ouragans de catégories 1 à 4 et l'autre se concentre sur ceux de catégories 3 et 4.

Pour prendre en compte les effets des sécheresses et des inondations, l'indice de précipitations standard (SPI) conçu par [McKee et al. \(1993\)](#) et calculé par CONAGUA est utilisé. Sur la base de [Dallmann and Millock \(2013\)](#), un certain nombre de variables sont calculées sur la période de migration: le nombre de mois avec des sécheresses/inondations modérées et sévères ; le nombre de sécheresses/inondations sévères ; la durée de la plus longue sécheresse/inondation ; l'ampleur de la sécheresse/inondation la plus longue; la durée de toutes les sécheresses/inondations ; et l'ampleur de toutes les sécheresses/inondations. Le nombre de sécheresses modérées ou sévères est calculé comme le nombre de mois au cours desquels le SPI est inférieur à  $-1$  ou  $-1,99$ , respectivement ; dans le cas des inondations, la même approche est appliquée mais sur la base de valeurs positives. En ce qui concerne la durée et l'ampleur des sécheresses/inondations, la définition fournie par [McKee et al. \(1993\)](#) est utilisée. Au total, 10 variables représentant les effets de précipitations limitées ou excessives sont calculées.

## Résultats

La durée comme l'ampleur des périodes de sécheresse et des inondations agissent comme facteurs d'incitation à la migration. Les résultats des modèles représentant les sécheresses et les inondations sont présentés dans le Tableau 3.6. Pour des raisons pratiques, ce tableau montre uniquement

les coefficients des ouragans, des tremblements de terre, et des différentes mesures de sécheresse et d'inondations. La durée des périodes de sécheresse a un effet positif et significatif sur les flux migratoires. Un mois supplémentaire dans la période de sécheresse la plus longue au cours de la période de migration est associé à une augmentation moyenne du flux de migration de 0,46%, alors qu'un mois supplémentaire de tous les épisodes de sécheresse est associé à une augmentation de 0,2%.

Dans le cas des inondations, leur durée comme leur ampleur ont un effet positif sur les flux migratoires moyens. Un mois supplémentaire dans l'épisode d'inondations le plus long au cours de la période de migration augmente le flux de migration moyen de 0,52%, alors qu'une augmentation d'une unité de l'ampleur de l'épisode d'inondations le plus long au cours de la période de migration augmente le flux de migration moyen de 0,3%. Ces résultats sont cohérents avec les conclusions de [Coniglio and Pesce \(2015\)](#) dans le cas de la migration internationale, mais contrastent avec les résultats de [Dallmann and Millock \(2013\)](#) qui trouvent que les inondations ne sont pas significatives pour expliquer les flux migratoires entre les États en Inde. Ceci pourrait s'expliquer par le fait que ces études prennent en compte des pays différents.

**Tableau 3** – Les résultats de la régression PPML - sécheresses et inondations au cours de la période de migration

|                              | (1)                   | (2)                  | (3)                   | (4)                   | (5)                   | (6)                 | (7)                  | (8)                  | (9)                  | (10)                  |
|------------------------------|-----------------------|----------------------|-----------------------|-----------------------|-----------------------|---------------------|----------------------|----------------------|----------------------|-----------------------|
| HURRICANE $1-4_{i,t}$        | -0.0508***<br>(-3.51) | -0.0232*<br>(-1.81)  | -0.0376***<br>(-2.97) | -0.0379***<br>(-2.92) | -0.0455***<br>(-3.43) | -0.160*<br>(-1.92)  | -0.0327**<br>(-2.28) | -0.0361**<br>(-2.39) | -0.0297**<br>(-2.06) | -0.0343***<br>(-2.26) |
| EARTHQUAKES $_{i,t}$         | -0.0305<br>(-1.34)    | -0.0123<br>(-0.54)   | -0.0143<br>(-0.62)    | -0.0106<br>(-0.45)    | -0.0207<br>(-0.88)    | -0.0221<br>(-0.23)  | -0.0235<br>(-1.10)   | -0.0240<br>(-1.09)   | -0.0253<br>(-1.17)   | -0.0252<br>(-1.15)    |
| DROUGHT FREQ LONG $_{i,t}$   | -0.00595<br>(-1.32)   |                      |                       |                       |                       |                     |                      |                      |                      |                       |
| DROUGHT LENGTH LONG $_{i,t}$ |                       | 0.00461***<br>(3.33) |                       |                       |                       |                     |                      |                      |                      |                       |
| DROUGHT MAG LONG $_{i,t}$    |                       |                      | 0.00226<br>(0.98)     |                       |                       |                     |                      |                      |                      |                       |
| DROUGHT LENGTH ALL $_{i,t}$  |                       |                      |                       | 0.00209*<br>(1.85)    |                       |                     |                      |                      |                      |                       |
| DROUGHT MAG ALL $_{i,t}$     |                       |                      |                       |                       | -0.000654<br>(-0.34)  |                     |                      |                      |                      |                       |
| FLOOD FREQ LONG $_{i,t}$     |                       |                      |                       |                       |                       | 0.0212<br>(0.94)    |                      |                      |                      |                       |
| FLOOD LENGTH LONG $_{i,t}$   |                       |                      |                       |                       |                       |                     | 0.00526***<br>(5.24) |                      |                      |                       |
| FLOOD MAG LONG $_{i,t}$      |                       |                      |                       |                       |                       |                     |                      | 0.00311***<br>(2.73) |                      |                       |
| FLOOD LENGTH ALL $_{i,t}$    |                       |                      |                       |                       |                       |                     |                      |                      | 0.00526***<br>(5.38) |                       |
| FLOOD MAG ALL $_{i,t}$       |                       |                      |                       |                       |                       |                     |                      |                      |                      | 0.00361***<br>(3.01)  |
| Constant                     | 11.84***<br>(20.75)   | 11.36***<br>(20.31)  | 11.65***<br>(20.45)   | 11.51***<br>(19.86)   | 11.78***<br>(20.05)   | 8.002***<br>(68.00) | 11.09***<br>(20.73)  | 11.28***<br>(20.90)  | 10.86***<br>(20.35)  | 11.16***<br>(20.56)   |
| Pseudo $R^2$                 | 0.876                 | 0.876                | 0.876                 | 0.876                 | 0.876                 | 0.015               | 0.876                | 0.876                | 0.876                | 0.876                 |
| Log-likelihood               | -942981.0             | -942228.3            | -943186.2             | -942961.3             | -943248.2             | -7476090.3          | -941346.2            | -942658.7            | -941100.3            | -942469.2             |
| Origin FE:                   | Yes                   | Yes                  | Yes                   | Yes                   | Yes                   | Yes                 | Yes                  | Yes                  | Yes                  | Yes                   |
| Time-Destination FE:         | Yes                   | Yes                  | Yes                   | Yes                   | Yes                   | Yes                 | Yes                  | Yes                  | Yes                  | Yes                   |
| Observations                 | 1984                  | 1984                 | 1984                  | 1984                  | 1984                  | 1984                | 1984                 | 1984                 | 1984                 | 1984                  |

<sup>1</sup> Statistiques  $t$  entre parenthèses

<sup>2</sup> \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.001$

<sup>3</sup> La variable dépendante est le flux migratoire entre les États mexicains

<sup>4</sup> Des écarts-types robustes regroupés par origine-destination

Les tests de fiabilité montrent que l'influence des facteurs climatiques sur la migration interne ne dépend pas du stade de développement ou de l'importance de l'agriculture dans l'État d'origine. Pour prendre en compte l'hétérogénéité potentielle, les variables climatiques sont croisées avec les écarts entre les PIB par habitant et la part du PIB dans l'agriculture. Cependant, aucune de ces interactions n'est significative. Le coefficient estimé de la durée de la plus longue période de sécheresse pendant la période de migration demeure significatif et du même ordre de grandeur que dans le cas du modèle de base lorsque croisé avec les deux variables. L'ampleur de la plus longue période de sécheresse est significative lorsque croisée avec la part du PIB dans l'agriculture. La part de l'agriculture dans l'État d'origine est négative et significative dans les deux modèles.

En tant que test de fiabilité supplémentaire, le modèle complet est calculé en prenant en compte un sous-échantillon qui n'inclut pas le couloir Distrito Federal - Mexico (le plus important flux de population au Mexique a lieu entre l'État de Mexico et le Distrito Federal). Les résultats de ce sous-échantillon sont en général très proches de ceux de l'échantillon complet.

Les résultats précédents suggèrent que les inondations et les périodes de sécheresse ont une influence directe sur la migration interne au Mexique, mais il est également possible qu'il existe des influences indirectes. Pour tester l'éventuelle présence de ces dernières, une régression de l'écart de revenus entre les États de destination et ceux d'origine sur les catastrophes et les variables liées aux conditions climatiques est effectuée, tout en contrôlant pour les homicides et les niveaux d'éducation. Les résultats de cette analyse montrent que les tremblements de terre, les ouragans, les inondations et les périodes de sécheresse ont un impact positif sur les écarts de salaires. Cela laisse penser que ces phénomènes naturels influencent indirectement la

migration interne au Mexique.

À la lumière des résultats précédents, un exercice est ensuite réalisé pour prendre en compte une méthode différente de mesure des écarts de salaires. En effet, à la lumière de l'endogénéité potentielle du PIB, le modèle complet est réalisé en utilisant un indice de privation comme proxy du revenu ou du salaire. Cet indice de privation couvre un certain nombre de dimensions associées au bien-être tels que le revenu, l'éducation et l'accès aux services de base <sup>7</sup>. Les résultats montrent que les variables représentant la durée et l'ampleur des périodes de sécheresse sont à la fois positives et significatives lorsque l'on considère l'indice de privation ; les coefficients liés à l'ampleur des inondations ne sont plus significatifs dans le cadre de la spécification qui utilise la privation comme proxy des salaires. Un résultat intéressant concerne les effets des ouragans. Lorsque l'indice de privation est utilisé comme proxy des salaires, l'effet des ouragans sur la migration est positif, mais il n'est significatif que lorsque les inondations ne sont pas contrôlées.

Je conclus l'analyse en utilisant une autre spécification du modèle complet qui tient compte à la fois des catastrophes naturelles et des variables climatiques, et ce dans les États d'origine comme dans ceux de destination. Pour ces derniers, toutes les variables sont présentées comme des écarts destination-origine. Les résultats montrent que les écarts de variables climatiques sont significatifs et négatifs. Cela suggère que les facteurs climatiques agissent comme facteurs d'incitation à la migration, mais aussi que les flux migratoires sont en moyenne orientés vers des destinations caractérisées par de meilleures conditions climatiques.

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<sup>7</sup> Cet indice est produit par le Comité d'évaluation des politiques de développement social (CONEVAL).



## Conclusion

Ce chapitre fournit une analyse fondée sur les faits en ce qui concerne les effets des changements environnementaux sur la migration interne au Mexique. En particulier, l'accent est mis sur le rôle des périodes de sécheresse et des inondations. À cette fin, un ensemble de données comprenant des informations sur la migration entre les États mexicains pour les périodes 2000 à 2005 et 2005 à 2010 est utilisé. Pour tenir compte des effets de la variabilité climatique sur la migration, une série d'indicateurs est construite sur la base d'un indice de précipitations standard (SPI). En outre, l'analyse contrôle pour les catastrophes naturelles qui ont également influencé la migration interne. En ce qui concerne la stratégie empirique, les informations sur les flux migratoires bilatéraux entre les États mexicains sont exploitées grâce à un modèle basé sur la gravité.

Les résultats montrent que les périodes de sécheresse comme les inondations agissent comme facteurs d'incitation à la migration interne au Mexique. En outre, les résultats montrent également que les écarts de revenu, les homicides, et le niveau d'éducation sont des facteurs clés de migration interne dans le pays.

Ce chapitre contribue à la littérature et alimente l'élaboration de politiques basées sur les faits en améliorant notre compréhension des effets de potentiels changements climatiques et des stratégies d'adaptation au Mexique. De plus, à ma connaissance, cette étude est la première à analyser des flux migratoires bilatéraux au Mexique grâce à un modèle basé sur la gravité et utilisant une structure de panel. Cette dernière limite les effets d'un éventuel biais de variables omises et fournit des résultats robustes.

# General introduction

The sustainability of water resources in Mexico is challenged, among other things, by inadequate regulation tools, limited enforcement capacity, and the uncertainty related to climate change. This thesis analyses key aspects of these challenges with the overall objective of contributing to the economic literature and providing inputs for evidence-based policy making.

The thesis is composed of three main chapters. The first chapter looks at the mechanisms regulating groundwater extraction and analyses the distortion caused by electricity subsidies and their effects on groundwater overdraft. The second chapter complements this analysis by looking at enforcement actions, studying the effects of environmental inspections on illegal water extraction. Finally, the third chapter addresses some of the concerns related to climate change by analysing the effects of droughts and floods on internal migration trends in Mexico.

The following paragraphs serve as an introduction to the thesis. They start by providing a general description of the situation of hydric resources and water institutions in Mexico during the last decade, which corresponds to the period of analysis of the three chapters. This is followed by a description of the main research questions. The introduction then concludes with an overview of each chapter.

## **A.1 Water in Mexico**

All around the world, water resources tend to be unevenly distributed both in space and in time. Mexico is not an exception. For historical reasons, both population and economic activities are located in the central and northern regions of Mexico. However, the largest water reservoirs are concentrated in southern parts of the country. This spatial mismatch between water supply

and demand translates into high accession costs, and further contributes to water stress in the main populated centres.

### **A.1.1 Water supply**

The water supply of a given territory is mainly defined by its geographic characteristics and the way they interact with the water cycle. During the water cycle, rainfall runs off into water reservoirs, where some of the water will remain as liquid and some will evaporate giving continuity to the cycle. Water reservoirs provide the actual water supply of a territory. These reservoirs can be on the surface in the form of rivers and lakes, or underground in the form of aquifers. Rivers and lakes are considered as renewable sources of water, however, their supplies vary according to the season, as well as from year to year. Groundwater, on the other hand, cannot always be considered as renewable. In some cases, when the time of recharge is too long, aquifers are actually treated as non-renewable resources.

The annual amount of rain in Mexico is considered to be close to 1,490 thousand million cubic meters. From this gross supply of water, it is estimated that 73% evaporates, 22% runs off into rivers and lakes and only 4% goes into groundwater deposits ([CONAGUA, 2010](#)). Once all this is taken into account, the net annual supply of renewal water in Mexico is estimated at 459 thousand million cubic meters<sup>8</sup>. On a per capita basis, the amount of available renewable water in Mexico is smaller than in other countries in the region. For instance, compared to its northern neighbours and in spite of having a bigger amount of rain during the year, Mexico's mean availability of renewable water per capita<sup>9</sup> represents 41% of that of the U.S. and 4% of

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<sup>8</sup> This amount takes into account international water imports and exports, as well as incidental recharges

<sup>9</sup> The mean availability of water refers to the total amount of renewable water, both

that of Canada, Table A.4.

**Table A.4** – International comparison of water supply.

| Region  | Country          | Rainfall<br>(Millimeters) | Mean availability<br>per capita (m <sup>3</sup> per hab) |
|---------|------------------|---------------------------|--|
| Africa  | Congo            | 1,646                     | 281,618  |
|         | Gabon            | 1,831                     | 126,154  |
|         | Liberia          | 2,391                     | 80,573   |
| America | Belice           | 1,705                     | 61,566   |
|         | Bolivia          | 1,146                     | 67,472   |
|         | Brazil           | 1,782                     | 44,081   |
|         | Canada           | 537                       | 93,549   |
|         | Chile            | 1,522                     | 57,291   |
|         | Colombia         | 2,612                     | 46,302   |
|         | United States    | 715                       | 10,293   |
|         | Guyana           | 2,387                     | 320,667  |
|         | French Guyana    | 2,895                     | 680,203  |
|         | <b>Mexico</b>    | <b>760</b>                | <b>4,312</b>   |
|         | Paraguay         | 1,130                     | 65,076   |
|         | Peru             | 1,738                     | 69,446   |
| Surinam | 2,331            | 250,501                   |  |
| Asia    | Laos             | 1,834                     | 56,836   |
|         | Turkey           | 593                       | 2,891  |
| Europe  | France           | 867                       | 3,320  |
|         | Greenland        | 350                       | 10,595,305   |
|         | Iceland          | 1,940                     | 574,588  |
|         | Norway           | 1,414                     | 81,967   |
| Oceania | Salomon Island   | 3,028                     | 90,298   |
|         | New Zeland       | 1,732                     | 78,146   |
|         | Papua New Guinea | 3,142                     | 146,651  |

**Source:** CONAGUA; Estadísticas del Agua en Mexico, 2008.

Water resources in Mexico are managed by the National Water Commission (CONAGUA)<sup>10</sup>. CONAGUA is a decentralised agency composed by 13 River Basin Organisations<sup>11</sup>. Each of them is in charge of one of the 13 Hydrological Administrative Regions (HAR) that govern water resources in the country.

superficial and groundwater, during a year. It does not include international water imports or exports.

<sup>10</sup> Comision Nacional del Agua (CONAGUA), <http://www.conagua.gob.mx/>

<sup>11</sup> *Organismos de cuenca* in Spanish

HARs are at the top of a nested administrative structure that accounts for both superficial and groundwater. Superficial water management is based on watersheds and river basins. There are 722 watersheds all across the country, which can be further divided into 1,471 river basins<sup>12</sup>. Groundwater resources are divided into aquifers. Today there are 653 aquifers in Mexico.

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<sup>12</sup> In Spanish, watersheds are defined as *Regiones Hidrológicas*, while river basins are defined as *Regiones Hidrográficas*.

Table A.5 – Mexico's water supply by HAR, 2008

| No.            | Hydrological<br>Administrative<br>Regions | Renewable<br>Water<br>( $\text{hm}^3/\text{year}$ ) | Renewable Water<br>per capita<br>( $\text{hm}^3/\text{hab}/\text{year}$ ) | Mean natural<br>surface runoff<br>( $\text{hm}^3/\text{year}$ ) | Mean aquifer<br>recharge<br>( $\text{hm}^3/\text{year}$ ) |
|----------------|---|---|---|---|---|
| I              | Peninsula de Baja California              | 4,626   | 1,257   | 3,367   | 1,259   |
| II             | Noroeste                                  | 8,323   | 3,208   | 5,074   | 3,250   |
| III            | Pacifico Norte                            | 25,627  | 6,471   | 22,364  | 3,263   |
| IV             | Balsas                                    | 21,680  | 2,049   | 17,057  | 4,623   |
| V              | Pacifico Sur                              | 32,794  | 7,955   | 30,800  | 1,994   |
| VI             | Rio Bravo                                 | 11,937  | 1,101   | 6,857   | 5,080   |
| VII            | Cuencas Centrales del Norte               | 7,884   | 1,898   | 5,506   | 2,378   |
| VIII           | Lerma-Santiago-Pacifico                   | 34,160  | 1,642   | 26,431  | 7,728   |
| IX             | Golfo Norte                               | 25,543  | 5,155   | 24,227  | 1,316   |
| X              | Golfo Centro                              | 95,866  | 9,969   | 91,606  | 4,260   |
| XI             | Frontera Sur                              | 157,754   | 24,043  | 139,739   | 18,015  |
| XII            | Peninsula de Yucatan                      | 29,645  | 7,442   | 4,329   | 25,316  |
| XIII           | Aguas del Valle de Mexico                 | 3,514   | 165   | 1,174   | 2,340   |
| National Total |   | 459,351   | 4,288   | 378,530   | 90,822  |

Note:  $1 \text{ hm}^3 = 1,000,000 \text{ m}^3$ . Source: Atlas del Agua 2010, CONAGUA.

The availability of renewable water per capita decreased in most hydrological administrative regions during the period 2001-2008. Indeed, only three out of the thirteen regions showed an increase in the availability of water per capita (Pacífico Norte, Cuencas Centrales del Norte, and Golfo Norte), Table A.5. The highest increase took place in the region Cuencas Centrales del Norte, where the availability in 2008 had increased by 6.4% with respect to 2001. The recharge of aquifers shows the opposite trend. In 2008, all but one region (Península de Baja California) showed an increase in their annual recharge compared to 2001 levels. Nevertheless, it should be mentioned that it is not clear from these data whether these changes are due to physical and meteorological phenomena or to human influence.

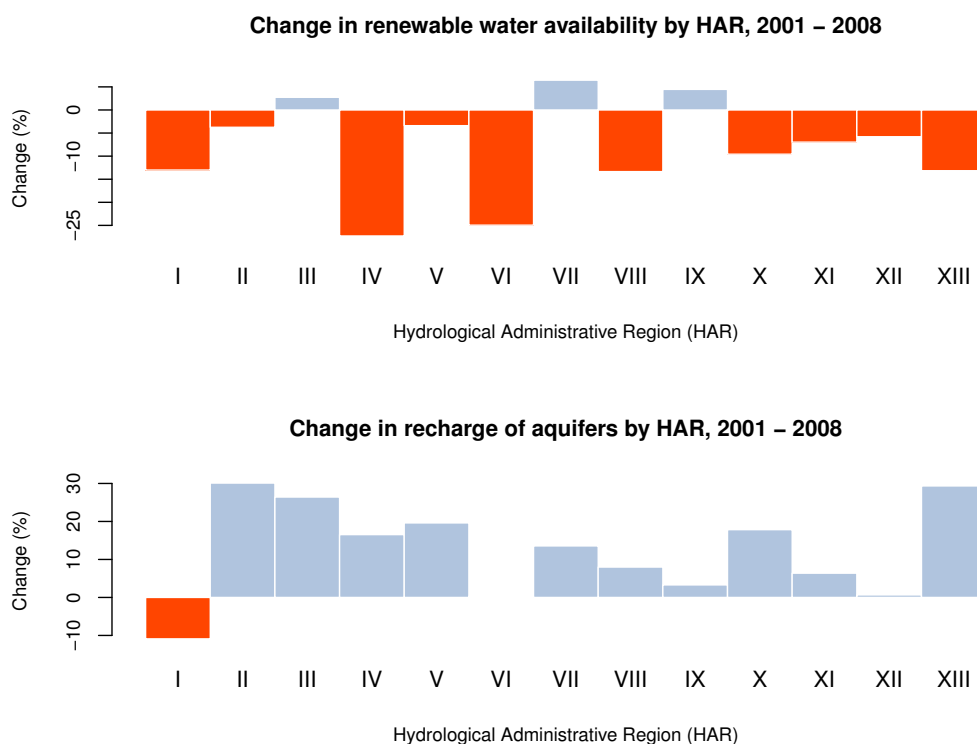
Southern regions in Mexico account for the biggest share of renewable water. Indeed, the region of Frontera Sur contains the highest concentration of superficial water, and the second highest concentration of groundwater; while its neighbouring region Península de Yucatan contains the biggest share of groundwater in the country. The region containing the smallest amount of both superficial and groundwater is the central region of Valle de Mexico (this region mainly comprises Mexico City). Due to the high concentration of population in this region, it also has the smallest value of renewable water per capita in the country ( $165 \text{ hm}^3/\text{hab}/\text{year}$ ), Table A.5.

### **A.1.2 Water consumption**

The amount of water consumed in a territory depends, among other things, on the size of its population as well as on the amount of goods and services produced. Between 2001 and 2008, Mexico's gross water extraction increased by 10%. This is equivalent to a yearly average growth rate of 1.36%. From a national perspective, this seems to be consistent with the annual average



**Figure A.2** – Change in water availability by HAR, 2001 - 2008

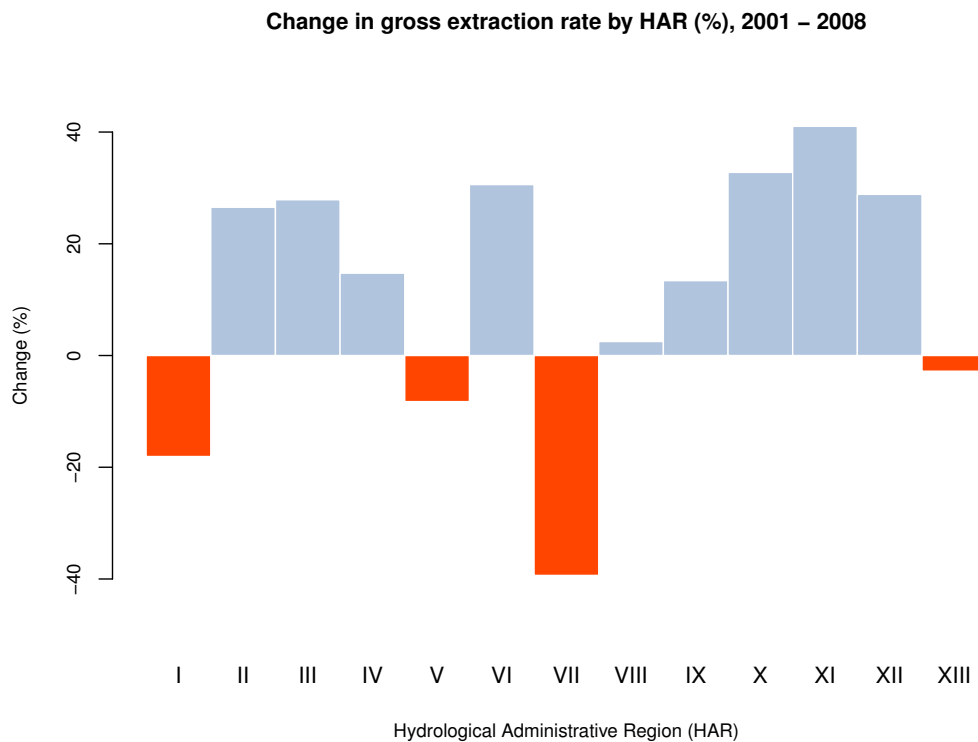


**Source:** Estadísticas de Medio Ambiente, INEGI.

growth rates of both population (1%) and real GDP (2.42%)<sup>13</sup>. However, during the same period, there were considerable differences in water extraction across HARs. Indeed, six out of the thirteen HARs increased their water extraction by more than 20%. This was particularly the case of the region Frontera Sur, where water extraction increased by 41%. The most important reduction in water extraction took place in the northern region of Cuencas Centrales del Norte, where water consumption decreased by 39%, Figure A.3.

Water use can be classified as consumptive and non-consumptive depending

<sup>13</sup> Computations made by the author using the real GDP estimates from the OECD's national accounts database and the population growth rate projections provided by the OECD's demographic database.

**Figure A.3** – Change in water extraction by HAR, 2001-2008

**Source:** Estadísticas de Medio Ambiente, INEGI.

on its use. Consumptive activities reduce water availability by not allowing any further use once water has been consumed. In contrast, non-consumptive activities have no impact on the availability of the resource. CONAGUA has classified consumptive activities in three general groups: agriculture, public supply, and self-supplying industry<sup>14</sup>. Non-consumptive activities on the other hand only considers hydropower generation.

In 2008, around 63% of the total water consumed came from superficial

<sup>14</sup> The agriculture class includes agricultural, livestock, aquaculture activities, as well as some of the irrigation districts that are not yet classified; the public supply class accounts for both municipal and domestic users; self-supplying industry refers to those industries that obtain water directly from rivers and aquifers.

water reserves, while the remaining percentage was obtained from aquifers (CONAGUA, 2010). During the same year, the user group that extracted the biggest share of water was agriculture (77%), followed respectively by public supply (14%), hydropower generation (5.1%) and self-supplying industry (4.1%). From a regional perspective, the HAR Lerma-Santiago-Pacifico was the one accounting for the highest water consumption in agriculture (14.63%), Table A.6.

**Table A.6** – Water allocation by HAR and type of activity, 2008

| No.           | HAR                          | Agriculture (%) | Public (%) | Industry (%) | Hydropower (%) |
|---------------|------------------------------|-----------------|------------|--------------|----------------|
| I             | Peninsula de Baja California | 3.63            | 0.41       | 0.11         | 0.25           |
| II            | Noroeste                     | 8.18            | 1.23       | 0.11         | 0.01           |
| III           | Pacifico Norte               | 12.21           | 0.80       | 0.07         | 0.00           |
| IV            | Balsas                       | 7.91            | 1.25       | 0.28         | 3.98           |
| V             | Pacifico Sur                 | 1.25            | 0.42       | 0.02         | 0.00           |
| VI            | Rio Bravo                    | 9.70            | 1.48       | 0.26         | 0.14           |
| VII           | Cuencas Centrales del Norte  | 4.23            | 0.47       | 0.08         | 0.04           |
| VIII          | Lerma-Santiago-Pacifico      | 14.63           | 2.58       | 0.52         | 0.03           |
| IX            | Golfo Norte                  | 4.62            | 0.66       | 0.59         | 0.08           |
| X             | Golfo Centro                 | 3.71            | 0.93       | 1.10         | 0.47           |
| XI            | Frontera Sur                 | 2.04            | 0.57       | 0.13         | 0.00           |
| XII           | Peninsula de Yucatan         | 1.81            | 0.59       | 0.56         | 0.01           |
| XIII          | Aguas del Valle de Mexico    | 2.82            | 2.64       | 0.27         | 0.10           |
| Country Total |                              | 76.76           | 14.04      | 4.09         | 5.11           |

**Source:** Atlas del Agua 2010, CONAGUA.

A number of HARs are characterised by water stress. Water stress refers to water scarcity. It is computed as the ratio between the water consumed and the amount of renewable water available in a region. In practical terms, water stress measures the incapacity of water supplies to satisfy the quantity of water demanded. Water stress is estimated at 17.4%, which under international standards is considered to be acceptable (CONAGUA, 2010). Nevertheless, certain regions in the country are particularly affected by water stress<sup>15</sup>. In 2008, eight out of thirteen HARs experienced water stress levels higher than 40%, Figure A.4. The region facing the highest level of scarcity is Valle de Mexico, where water stress reached 132%.

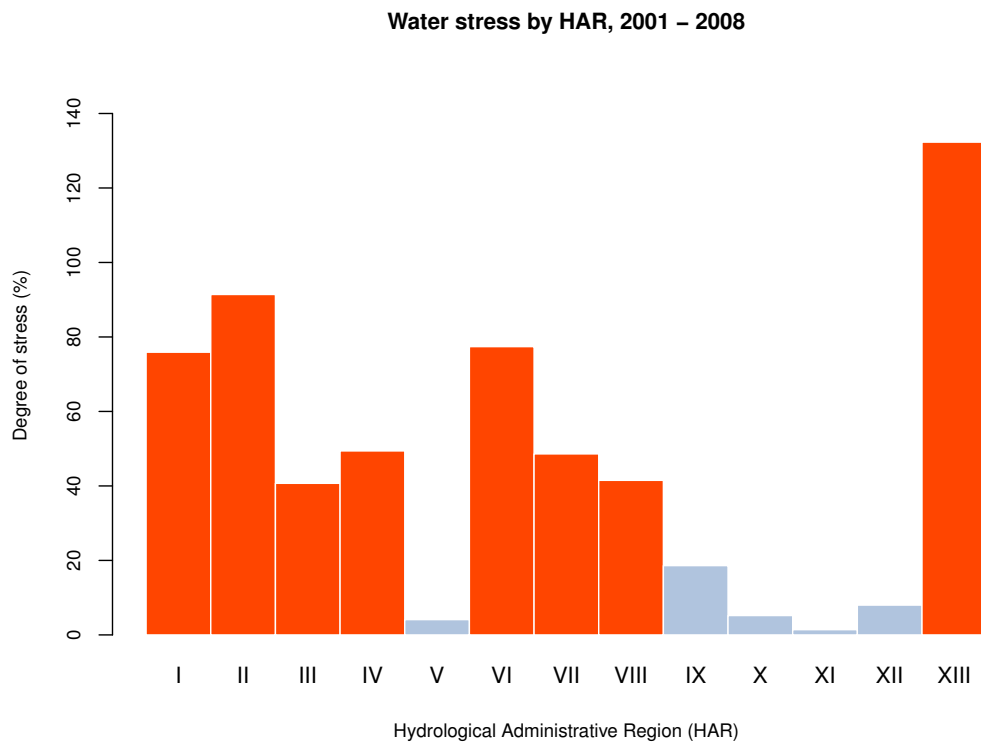
### A.1.3 Water and population

Although population growth rates have significantly decreased in the past three decades, Mexico still faces significant challenges regarding the high concentration of population in particular regions of the country. During the 70s, the average annual growth rate at the national level was 2.6%. By the end of the 90s, the average growth rate had decreased by 40% (compared to the 70s), reaching an average value of 1.66%. The average annual growth rate during the period 2000 - 2010 was 1.02%, i.e. 60% lower than during the 70s.

In 2009, the total population in Mexico was estimated in 107 million people (INEGI, 2009). Most of this population was concentrated in a small number of populated centres. Indeed, the highest concentration of population was found in the centre of the country in Mexico City. Mexico City metropolitan area accounted for 20% of the total population in the country (INEGI, 2010a).

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<sup>15</sup> Regions with values of water stress higher than 40% are usually considered as under sever scarcity.

**Figure A.4** – Degree of water stress by HAR, 2001-2008

**Source:** Atlas del Agua 2010, CONAGUA.

Table A.7 – Socio-economic characteristics by HAR, 2008

| No.  | HAR                          | Surface (%) | Renewable Water (%) | Population (%) | GDP (%) |
|------|------------------------------|-------------|---------------------|----------------|---------|
| I    | Península de Baja California | 7.42        | 1.01                | 3.44           | 3.51    |
| II   | Noroeste                     | 10.47       | 1.81                | 2.42           | 2.58    |
| III  | Pacífico Norte               | 7.76        | 5.58                | 3.70           | 3.12    |
| IV   | Balsas                       | 6.09        | 4.72                | 9.88           | 11.03   |
| V    | Pacífico Sur                 | 3.96        | 7.14                | 3.85           | 1.83    |
| VI   | Río Bravo                    | 19.37       | 2.60                | 10.12          | 14.70   |
| VII  | Cuencas Centrales del Norte  | 10.34       | 1.72                | 3.88           | 2.66    |
| VIII | Lerma Santiago Pacífico      | 9.72        | 7.44                | 19.42          | 14.53   |
| IX   | Golfo Norte                  | 6.49        | 5.56                | 4.63           | 6.79    |
| X    | Golfo Centro                 | 5.35        | 20.87               | 8.98           | 4.78    |
| XI   | Frontera Sur                 | 5.17        | 34.34               | 6.13           | 4.76    |
| XII  | Península de Yucatán         | 7.03        | 6.45                | 3.72           | 8.45    |
| XIII | Valle de México              | 0.84        | 0.76                | 19.85          | 21.27   |
|      | Total                        | 100.00      | 100.00              | 100.00         | 100.00  |

Source: Atlas del Agua 2010, CONAGUA.

The availability of renewable water resources does not match the spatial concentration of the Mexican population. The hydrological administrative region of the Valle de Mexico accounts for almost 20% of the population of the country, however it has access to less than 1% of the total amount of renewable water resources. In contrast, the region of Frontera Sur has 34% of the renewable water of the country, while it only hosts 6% of the population, Table A.7.

Economic activity is also concentrated in regions with low water availability. In 2008, the HAR of the Valle de Mexico accounted for 21.3% of the GDP, while it only had access to less than 1% of the renewable water resources in the country, Table A.7. Moreover, the three HARs with the highest share of the GDP (which account for almost 50% of total GDP) only have about 11% of the total renewable water resources.

## A.2 Water institutions

There is no single definition for the term institutions. Nevertheless, institutions can be broadly seen as a set of rules and norms that apply to a particularly group of people, in a specific moment in time. From an economic perspective, institutions tend to be seen as the rules of a game. These rules, through a set of constraints, define the behaviour of the players, who in practice are represented by economic agents ([North, 2009](#)). Following this notion of institutions, as well as the political structure of Mexico, water institutions can be framed on the three levels of the Mexican government: Constitutional, Federal and State levels.

The Mexican Constitution is placed at the top level. It establishes one of the most relevant concepts regarding the use of water resources in Mexico: all



water bodies, on the surface and underground, belong to the Mexican State. The latter is embodied in Article 27, which further states that the Mexican government is the only one in charge of providing concessions to firms, individuals or public agencies for the use and extraction of water resources.

Federal laws lie below the Mexican Constitution. At present, most of the instruments and mechanisms for managing water resources in Mexico are defined by the National Water Law (Ley de Aguas Nacionales, LAN). The LAN is the most important law regarding water resources in Mexico. It is complemented by the Federal Duties Law (Ley Federal de Derechos, LFD), which defines the fees to be paid for water extraction activities as well as those for water discharges.

Laws at state level are established by their respective congress, and are applied by state ministries. Although they must respect federal legislation, they allow state and local governments to define the tariffs of water and sanitation services. They also allow local governments to define their own pollution standards.

### **A.2.1 Institutional change in the water sector**

The institutions governing water resources in Mexico have evolved during the last century. Once mainly concerned with issues regarding water supply infrastructure, institutions today aim to account not only for hydrologic considerations, but also for the most relevant socio-economic and environmental processes interacting with water resources. Nevertheless, certain factors such as the spatial mismatch between supply and demand, and the limited implementation capacity have hindered the potential benefits from such institutional changes.

Following the Mexican revolution in 1910, a series of laws referring mainly to the procedures related to the development of infrastructure for water conveyance were conceived by the federal government. It was not until 1972 when the first water law was adopted. From a legal point of view, its main purpose was to centralise all the different laws affecting the water sector. As described by [Roemer \(1997\)](#), the next two decades following the adoption of this law were characterised by a legal system that promoted an inefficient allocation of water among the different users and economic activities. Indeed, concessions did not take into account criteria such as use value or scarcity, instead they were based on a user priority system. Domestic users received the highest priority, followed by agriculture and industrial users. Inefficiencies were also echoed within economic activities. For instance, during a drought, irrigation districts would allocate water evenly among users without taking into consideration the value of the crops produced. Legal uncertainty also played an important role by not providing the incentives for an adequate use of the resource. This was particularly the case of the terms of use of concessions: concessions could be canceled after two years of not being used or when the government decided so. In addition to the latter, since private investment was not allowed by law, most of the investment done in the water sector came from the federal government. However, most water projects were characterised by an incorrect pricing scheme that did not allow to recover infrastructure and operational costs. As a result, probably accentuated by public budget constraints, water infrastructure was undersupplied. It should be mentioned that today, in spite of a clear cost-recovery policy established by the LAN, this problem is still present.

In reaction to the recurrent economic crisis during the decades of the 70s and 80s, Mexican authorities intended to carry out a structural change for the

whole economy. These reforms aimed to remove the inefficiencies caused by public interventions, and to reduce the government deficit, which was driven by direct and indirect transfers to key economic sectors, (Roemer, 1997). Moreover, in order to participate in NAFTA, Mexico was under a lot of pressure to modernise its water sector. Given the state of the infrastructure, it was necessary to establish a new water policy that would increase industrial and agriculture productivity, ensure conservation, and address supply and maintenance issues. It was thus necessary to improve the regulation of water extraction. As a result the National Water Law (LAN) was promulgated in 1992. The main objectives of this law were:

- To improve the participation of water users in the water management process;
- To centralise planning activities in one federal organism in charge of both the quality and quantity of water;
- To improve legal security to facilitate private investment on the medium and long terms; and
- To incorporate environmental principles as the "polluter pays".

In practice, the LAN intended to incorporate economic mechanisms to manage both the supply and demand of water resources. To do so, key economic and regulatory instruments were put into place. To improve the supply of water infrastructure, the LAN allowed the participation of the private sector in water projects. Water projects had to include a pricing scheme that would allow full-cost recovery of operations, maintenance, and system improvements. Furthermore, the LAN also established that all water users were to pay a fee for the development of national water projects, as well as an additional fee to manage water discharges for avoiding pollution in water

bodies. To correct for the inefficiencies during the water allocation process, the LAN provided the legal tools to create formal water markets. Markets were limited to exchanges at the basin level. To formalise these markets, and to have control on the extraction of both superficial and groundwater resources, it was compulsory for all concession holders to be registered in the public registry of water duties (Registro Publico de Derechos de Agua, REPDA).

In 1992, in parallel to the creation of the LAN, the Article 27 was modified in order to amend the rights regarding communal lands. The land reforms carried out during the 1930s in rural areas resulted in two types of land ownership: "pequeña propiedad" (small property) and "ejido" (communal land). Ejidos were characterised by having a legal identity, and their members (known as "ejidatarios") were allowed to use and inherit the land but they were not allowed to sell it. The reforms to Article 27 allowed the sale and mortgage of ejidos.

The LAN imposed a radical change in the way that water resources were managed. On the one hand, it centralised the national water policy in the hands of the CONAGUA, which was also assigned with full control of the allocation of water concessions in the country. On the other hand, the LAN carried out an aggressive decentralisation process that removed key responsibilities regarding water provision from the federal government.

In 2004, following the experienced gained in the previous 12 years, the LAN was amended. The main objective of this reform was to recognise the concept of Integrated Water Resources Management (IWRM) as a national security priority and to define the aquifers and basins as the main units for water management in Mexico. The main outcome of this reform was the creation

of the 13 River Basin Organisations (RBOs) that were put in charge of managing water resources at the basin level. Although these reforms required the decentralisation of CONAGUA into 13 regional offices, the government decided to maintain CONAGUA's headquarters in Mexico City.

In spite of the potential benefits following these reforms, key issues are still unsolved. For instance, reforms did not take into account disparities in terms of availability and accessibility of water resources; and provided the federal government with full control of the allocation of water in the country while passing all the investment costs onto regional authorities ([Wilder and Romero-Lankao, 2006](#)). Overall, the decentralisation process has been considered by law, but not fully implemented in practice ([Barkin, 2005](#); [Shah et al., 2004](#); [Wilder, 2010](#)). Moreover, key issues at the core of these reforms are still unsolved. The latter regards the lack of proper enforcement and inadequate pricing mechanisms (further enhanced by distorting agricultural subsidies) that have hindered the expected outcomes of these reforms ([Shah et al., 2004](#)).

### **A.3 Research questions**

The outcomes of the reforms in the water sector in Mexico did not translate into a regulatory system that effectively controls groundwater extraction. In particular, the lack of an adequate pricing scheme and the provision of subsidies embedded in electricity fees are two of the most important factors promoting groundwater overdraft.

Inefficiencies in the internal design of the concessions prevent the adequate allocation of water resources in Mexico. Probably the most important deficiency in the design of the concessions is the method establishing the maxi-

mum limit for extraction. The maximum limit established by the concessions is based on the technical characteristics of the pumping system (Shah et al., 2004; Cob and Romero, 2011) and not on a scheme promoting the conservation of the resource. The latter implies that the constraints imposed by the concessions are rarely binding. Moreover, even when this constraint is binding, the price paid for any additional cubic meter is very low. Actually, agricultural activities pay the lowest price in the country. This price is the same for all the regions of the country, independently of the availability of water in the region.

Irrigation activities benefit from highly subsidised electricity tariffs. Since 2003, Mexican authorities have promoted the competitiveness of the agricultural sector by subsidising the electricity tariffs for irrigation activities. Estimates suggest that electricity tariffs have received subsidies up to 83% of energy production costs (Cob and Romero, 2011).

As a result of ineffective regulatory mechanisms, the number of Mexican aquifers classified as overexploited has increased in the past decades. By the end of 2010, there were 101 (out of 653) aquifers in the country classified as overexploited, compared to 32 overexploited aquifers in 1975 (CONAGUA, 2010).

Based on these issues, the first research question of this thesis is: *how does the allocation of groundwater and other key inputs react to changes in pumping costs?*

In addition to the inadequate regulatory system, groundwater overdraft seems to have been enhanced by illegal water extraction. Although Mexican authorities have attempted to control illegal water extraction, a series of constraints have hindered these efforts.

Imposing the legal framework governing water resources has been one of the most important challenges faced by Mexican authorities during the last decades. Despite being compulsory for every agricultural, industrial, and municipal water user to have a concession, an important number of these users operate without it. Unauthorised water extraction is particularly frequent among agricultural users. Considering that irrigators are the most intensive users of groundwater in the country, reducing unauthorised extraction within the agricultural sector is key for limiting water overdraft.

Regulatory efforts are further challenged by the fact that a large number of water users is scattered across large extensions of land. Thus, verifying the compliance of users can be very costly. As a consequence, a number of producers does not respect extraction limits or even lacks a concession (permit) to extract groundwater. This type of producers is present all across the country showing a complex spatial pattern: they are present in regions with different levels of water availability and income; tend to cluster without respecting administrative boundaries; and can be close or remote from important populated centres.

Regional basin organisations implement inspections according to their financial capacity and priorities. Some of the main challenges faced by CONAGUA have been related to the limited capacity of basin councils and regional offices for carrying out inspections. The latter included unskilled personnel and the lack of adequate equipment (CONAGUA, 2012b).

The second research question is thus: *whether environmental inspections reduce the number of illegal water users in Mexico?*

Water stress is not only induced by institutional failures, it can also be prompted by external shocks associated to climatic changes. Moreover, these

changes influence a number of socio-economic processes among them migration.

Although most of the attention of academics and international organisations has been focused on international migration - Mexico being one of the most important migration corridors in the world - internal migration accounts today for a much bigger flow of population. Between the period 2005-2010, the migration flow across Mexican states represented 3.3% of the total population in the country, compared to 1.1% for the population moving to another country ([INEGI, 2010b](#)).

Climate change will have significant and negative impacts on Mexico, but the extent of these impacts will be different across regions within the country. Recent projections suggest that by the end of the century temperatures may increase between 1 and 4 degrees Celsius, while rainfall could decrease by 11%. Moreover, these projections further suggest that effects will be stronger in northern and northwestern areas of Mexico, which are characterised by arid climates ([Estrada et al., 2013](#)).

Migration is one of many possible strategies that individuals can adopt following environmental changes ([Millock, 2015](#)). For instance, economic activities in rural areas tend to rely on the environment as an input for production, which makes the population in these areas particularly exposed to environmental changes.

Mexico's geographic characteristics make some regions more prone to be affected by droughts. [Ortega-Gaucin and Velasco \(2013\)](#) revise the latest droughts that have affected Mexico since the 1990s pointing out the high frequency and magnitude that have characterised recent episodes of droughts. For instance, the basin of the Bravo river experienced one of the longest



drought episodes in Mexico’s modern history, lasting between 1993 and 2005 and having important hydrological side-effects in Nuevo Leon, Chihuahua, Coahuila, and Tamaulipas. Moreover, between 2009 and 2011, Mexico experienced some of the strongest droughts of the last 70 years.

Floods are also common in some states of the country, causing important material losses. In 2010, extreme precipitation and floods in the states of Michoacan, Distrito Federal, Mexico, Oaxaca and Chiapas caused losses for over MEX\$15,000 million, or approximately US\$1,200 million ([García Arróliga et al., 2011](#)).

The third and last question addressed by this thesis is: *whether droughts and floods are drivers for internal migration across Mexican states?*

## **A.4 Overview of the chapters**

### **A.4.1 Groundwater overdraft, electricity, and wrong incentives: evidence from Mexico**

In this chapter, I focus my attention on irrigators based in aquifers suffering from groundwater overdraft in Mexico. I analyse the different effects following a change in the price of groundwater over the allocation of production inputs. To this end, I use a combination of data sources to estimate a cost function that further allows to compute different types of elasticities. These data sources include a unique dataset containing micro-data on the most relevant characteristics of firms based in aquifers suffering from high extraction rates, official statistics, as well as information on environmental characteristics built through geographic information systems (GIS).

This chapter contributes to the existing literature by providing estimates on

cross-price elasticities related to irrigation water demand in Mexico. Indeed, my results show that changes in the price of groundwater affect the allocation of labour and fertilisers. Cross-price elasticity estimates show that labour and fertilisers act as a substitute for groundwater. According to my estimates, an increase of 10% in groundwater price in overexploited aquifers could reduce on average water consumption by 5%.

The results from this study aim to provide Mexican policymakers with evidence that contributes to the ongoing water reforms. Results further suggest that implementation of programmes aiming at decoupling electricity subsidies and raising electricity fees will face important challenges. The small willingness to accept the potential decoupling of electricity subsidies imposes real and critical challenges for Mexican authorities. Moreover, this percentage hides important regional variations. The latter suggests that existing policy strategies should not only account for territorial difference, but further acknowledge the spatial heterogeneity of policy outcomes.

#### **A.4.2 The geography of illegal groundwater extraction in Mexico**

This analyses the deterrence effect of environmental inspections on the number of illegal water users. To this end, I control for socio-economic characteristics, as well as for territorial policies such as prohibition zones and closed aquifers. For the latter, I build a series of indicators using official data sources and geographic information systems (GIS). With regard to my empirical strategy, I estimate the effect of environmental inspections through an instrumental variable approach.

Results show that one additional inspection during the previous year can reduce the average number of illegal water users in each municipality by

1% - 3%. Although this effect appears to be strong, the effectiveness of environmental inspections as a mechanism for achieving water sustainability is hindered by the low frequency of inspections across the country. Indeed, the average number of inspections per year in Mexico was 2 per municipality in the period used for the analyses (2007-2009).

This chapter provides the first econometric analysis regarding illegal water extraction in Mexico. Moreover, to my knowledge it is also the first one analysing the effects of environmental inspection outside industrial and manufacturing activities in the country. This chapter contributes to the economic literature by improving our understanding of the effectiveness of enforcement mechanisms in a context characterised by weak institutions. Moreover, it also provides guidance on how to enhance development strategies aiming to both curb the number of unauthorised water users and reduce groundwater overdraft.

#### **A.4.3 Do climatic events influence internal migration? Evidence from Mexico**

This chapter provides evidence-based analysis regarding the effects of environmental change on internal migration in Mexico. In particular, I focus on the role of droughts and floods. To this end I exploit a dataset including information on migration across Mexican states for the periods 2000 - 2005 and 2005 - 2010. To account for the effects of weather variability on migration, I build a series of indicators based on a Standardised Precipitation Index (SPI). Moreover, I control for natural disasters that have further influenced internal migration. Regarding the empirical strategy, I exploit the information on bilateral migration flows across Mexican states through a gravity-based model.

Results show that both droughts and floods act as push factors for internal migration in Mexico. In addition, results also show that income differential, murders, and educational attainments are key drivers for internal migration in the country.

This chapter contributes to both the literature and evidence-based policy making by improving our understanding of the effects of potential climatic changes and adaptation strategies in Mexico. Moreover, to my knowledge, it is the first analysis of bilateral migration flows in Mexico carried out through a gravity-based model using a panel structure. The latter limits the effects of a potential omitted-variable bias, providing robust results.



## Chapter 1

Groundwater overdraft, electricity, and  
wrong incentives: evidence from Mexico

## 1.1 Introduction

The high rate of groundwater extraction in Mexico is threatening the sustainability of an increasing number of aquifers in the country. Today in Mexico 1 out of 6 aquifers is considered to be overexploited (CONAGUA, 2010). Groundwater overdraft is not only an important cause of major environmental problems, but it has also a direct impact on economic activities and the wellbeing of a high share of the population. Indeed, overexploited aquifers in Mexico are the main source of fresh water for 75 million people (CONAGUA, 2010).

Groundwater overdraft has been mostly driven by the agricultural sector. Agriculture accounts for 70% of all the groundwater extracted in Mexico. Policies trying to improve the competitiveness of the agricultural sector have distorted the price of groundwater. These include the lack of an adequate pricing scheme and the provision of subsidies for production inputs. In the case of the latter, subsidies embedded in electricity fees have been probably one of the most important factors promoting groundwater overdraft. This follows from the fact that electricity is the main source of energy for pumping groundwater in Mexico; and that under the current system of concessions, the price of groundwater is practically equal to zero.

Although during the past decade the possibility of decoupling this subsidy has been at the centre of important debates, there is little empirical evidence on the effects of changes in the price of groundwater over the allocation of key production inputs. This paper contributes to evidence-based policy making in Mexico by estimating cross-price elasticities for groundwater, labour and fertiliser.

My analysis builds on previous empirical work analysing the factors driving groundwater demand<sup>1</sup>. Irrigation technology appears in the literature as one of the most important determinants of groundwater consumption. More precisely, the choice of irrigation technology has a direct impact on groundwater demand. Traditional irrigation methods like furrow and flooding are more water intensive than sprinklers and drip technologies. Moreover, the choice of irrigation method is closely linked to the type of crop being produced. [Caswell and Zilberman \(1985\)](#) study the determinants of irrigation technology in six counties in California using a multinomial econometric model. Their results show that the likelihood of adopting a more water-saving technology increases when the price of water increases. Moreover, according to these results the adoption of more efficient technologies seems to be more important in the case of irrigators relying exclusively on groundwater. Following a similar methodology, [Green et al. \(1996\)](#) show that the adoption of irrigation technologies is highly dependent on crop choice. Their results show that the price of water does influence the adoption of more efficient technologies, however it is not the most important factor. Instead, physical and agronomic characteristics seem to play a more important role.

Another important area of research within the literature from which my analysis builds on is the estimation of groundwater elasticity. Although estimation methods have varied mostly depending on data availability and the type of pricing scheme (or lack of it), previous results show that the demand for groundwater is inelastic. Since in most cases groundwater lacks a proper pricing system, it is a common practice to use an indirect method to identify the marginal cost of groundwater extraction (also known as pumping costs).

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<sup>1</sup> For a more detailed discussion on the economic aspects of groundwater extraction and a more extensive review of the literature see [Koundouri \(2004\)](#) and [Schoengold and Zilberman \(2007\)](#).



For instance, [Nieswiadomy \(1988\)](#) computes the price of pumping water as the energy needed to pump one acre foot of water per foot of lift times the average lift expressed in dollars. Nieswiadomy uses county data to analyse the adaptability of irrigators in Texas to changes in the relative prices of different inputs including groundwater. To capture input substitution effects this study uses a Translog cost function. This model provides an estimate for the elasticity of groundwater equal to  $-0.25$ . In addition, these results suggest that groundwater is used as a substitute for both labour and furrow (irrigation method). Having access to a richer dataset, [Ogg and Gollehon \(1989\)](#) analyse a sample of farms in 16 Western states in the United States. The price of groundwater is computed as the total cost of the fuels used for groundwater extraction divided by the total amount of water used. These authors use different specifications while controlling for different climatic regions. Their elasticity estimates, despite the fact that they vary across regions, are similar to the ones from [Nieswiadomy \(1988\)](#) ranging from  $-0.24$  to  $-0.34$ . [Moore et al. \(1994b\)](#) also account for differences across regions and across different types of crops. These results further suggest that the response to a change in the price of groundwater is different among crops, and in some cases could even be positive.

All these studies assume that the marginal cost of extraction remains the same independently of the pumping intensity, but this may not be the case in practice. [Kanazawa \(1992\)](#) considers this assumption to be inadequate and highlights the possible presence of endogeneity when estimating water demand through a specification relying on a single equation. This author proposes to use a system of equations accounting for both the demand and supply of groundwater while controlling for certain hydrological characteristics of the aquifers under study. The results following this analysis not only

confirm the presence of increasing marginal costs of pumping water, but they also suggest that water and physical capital can be considered as substitutes for production.

The linkage between energy and groundwater has received increasing attention in the economic literature. [Zilberman et al. \(2008\)](#) provide an extensive discussion on the linkage between energy and water, highlighting the fact that higher energy prices will make extraction and conveyance of water more costly. The latter suggests that energy prices could be considered as a useful policy tool for coping with environmental issues related to groundwater overdraft. Nevertheless, these authors further highlight that technological improvements making extraction and transportation cheaper can offset the effects of rising energy prices. For this reason, institutional capacity and mechanisms that improve water allocation will be key for future reforms aiming to improve water sustainability.

Evidence shows that changes in energy prices have a direct influence on water consumption, but also on crop choices. In the case of developed countries, [Schoengold et al. \(2006\)](#) is one of the first studies using panel data for analysing the energy water linkage. These authors analyse the effects of changes in the prices of energy over the water demand in California's San Joaquin valley. The results from this study show that farmers respond to changes in the marginal price of water, both by reducing the consumption of water (intensive margin) and by modifying crop allocation (extensive margin). The total own price elasticity estimated in this study is  $-0.78$ , which is a value significantly higher than previous estimates. [Hendricks and Peterson \(2012\)](#) study the demand for irrigation water in the High Plains (U.S.). Also relying on a long panel dataset, they estimate the elasticity for irrigation water at  $-0.1$ , further showing that most of the adjustment in water occurs

at the intensive margin. They suggest that constraints on the number wells following water rights could be a possible reason for such a low value. [Pfeiffer and Lin \(2014\)](#) also analyse the effects of changes in energy prices on irrigation demand in Kansas through a panel dataset between 1996 and 2013. Their results are consistent in showing changes in both the intensive and extensive margin; they estimate the elasticity of irrigation water at  $-0.26$ . [Hornbeck and Keskin \(2014\)](#) analyse the evolution of irrigation practices in the Ogallala aquifer in the U.S. Using longitudinal, they compare counties in the Ogallala with those outside the aquifer in the same state. Results show that better water accessibility in the Ogallala allowed farmers in the short run to increase irrigation intensity, making crop yields less sensitive to drought. However, in the long run, farmers shifted land towards water intensive crops, making crop yields more sensitive to drought. Using a different approach based on positive mathematical programming, [Graveline and Mérel \(2014\)](#) analyse the effects of reduced water availability in the northern French region of Beauce. According to these results, changes in water availability will not only be reflected in both the intensive and extensive margins, but also will bring farmers to increase the acreage of rain-fed crops at the expense of irrigated crops. This change is considered to account for 57% of the total adjustment.

In the case of developing countries, India has received particular attention. [Kumar \(2005\)](#) provides a theoretical model to analyse farmers' response to changes in electricity tariffs and groundwater allocation regimes. This analysis shows that unit pricing of electricity promotes a more efficient use of groundwater. Moreover, this author also suggests that a combination of electricity pricing schemes, along with fixed allocation of groundwater, can further enhance both water and electricity productivity. Also for India, [Badi-](#)

[ani and Jessoe \(2013\)](#) empirically analyse the effects of changes in electricity prices on groundwater extraction at the district level. According to their estimates, groundwater elasticity equals  $-0.13$ . Moreover, these authors further suggest that electricity subsidies in India promote the production of water intensive crops such as rice.

Only a small number of studies have empirically analysed the effects of groundwater overdraft in Mexico. The increasing number of overexploited aquifers in the country, and the recognition by Mexican authorities of the perverse incentives created by electricity subsidies, has caught the attention of a small number of academics. However, so far, most of these studies have been limited to analysing the political economy behind the linkage of groundwater overdraft and electricity. [Shah et al. \(2004\)](#) compare the Indian and Mexican experience in terms of groundwater management, and provide a comprehensive review of the water reforms carried out in Mexico during the last two decades. [Scott and Shah \(2004\)](#) provide an insightful review of the institutional context and key policy constraints characterising the groundwater sector in India and Mexico. Based on the experiences of both countries, this study further suggests that regulatory instruments based on power supply controls could provide incentives for a more efficient use of groundwater. However, these types of instruments could impose certain technical and political costs that should be considered before any attempt of implementation. [Muñoz et al. \(2006\)](#) analyse the effects of changes in electricity prices over groundwater consumption in Mexico. This study uses a cross-sectional sample of irrigators in different Mexican states. The price of groundwater for each farmer is computed using a methodology similar to [Ogg and Gollehon \(1989\)](#), i.e. the price of groundwater is considered as the ratio of the electricity bill with respect to the total water consumed. The value of the elasticity

of groundwater found by these authors is equal to  $-0.16$ . More recently, following the efforts of Mexican authorities in reducing poverty, the World Bank carried out a study analysing the linkage between groundwater overdraft and poverty at the municipal level (WorldBank, 2009). This study agrees with Muñoz et al. (2006) on the role of electricity as one of the main drivers of groundwater overdraft, but concludes that the effect of aquifer overexploitation on the level of municipal poverty is not significant. The latter may be due to the fact that poor producers do not use groundwater, instead they rely on water-wheels and surface water. In spite of the important contributions provided by these studies there are still some important issues to be addressed, including the way in which producers substitute groundwater for other production inputs, as well as policy alternatives for decoupling the electricity subsidy.

In this paper I focus my attention on irrigators based in aquifers suffering from groundwater overdraft in Mexico. I analyse the different effects following a change in the price of groundwater over the allocation of production inputs. To this end, I use a combination of data sources to estimate a cost function that further allows to compute different types of elasticities. These data sources include a unique dataset containing micro-data on the most relevant characteristics of firms based in aquifers suffering from high extraction rates, official statistics, as well as information on environmental characteristics built through geographic information systems (GIS).

My empirical strategy exploits regional variation across producers in different Mexican states. Due to limited data availability I cannot analyse changes in water consumption or the allocation of other key production inputs in the long-run. Instead, I focus on changes in the short-run. I frame my analysis around the neo-classical theory of the firm and model producers technology

through a Translog cost function. The main advantage of this approach is that it allows to compute cross-price effects, i.e. the effects of changes in the price of one input over the quantity consumed of other variable inputs. To improve the robustness of my results I use simulation techniques to compute standard errors and confidence intervals of all estimates. The latter follows the concerns highlighted in the literature about classical statistical test (relying on linear approximations) applied to Translog elasticity estimates (Anderson and Thursby, 1986; Krinsky and Robb, 1991).

The contribution of this study is twofold. In the first place, this study aims to contribute to the existing literature by providing estimates on cross-price elasticities related to irrigation water demand in Mexico. Indeed, my results show that changes in the price of groundwater affect the allocation of labour and fertilisers. Cross-price elasticity estimates show that labour and fertilisers act as a substitute for groundwater. In other words, an increase in the price of groundwater increases the quantity consumed of both labour and fertilisers. To my knowledge, this is the first study focusing on Mexico providing these estimates. In addition to cross-price elasticities, this study provides a more up to date estimate on the price elasticity of groundwater. According to my estimates, an increase of 10% in the price of groundwater in overexploited aquifers *on average* could reduce water consumption by 5%. Secondly, the results from this study aim to provide evidence to support policy makers in the ongoing water reform process currently taking place in Mexico. In addition to providing compelling evidence on the link between electricity and groundwater extraction, results further suggest that implementation of programmes aiming at decoupling electricity subsidies and raising electricity fees will face important challenges. Only 11% of the producers considered in the sample analysed would accept to decouple the subsidy and receive it

as a direct transfer. The small willingness to accept the potential decoupling of electricity subsidies imposes real and critical challenges for Mexican authorities. Moreover, this percentage hides important regional variations. Producers in northern states close to the U.S. border are significantly less interested in such a policy alternative, while for those in central states this policy alternative seems to be more appealing. The latter suggests that existing policy strategies should not only account for territorial difference, but further acknowledge the spatial heterogeneity of policy outcomes.

This paper is structured as follows. The first section provides background information on the main characteristics of aquifers and consequences of groundwater overdraft. This section also describes the institutional settings and regulatory mechanisms governing groundwater extraction in Mexico. Section two presents my empirical strategy including the analytical framework and econometric model used to estimate cross-price elasticities. Section three provides a description of the data, and section four presents the results of the econometric model estimating the parameters of the cost function. Section five discusses the policy implications of the empirical analysis including the willingness to accept the possibility of decoupling electricity subsidies. Finally, the paper provides a short conclusion.

## 1.2 Background

### 1.2.1 Groundwater overdraft?

Contrary to the common belief, aquifers are not shallow reservoirs of water. Instead they are layers of sand, soil and rocks where groundwater flows. Groundwater is naturally brought to the surface by springs or is discharged into lakes and streams. Aquifers are recharged by rainfall or snow melt. The area in the aquifer filled with water is called the saturated zone; the top of this zone is called the water table<sup>2</sup>. Water tables can be found a few meters below the land surface or hundreds of meters below the ground.

Groundwater overdraft refers to the consumption of large amounts of water disturbing the relationship between the extraction and the recharge of an aquifer. Groundwater overdraft not only has a direct effect on aquifer water tables, but it also affects groundwater flow patterns. These disruptions are the main cause of a series of environmental problems that compromise the availability and quality of groundwater, and contribute to the degradation of a wide variety of ecosystems.

A direct effect of high extraction rates is the reduction of the water table. Lower water tables tend to be associated with groundwater of a lower quality. The latter is due to the presence of higher concentrations of salts and minerals in lower levels of the water table. In the case of over-exploited aquifers close to coastal areas, lower water tables can favour seawater intrusion which can further compromise water quality by increasing the concentration in salts.

Groundwater quality can be also compromised by irrigation activities. Not all irrigation water is absorbed by the plants or evaporated, instead it in-

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<sup>2</sup> <http://www.groundwater.org/>



filtrates or percolates into the aquifer. Irrigation water percolating into the soil usually contains higher concentrations of salts. Moreover, in some cases, irrigation water may also contain pollutants coming from fertiliser and pesticides. Changes in groundwater flow patterns can further reduce water quality by favouring the infiltration of polluted irrigation water and by contributing to the displacement of saline water bodies ([Custodio and Botín, 2000](#)).

A significant reduction in the water table can also affect the capacity of the aquifer to support the soil above, making the land in the surface to settle and compress. This phenomenon is called land subsidence. Land subsidence manifests itself through changes in the surface elevation. These changes in the surface can go from a small depression to the total collapse of the aquifer. Land subsidence can seriously affect certain types of infrastructures like buildings and roads.

The over-exploitation of aquifers can also have an impact on water bodies on the surface. Aquifers belong to an hydrologic system that interconnects groundwater to surface water. Thus, groundwater overdraft further affects spring discharges, river base flows, and the surface area of wetlands ([Custodio and Botín, 2000](#)). Moreover, the latter directly affects the ecosystems embedding these water sources by reducing the population of flora and fauna, and threatening endemic species with extinction ([Zektser et al., 2005](#)).

Groundwater overdraft also has a direct impact on economic activities. The reduction in groundwater levels forces irrigators to drill deeper wells, which implies higher pumping and maintenance costs. Moreover, if the quality of groundwater has been compromised, irrigators have to incur into additional filtration costs. Under normal circumstances, higher production costs will translate into higher output prices or into lower revenues.

The number of Mexican aquifers classified as overexploited or suffering from salinisation problems has increased in the past decades. Mexican authorities consider an aquifer to be overexploited when the amount of water extracted is higher than the amount of water filtering in and recharging the aquifer. According to the Mexican National Water Commission (CONAGUA), by the end of 2010 there were 101 (out of 653) aquifers in the country classified as overexploited, compared to 32 overexploited aquifers in 1975 (CONAGUA, 2010). Moreover, some aquifers not considered as overexploited can also suffer from salinisation and pollution-related problems. Custodio and Botín (2000) suggest that, in some cases, even moderate extraction rates can affect the balance of the aquifer and deteriorate water quality. By 2010, and considering both exploited and non-exploited aquifers, there were 16 aquifers suffering from seawater intrusion and 32 suffering from salinisation problems (CONAGUA, 2010). In addition to the environmental concerns, further issues regarding the wellbeing of the population are becoming key topics in the agenda of Mexican authorities. Indeed, overexploited aquifers in Mexico supply close to 60% of all the groundwater consumed by the agricultural, industrial and municipal users (CONAGUA, 2010).

### **1.2.2 The elusive quest for groundwater management in Mexico**

The management of groundwater resources in Mexico relies on an allocation system that does not provide the right incentives for a sustainable use of this resource. Indeed, in spite of the existence of a complete institutional framework regulating the extraction of groundwater, failures in the design of the current regulatory instruments and inconsistent crossed-sectoral policies have contributed to the excessive extraction of groundwater by the agricultural sector.

Agriculture is the most intensive water-user in Mexico. In 2009, agriculture accounted for 77% of all the water consumed and for 69% of all groundwater extracted in the country. Moreover, groundwater is the main input for irrigation activities in arid and semi-arid regions in the centre, north-west, and north side of the country. Some of the main advantages of groundwater-based production include reliability on the water supply, a better control on the volume of water applied to crops, and amenability to improved irrigation technologies (Scott and Shah, 2004). In the past three decades, important reforms attempting to regulate the extraction of this resource were implemented by Mexican authorities. These reforms attempted to move from a water management approach based on the supply, to a regulatory system controlling for the demand of water (Roemer, 1997). In practice, this translated into a more robust regulatory system and into governmental bodies explicitly in charge of managing water resources.

Water resources are regulated by a system of complementary laws at the federal level. The Mexican Constitution establishes that all water bodies, on the surface and underground, belong to the Mexican State who is the only one in charge of providing concessions to firms, individuals or public agencies for the use and extraction of water resources (Article 27). The instruments and mechanisms managing water resources aiming at implementing this constitutional mandate are embedded in the National Water Law (Ley de Aguas Nacionales, LAN). The LAN is the most important law regarding water resources in Mexico. It is complemented by the Federal Duties Law (Ley Federal de Derechos, LFD), which defines the fees for water consumption.

In practice, the management of water resources is carried out by the National Water Commission (Comisión Nacional del Agua, CONAGUA). Being a federal agency, CONAGUA's jurisdiction applies everywhere in the country.

CONAGUA is not only in charge of defining water policy at the national level, but it is also in charge of verifying water availability and of granting permits and concessions.

The allocation of water resources in Mexico is based on a system of concessions. A concession defines the maximum amount of water, as well as the number of water sources, that a concession holder is allowed to use. Concessions are priced according to both the type of activity the water is used for and the water availability in the municipality where the consumption (or extraction) is taking place<sup>3</sup>. Concessions have a duration of 5 to 10 years. Once the concession fees are paid, the concession holder is entitled to extract water up to the maximum limit defined by the concession without any additional costs. In case of water extraction beyond the limit of the concession, the user is charged with a volumetric fee. It is compulsory for all irrigators to have a concession. The LAN establishes that all irrigators lacking a concession are incurring into an illegal activity. In regions with high water stress, the provision of additional concession is banned; thus, for these regions, concessions serve as an entry-control tool. Holding a concession also grants irrigators access to cheaper electricity prices.

Irrigation activities benefit from highly subsidised electricity tariffs. Since 2003, Mexican authorities have promoted the competitiveness of the agricultural sector by subsidising the electricity tariffs for irrigation activities. There are two different groups of electricity tariffs for irrigation. The first group corresponds to those tariffs accessible for concession holders; these tariffs are coded 9CU (day tariff) and 9N (night tariff). Although the LAN establishes that it is compulsory to have a concession in order to irrigate, a

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<sup>3</sup> The LFD classifies municipalities in nine different zones depending on the scarcity of water.

second group of tariffs is available for those irrigators without a concession: 9 and 9M. Both groups of tariffs are subsidised, though the first group receives a bigger subsidy. Indeed, estimates suggest that the first group of tariffs has received a subsidy up to 83% (Cob and Romero, 2011).

The main source of energy used to extract groundwater in Mexico is electricity. In 1993, water pumping for irrigation accounted for 6.5% of total electricity yearly consumed in the country (Tsur, 2004). However, due to illegal connections, the actual electricity consumption of water pumping could have been close to 10% (Tsur, 2004). The incentives created by these subsidies are not the only cause behind the overexploitation of aquifers in Mexico; additional policy and institutional failures exist that contribute to groundwater overdraft.

Inefficiencies in the internal design of the concessions, along with external factors blocking the implementation of the LAN, prevent the adequate allocation of water resources in Mexico. Probably the most important deficiency in the design of the concessions is the method establishing the maximum limit for extraction. The maximum limit established by the concessions is based on the technical characteristics of the pumping system (Shah et al., 2004; Cob and Romero, 2011) and not on a scheme promoting the conservation of the resource. The latter implies that the constraints imposed by the concessions are rarely binding. Moreover, even when this constraint is binding, the price paid by any additional cubic meter is very low. Actually, the LFD assigns to agricultural activities the lowest price in the country. This price is the same for all the regions in the country, independently of the availability of water in the region.

External factors preventing the proper implementation of the LAN include

high monitoring costs and inefficiencies in law procurement which hamper the capacity of Mexican authorities to control for illegal water extraction. Illegal water extraction mainly refers to users extracting water without a valid concession. In 2009, the rate of Illegal Water Users (IWU) across Mexican states ranged from 8% in Aguascalientes to 60% in the state of Mexico. In northern states like Sonora and Baja California IWU ranged between 8% - 14%, while in Nuevo Leon it reached 40%; in contrast, in states like San Luis Potosi and Puebla it ranged between 15% and 25%. One of the main reasons for illegal water extraction is the high administrative cost associated with environmental inspections and the lack of qualified personnel. Indeed, Mexican authorities cannot verify that water users comply with the LAN. For instance, it is common knowledge that not every concession holder has a water metering unit; even if they do, in some cases, the metering units are trafficked ([Scott and Shah, 2004](#)). Aware of these issues, Mexican authorities have promoted the implementation of participatory instruments. These instruments attempt to complement the system of concessions and to induce a better management of groundwater resources at the local level.

The main participatory instrument promoted by CONAGUA is the Technical Committees for Groundwater (*Comites Tecnicos de Aguas Subterraneas*, COTAS). The main objective of the COTAS is to provide technical advice to farmers whose water supply comes from overexploited aquifers. However, in practice, it seems that its main objective is to help in the application of the LAN, and more precisely, to contribute to the regularisation process of groundwater users. COTAS are expected to mediate between both federal and state authorities and water users, as well as to constrain the illegal extraction of groundwater and to help respect the limits stipulated by the concessions. COTAS were born in the state of Guanajuato, but by now they

are implemented in over-exploited aquifers across the country. The domain of each COTAS is defined by the boundaries of the corresponding aquifer. The main limitation of the COTAS is that, on the one hand, they depend on the contributions made by their members while, on the other hand, their objective is to apply the LAN. In other words, they are designed to spy and denounce their members who pay a contribution for their own existence (Shah et al., 2004).

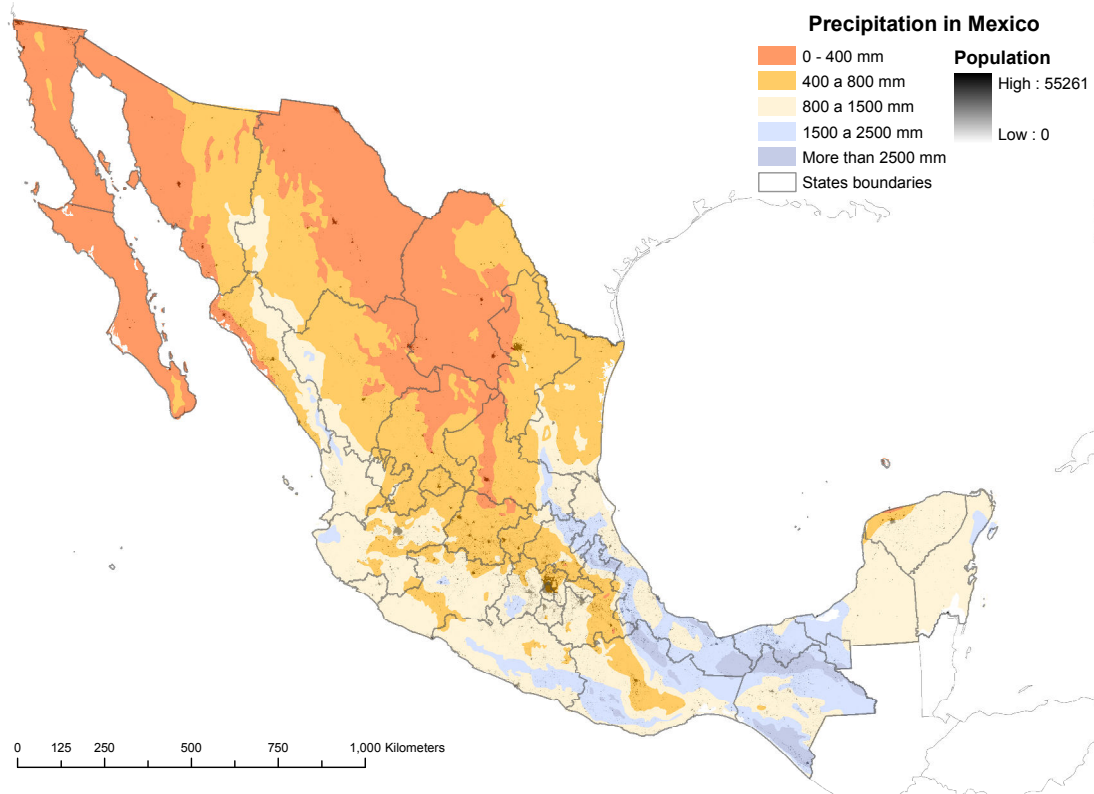
### 1.2.3 Agriculture in Mexico

A large extent of Mexico's territory is dominated by arid regions. Mexico's territory extends over an area of 1,964,375 km<sup>2</sup>, which is characterised by dry and arid regions in the north, and warm and humid climates in the south. Indeed, 51.08% of Mexico's climate can be classified as dry, 25.9% as warm, 23.01% as mild, and only 0.01% as cold (INEGI, 2010a). Climatic differences are further portrayed through the distribution of precipitation across the country. Rain tends to be more prominent in the southern part of the country, in particular in states bordering the Gulf of Mexico like Veracruz and Tabasco, as well as further south in states like Chiapas, and on the coastal area of Oaxaca, Figure 3.2. Figure 3.2 also shows the distribution of the population across the country<sup>4</sup>. With the exception of Monterrey, in the northern state of Nuevo Leon, most population centres are placed in mild climates. However, they also tend to be placed in regions with precipitation levels lower than 1,500 mm per year.

Mexico's wide range of climates has contributed to the development of different types of crops. According to Mexican authorities, the main crops in the

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<sup>4</sup> Population is expressed in the maps as the total number of people in a cell of approximately 1 km<sup>2</sup>.

**Figure 1.1** – Precipitation in Mexico

**Sources:** Precipitation data: National Geo-statistical Framework, INEGI; spatial distribution of the population: LandScan. Computations and maps elaborated by the author.

county are: alfalfa, oat, chilli, beans, maize, forage, sorghum, red tomato, green tomato, and wheat. In 2009, the production of these crops represented MEX\$ 589,324 millions (US\$ 43,654 millions). During the same year, the states of Michoacan, Sinaloa, Sonora, Veracruz, and Jalisco had the five highest shares of the total production of these crops in the country, Table 1.1.

A small number of northern states including Chihuahua, Durango, Sinaloa, and Sonora concentrate the output of some of these crops. For instance, in 2009, the states of Chihuahua and Durango together accounted for more than 40% of the volume of oat produced in the country, Table 1.1. Also the state



of Chihuahua along with the state of Sinaloa accounted for more than 45% of the volume of green chilli produced in the country. During the same year, Sinaloa also accounted for the biggest share of beans produced in Mexico (26%).

A big share of agricultural production takes place in regions with low water availability. Agriculture is the most water intensive user in the economy. In 2009, agricultural users accounted for 80% of the superficial water extracted in the country, and for 70% of the groundwater consumed, ([CONAGUA, 2010](#)). Moreover, some water intensive crops such as wheat and alfalfa are mostly produced in regions characterised by low water supplies and increasing number of aquifers experiencing overdraft. This is the case of the states of Baja California, Chihuahua and Guanajuato - all characterised by considerable levels of water stress - which account for almost 40% of the production of alfalfa in Mexico. In the case of wheat, the neighbouring states of Baja California and Sonora accounted for almost 60% of the total volume produced in the country in 2009.

The biggest number of production units involved in agriculture and livestock activities is, however, concentrated in southern states. Indeed, the states of Chiapas (364,404), Puebla (348,736), and Veracruz (337,191) account for the biggest number of production units involved in agriculture, Table 1.2. Regarding livestock, the states of Veracruz (71,431), Chiapas (29,037), and Tabasco (23,255) concentrate the biggest number of production units involved in this activity.

Irrigation is concentrated in northern states of the country. In 2007, close to 17% of the land used for agriculture in Mexico relied on irrigation. However, in states like Baja California Sur, Baja California, and Sonora more than

half of the total number of hectares rely on irrigation. By contrast, in states like Quintana Roo, Campeche, or Chiapas less than 3% of the agricultural land counts with irrigation technologies; instead, production in these states relies on rain-fed production. These north-south differences further reflect the water availability of the country. Indeed, northern regions are characterised by arid climates, water scarcity, and the largest extension of closed aquifers. In contrast, the south of Mexico has mild climates and the biggest supply of rain (CONAGUA, 2010).

Most production units still rely on non-mechanical irrigation methods. During 2007, more than 560 thousand production units used either lined or earthen canals for irrigation; this number represents almost 80% of the country total, Table 1.13. After canals, aspersion is the method most frequently used, followed by dripping a micro-aspersion. However, there are some exceptions, such as the southern state of Yucatan, where both aspersion and micro-aspersion are the most common irrigation technologies. Another remarkable exception is Baja California Sur in the north of the country, where almost 45% of production units count with dripping irrigation systems. By contrast, in states like Sinaloa or Tamaulipas more than 75% of the production units use earthen canals.

Wells and damns are the main sources of water for agriculture in Mexico. Table 1.4 presents the shares of water sources by state. Southern states like Quintana Roo (88.39%), Yucatan (74.33%), and Campeche (73.68%) had the highest shares of production units using deep wells as main water sources in 2007. By contrast, in central-northern states like Sinaloa (82.05%), Hidalgo (58.95%), Tamaulipas (48.97%), and Sonora (48.35%) production units tend to rely on water dams.

Table 1.1 – Regional distribution of main crops and closed aquifers in Mexico

| Region              | Alfalfa | Oat     | Green   |         |         |         |         |         | Red     |         | Wheat   | Production |
|---------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|------------|
|                     |         |         | Chilli  | Beans   | Maize   | Forage  | Sorghum | tomato  | tomato  |         |         |            |
| Aguascalientes      | 1.95%   | 0.88%   | 0.45%   | 0.18%   | 0.23%   | 0.33%   | 0.00%   | 0.38%   | 0.92%   | 0.00%   | 0.57%   |            |
| Baja California     | 7.43%   | 1.17%   | 1.07%   | 0.00%   | 0.00%   | 0.02%   | 0.09%   | 8.81%   | 1.12%   | 14.40%  | 3.18%   |            |
| Baja California Sur | 1.56%   | 0.00%   | 1.68%   | 0.21%   | 0.10%   | 0.01%   | 0.17%   | 5.02%   | 0.67%   | 0.50%   | 0.69%   |            |
| Campeche            | 0.00%   | 0.00%   | 0.34%   | 0.15%   | 1.38%   | 0.00%   | 0.56%   | 0.22%   | 0.03%   | 0.00%   | 0.63%   |            |
| Chiapas             | 0.00%   | 0.00%   | 0.95%   | 6.72%   | 6.05%   | 12.44%  | 0.81%   | 1.64%   | 0.29%   | 0.00%   | 5.30%   |            |
| Chihuahua           | 16.89%  | 32.81%  | 25.64%  | 11.27%  | 4.84%   | 0.35%   | 1.76%   | 0.63%   | 0.35%   | 6.39%   | 5.23%   |            |
| Coahuila            | 5.89%   | 5.21%   | 0.80%   | 0.10%   | 0.08%   | 1.97%   | 0.12%   | 2.44%   | 0.65%   | 0.57%   | 1.64%   |            |
| Colima              | 0.00%   | 0.00%   | 1.02%   | 0.01%   | 0.14%   | 2.89%   | 0.10%   | 0.54%   | 0.64%   | 0.00%   | 1.26%   |            |
| Distrito Federal    | 0.01%   | 1.02%   | 0.00%   | 0.02%   | 0.04%   | 0.00%   | 0.00%   | 0.00%   | 0.07%   | 0.00%   | 0.41%   |            |
| Durango             | 6.59%   | 18.57%  | 2.33%   | 13.33%  | 1.66%   | 0.60%   | 0.25%   | 0.36%   | 0.00%   | 1.02%   | 2.00%   |            |
| Guanajuato          | 12.72%  | 2.02%   | 1.88%   | 2.71%   | 4.19%   | 0.17%   | 19.62%  | 0.27%   | 3.12%   | 15.92%  | 4.44%   |            |
| Guerrero            | 0.00%   | 0.00%   | 0.30%   | 0.98%   | 5.64%   | 4.96%   | 0.79%   | 1.03%   | 1.67%   | 0.00%   | 2.83%   |            |
| Hidalgo             | 17.26%  | 2.13%   | 0.43%   | 2.36%   | 2.55%   | 2.06%   | 0.02%   | 0.54%   | 1.86%   | 0.21%   | 1.69%   |            |
| Jalisco             | 2.51%   | 2.54%   | 3.86%   | 0.98%   | 12.63%  | 21.13%  | 2.12%   | 5.65%   | 9.23%   | 3.52%   | 6.30%   |            |
| Mexico              | 2.16%   | 12.46%  | 0.04%   | 0.95%   | 6.53%   | 5.35%   | 0.03%   | 3.42%   | 8.35%   | 0.79%   | 4.66%   |            |
| Michoacan           | 0.82%   | 2.70%   | 2.28%   | 1.05%   | 5.87%   | 2.06%   | 6.72%   | 6.86%   | 6.20%   | 4.46%   | 10.09%  |            |
| Morelos             | 0.04%   | 0.13%   | 0.03%   | 0.16%   | 0.42%   | 0.05%   | 2.94%   | 3.28%   | 5.28%   | 0.03%   | 1.35%   |            |
| Nayarit             | 0.02%   | 0.00%   | 1.57%   | 7.27%   | 1.06%   | 4.06%   | 5.87%   | 2.46%   | 5.09%   | 0.00%   | 2.21%   |            |
| Nuevo Leon          | 0.56%   | 0.14%   | 0.60%   | 0.14%   | 0.18%   | 4.12%   | 0.57%   | 0.80%   | 1.95%   | 1.33%   | 1.11%   |            |
| Oaxaca              | 1.34%   | 0.08%   | 0.52%   | 2.32%   | 2.95%   | 18.20%  | 1.11%   | 1.34%   | 0.58%   | 0.45%   | 3.57%   |            |
| Puebla              | 3.88%   | 0.68%   | 0.47%   | 1.76%   | 3.27%   | 0.02%   | 0.92%   | 1.47%   | 7.49%   | 0.09%   | 3.45%   |            |
| Queretaro           | 2.12%   | 0.90%   | 0.45%   | 0.48%   | 1.07%   | 0.04%   | 0.53%   | 1.36%   | 1.58%   | 0.08%   | 0.56%   |            |
| Quintana Roo        | 0.00%   | 0.00%   | 1.03%   | 0.22%   | 0.17%   | 0.00%   | 0.03%   | 0.05%   | 0.00%   | 0.00%   | 0.31%   |            |
| San Luis Potosi     | 5.47%   | 3.85%   | 7.99%   | 1.34%   | 0.57%   | 2.77%   | 1.26%   | 5.49%   | 1.03%   | 0.01%   | 2.33%   |            |
| Sinaloa             | 0.33%   | 0.00%   | 19.44%  | 15.61%  | 26.00%  | 1.78%   | 8.45%   | 32.70%  | 20.97%  | 2.39%   | 10.05%  |            |
| Sonora              | 7.48%   | 1.20%   | 2.34%   | 0.81%   | 0.51%   | 0.20%   | 0.72%   | 2.03%   | 6.50%   | 44.35%  | 7.00%   |            |
| Tabasco             | 0.00%   | 0.00%   | 0.16%   | 0.21%   | 0.58%   | 0.00%   | 0.55%   | 0.02%   | 0.00%   | 0.00%   | 1.22%   |            |
| Tamaulipas          | 0.01%   | 0.04%   | 5.75%   | 0.34%   | 2.13%   | 3.21%   | 42.45%  | 3.21%   | 1.98%   | 0.01%   | 4.10%   |            |
| Tlaxcala            | 0.59%   | 0.67%   | 0.00%   | 0.96%   | 1.36%   | 0.01%   | 0.00%   | 0.01%   | 2.72%   | 2.60%   | 0.75%   |            |
| Veracruz            | 0.00%   | 0.22%   | 1.82%   | 1.94%   | 5.65%   | 0.47%   | 1.39%   | 3.21%   | 1.07%   | 0.02%   | 6.93%   |            |
| Yucatan             | 0.00%   | 0.00%   | 0.22%   | 0.01%   | 0.22%   | 10.21%  | 0.02%   | 0.12%   | 0.01%   | 0.00%   | 0.69%   |            |
| Zacatecas           | 2.37%   | 10.59%  | 14.54%  | 25.42%  | 1.92%   | 0.53%   | 0.03%   | 4.65%   | 8.58%   | 0.86%   | 3.45%   |            |
| Total               | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% |            |

Source: Data obtained from the state and municipal information system (SIMBAD), INEGI.

**Table 1.2** – Number of production units by type of activity and share of hectares by type of production method.

| Region              | Units     | Agriculture | Livestock | Forestry | Harvesting | Other   | Total Ha   | Irrigation Ha | Rainfed Ha |
|---------------------|-----------|-------------|-----------|----------|------------|---------|------------|---------------|------------|
| Aguascalientes      | 18,962    | 17,123      | 1,175     | 5        | 6          | 653     | 170,696    | 50,543        | 120,154    |
| Baja California     | 7,601     | 5,390       | 1,762     | 12       | 19         | 418     | 378,513    | 261,295       | 117,218    |
| Baja California Sur | 5,902     | 2,314       | 3,317     | 1        | 16         | 254     | 129,337    | 94,233        | 35,104     |
| Campeche            | 41,466    | 30,108      | 9,240     | 38       | 118        | 1,962   | 817,956    | 15,832        | 802,125    |
| Coahuila            | 37,245    | 28,961      | 6,454     | 11       | 413        | 1,406   | 898,673    | 304,578       | 594,095    |
| Colima              | 12,541    | 9,472       | 2,154     | 16       | 20         | 879     | 202,238    | 67,228        | 135,010    |
| Chiapas             | 406,307   | 364,404     | 29,037    | 217      | 326        | 12,323  | 2,200,156  | 45,820        | 2,154,335  |
| Chihuahua           | 87,279    | 75,286      | 9,621     | 637      | 27         | 1,708   | 1,728,118  | 479,375       | 1,248,743  |
| Distrito Federal    | 12,234    | 11,740      | 158       | 18       | 1          | 317     | 18,814     | 1,142         | 17,671     |
| Durango             | 67,166    | 61,418      | 3,761     | 70       | 15         | 1,902   | 934,823    | 185,597       | 749,226    |
| Guanajuato          | 152,819   | 144,254     | 4,084     | 38       | 84         | 4,359   | 1,030,730  | 341,955       | 688,775    |
| Guerrero            | 275,878   | 258,602     | 11,129    | 164      | 237        | 5,746   | 1,615,258  | 93,652        | 1,521,606  |
| Hidalgo             | 205,539   | 185,284     | 7,633     | 117      | 447        | 12,058  | 587,597    | 97,791        | 489,806    |
| Jalisco             | 127,915   | 101,483     | 18,172    | 156      | 56         | 8,048   | 1,694,487  | 191,967       | 1,502,520  |
| Mexico              | 345,927   | 330,809     | 4,225     | 139      | 137        | 10,617  | 710,422    | 107,642       | 602,780    |
| Michoacan           | 192,499   | 172,302     | 5,797     | 268      | 296        | 13,836  | 1,422,771  | 306,512       | 1,116,259  |
| Morelos             | 43,061    | 39,298      | 715       | 20       | 10         | 3,018   | 150,219    | 41,922        | 108,297    |
| Nayarit             | 64,767    | 56,954      | 4,937     | 36       | 30         | 2,810   | 602,406    | 110,895       | 491,512    |
| Nuevo Leon          | 34,227    | 24,901      | 7,653     | 26       | 27         | 1,620   | 594,937    | 128,264       | 466,673    |
| Oaxaca              | 354,038   | 324,275     | 16,321    | 282      | 399        | 12,761  | 1,653,708  | 73,240        | 1,580,468  |
| Puebla              | 375,912   | 348,736     | 3,964     | 269      | 362        | 22,581  | 1,011,643  | 118,968       | 892,675    |
| Queretaro           | 48,457    | 44,983      | 1,886     | 57       | 49         | 1,482   | 237,031    | 68,260        | 168,772    |
| Quintana Roo        | 26,689    | 24,041      | 1,625     | 99       | 24         | 900     | 373,719    | 4,591         | 369,128    |
| San Luis Potosi     | 154,909   | 137,393     | 10,060    | 51       | 367        | 7,038   | 1,039,812  | 102,127       | 937,685    |
| Sinaloa             | 72,974    | 62,971      | 6,405     | 77       | 58         | 3,463   | 1,335,592  | 618,813       | 716,779    |
| Sonora              | 32,054    | 13,833      | 16,672    | 29       | 15         | 1,505   | 1,259,606  | 748,795       | 510,811    |
| Tabasco             | 90,051    | 60,943      | 23,255    | 110      | 67         | 5,676   | 597,934    | 5,519         | 592,415    |
| Tamaulipas          | 54,798    | 37,323      | 14,529    | 153      | 88         | 2,705   | 1,348,457  | 301,387       | 1,047,070  |
| Tlaxcala            | 71,290    | 64,829      | 180       | 15       | 12         | 6,254   | 205,150    | 10,738        | 194,411    |
| Veracruz            | 440,523   | 337,191     | 71,431    | 922      | 499        | 30,480  | 2,644,988  | 88,377        | 2,556,611  |
| Yucatan             | 68,821    | 55,096      | 10,444    | 51       | 535        | 2,695   | 568,739    | 45,092        | 523,647    |
| Zacatecas           | 137,767   | 123,874     | 6,387     | 11       | 51         | 7,444   | 1,737,561  | 198,470       | 1,539,090  |
| Total               | 4,067,618 | 3,555,591   | 314,183   | 4,115    | 4,811      | 188,918 | 29,902,092 | 5,310,622     | 24,591,470 |

**Source:** Data obtained from the Agricultural Census 2007, INEGI. Data on the share of production units is presented in Table 1.12 in the Appendix.

**Table 1.3** – Shares of production units by type of irrigation technology

| Region              | Lined<br>Canals | Earthen<br>Canals | Aspersion | Micro<br>Aspersion | Dripping | Other  |
|---------------------|-----------------|-------------------|-----------|--------------------|----------|--------|
| Aguascalientes      | 35.97%          | 29.15%            | 20.28%    | 1.40%              | 3.05%    | 10.15% |
| Baja California     | 30.74%          | 46.85%            | 3.29%     | 0.47%              | 17.01%   | 1.64%  |
| Baja California Sur | 2.60%           | 16.31%            | 7.26%     | 3.08%              | 44.65%   | 26.10% |
| Campeche            | 2.82%           | 32.68%            | 11.50%    | 4.03%              | 27.28%   | 21.68% |
| Chiapas             | 22.13%          | 50.00%            | 8.20%     | 1.84%              | 3.96%    | 13.88% |
| Chihuahua           | 24.05%          | 48.69%            | 8.14%     | 3.84%              | 1.96%    | 13.33% |
| Coahuila            | 35.32%          | 55.03%            | 4.59%     | 0.57%              | 2.09%    | 2.40%  |
| Colima              | 26.12%          | 50.48%            | 5.23%     | 4.46%              | 6.92%    | 6.79%  |
| Distrito Federal    | 1.23%           | 43.04%            | 5.05%     | 0.14%              | 2.96%    | 47.58% |
| Durango             | 36.41%          | 53.78%            | 2.52%     | 0.46%              | 0.76%    | 6.07%  |
| Guajuato            | 21.47%          | 52.82%            | 7.55%     | 0.32%              | 1.29%    | 16.54% |
| Herrero             | 19.96%          | 48.28%            | 7.82%     | 1.00%              | 3.92%    | 19.03% |
| Hidalgo             | 25.93%          | 66.35%            | 0.66%     | 0.05%              | 0.86%    | 6.14%  |
| Jalisco             | 16.36%          | 47.64%            | 15.05%    | 0.46%              | 6.65%    | 13.85% |
| Mexico              | 33.84%          | 61.60%            | 1.00%     | 0.15%              | 1.17%    | 2.23%  |
| Michoacan           | 16.53%          | 69.88%            | 2.94%     | 0.50%              | 3.53%    | 6.62%  |
| Morelos             | 25.05%          | 63.42%            | 1.20%     | 0.24%              | 1.39%    | 8.70%  |
| Nayarit             | 13.23%          | 15.85%            | 54.67%    | 1.13%              | 4.23%    | 10.90% |
| Nuevo Leon          | 9.75%           | 58.77%            | 20.47%    | 2.47%              | 4.16%    | 4.38%  |
| Oaxaca              | 15.42%          | 54.92%            | 9.90%     | 1.33%              | 1.88%    | 16.54% |
| Puebla              | 21.80%          | 66.19%            | 5.51%     | 0.20%              | 0.50%    | 5.81%  |
| Queretaro           | 31.75%          | 46.88%            | 6.14%     | 0.26%              | 3.22%    | 11.75% |
| Quintana Roo        | 1.66%           | 39.90%            | 17.26%    | 4.99%              | 14.32%   | 21.87% |
| San Luis Potosi     | 16.05%          | 62.60%            | 6.49%     | 0.78%              | 4.98%    | 9.09%  |
| Sinaloa             | 9.92%           | 80.52%            | 1.73%     | 0.17%              | 3.41%    | 4.25%  |
| Sonora              | 24.78%          | 67.05%            | 1.51%     | 0.34%              | 2.76%    | 3.55%  |
| Tabasco             | 6.18%           | 17.35%            | 12.67%    | 3.62%              | 13.73%   | 46.46% |
| Tamaulipas          | 12.69%          | 76.56%            | 1.98%     | 3.79%              | 1.42%    | 3.55%  |
| Tlaxcala            | 63.45%          | 19.83%            | 11.77%    | 0.30%              | 0.54%    | 4.11%  |
| Veracruz            | 11.89%          | 60.22%            | 6.63%     | 1.14%              | 4.64%    | 15.47% |
| Yucatan             | 7.69%           | 14.38%            | 30.61%    | 24.03%             | 5.01%    | 18.28% |
| Zacatecas           | 29.58%          | 49.06%            | 4.74%     | 0.77%              | 5.40%    | 10.45% |
| Total               | 22.60%          | 57.36%            | 6.88%     | 1.16%              | 2.95%    | 9.06%  |

**Source:** Data obtained from the Agricultural Census 2007, INEGI. Data on the number of production units is presented in Table 1.13 in the Appendix.

**Table 1.4** – Shares of production units by type of water source.

| Region              | Reservoirs | Deep wells | Shallow wells | Rivers | Springs | Damms  | Other  |
|---------------------|------------|------------|---------------|--------|---------|--------|--------|
| Aguascalientes      | 2.76%      | 61.02%     | 1.58%         | 0.82%  | 0.75%   | 32.51% | 0.57%  |
| Baja California     | 1.42%      | 43.09%     | 3.10%         | 43.41% | 0.57%   | 7.36%  | 1.05%  |
| Baja California Sur | 1.39%      | 71.06%     | 8.68%         | 0.66%  | 8.37%   | 5.98%  | 3.86%  |
| Campeche            | 1.19%      | 73.68%     | 19.27%        | 4.25%  | 0.00%   | 0.26%  | 1.35%  |
| Chiapas             | 5.92%      | 9.19%      | 4.70%         | 58.83% | 11.68%  | 8.04%  | 1.64%  |
| Chihuahua           | 1.75%      | 42.21%     | 2.51%         | 19.78% | 3.97%   | 26.76% | 3.02%  |
| Coahuila            | 0.97%      | 21.22%     | 0.80%         | 14.77% | 15.56%  | 43.78% | 2.90%  |
| Colima              | 3.07%      | 25.70%     | 0.75%         | 35.48% | 3.81%   | 30.69% | 0.50%  |
| Distrito Federal    | 2.10%      | 4.85%      | 5.58%         | 3.04%  | 1.45%   | 4.78%  | 78.20% |
| Durango             | 2.31%      | 25.39%     | 1.34%         | 26.49% | 3.91%   | 39.40% | 1.16%  |
| Guanajuato          | 3.19%      | 46.58%     | 1.14%         | 12.33% | 0.85%   | 34.72% | 1.19%  |
| Guerrero            | 2.46%      | 8.86%      | 3.99%         | 38.73% | 13.79%  | 26.30% | 5.87%  |
| Hidalgo             | 3.10%      | 10.07%     | 0.40%         | 18.06% | 5.68%   | 58.95% | 3.74%  |
| Jalisco             | 6.64%      | 30.23%     | 2.82%         | 21.09% | 4.05%   | 32.70% | 2.46%  |
| Mexico              | 10.71%     | 18.28%     | 1.64%         | 20.57% | 9.04%   | 37.28% | 2.48%  |
| Michoacan           | 7.37%      | 18.82%     | 2.77%         | 32.93% | 12.00%  | 24.36% | 1.75%  |
| Morelos             | 8.68%      | 16.78%     | 0.64%         | 40.93% | 22.63%  | 8.58%  | 1.75%  |
| Nayarit             | 8.97%      | 12.48%     | 2.39%         | 58.20% | 4.63%   | 4.72%  | 8.61%  |
| Nuevo Leon          | 1.27%      | 36.67%     | 2.21%         | 39.24% | 6.96%   | 12.30% | 1.35%  |
| Oaxaca              | 2.01%      | 13.50%     | 10.33%        | 50.58% | 7.66%   | 13.03% | 2.90%  |
| Puebla              | 5.11%      | 42.70%     | 2.38%         | 17.71% | 12.09%  | 17.79% | 2.22%  |
| Queretaro           | 8.86%      | 41.71%     | 2.70%         | 10.00% | 4.86%   | 31.00% | 0.86%  |
| Quintana Roo        | 1.40%      | 88.39%     | 5.87%         | 0.89%  | 0.38%   | 0.26%  | 2.81%  |
| San Luis Potosi     | 2.69%      | 45.67%     | 5.89%         | 15.33% | 12.73%  | 11.77% | 5.92%  |
| Sinaloa             | 2.50%      | 5.49%      | 1.19%         | 7.86%  | 0.20%   | 82.05% | 0.71%  |
| Sonora              | 1.65%      | 23.46%     | 9.33%         | 14.50% | 1.66%   | 48.35% | 1.06%  |
| Tabasco             | 22.86%     | 31.43%     | 8.72%         | 23.46% | 1.50%   | 1.65%  | 10.38% |
| Tamaulipas          | 0.71%      | 9.46%      | 1.34%         | 32.67% | 5.86%   | 48.97% | 0.99%  |
| Tlaxcala            | 5.10%      | 51.63%     | 1.42%         | 32.90% | 1.53%   | 7.18%  | 0.25%  |
| Veracruz            | 2.89%      | 11.93%     | 2.01%         | 63.36% | 8.42%   | 7.52%  | 3.86%  |
| Yucatan             | 0.26%      | 74.33%     | 23.06%        | 0.00%  | 0.07%   | 0.11%  | 2.17%  |
| Zacatecas           | 2.38%      | 60.46%     | 2.76%         | 3.34%  | 3.49%   | 27.01% | 0.56%  |
| Total               | 4.71%      | 26.83%     | 3.10%         | 24.75% | 7.39%   | 30.62% | 2.59%  |

**Source:** Data obtained from the Agricultural Census 2007, INEGI. Data on the number of production units is presented in Table 1.14 in the Appendix.

### 1.3 Empirical analysis

The main objective of this paper is to analyse producers' behaviour following a structural approach. To this end, I model the production technology through a Translog cost function. Due to the limited data availability on irrigation activities (at a disaggregated level), I cannot analyse changes in the allocation of crops in the long-run as is the case with recent studies focusing on the demand for irrigation water (Schoengold et al., 2006; Hendricks and Peterson, 2012; Pfeiffer and Lin, 2014; Hornbeck and Keskin, 2014). Instead, I focus on short-run changes. By construction, analysing short-run changes further assumes that capital assets and irrigation technology remain constant, which in the literature have been identified to react to changes in water and energy prices (Caswell and Zilberman, 1985; Zilberman et al., 2008). The main advantage of using a flexible form such as the Translog cost function is the possibility of the existence of cross-price effects between groundwater and other production inputs (Chambers, 1988).

This section presents the analytical framework used to model the behaviour of producers and the resulting specification of the empirical model. This section also describes the covariates included in the econometric model, which are further described in Table 1.6 and Table 1.7.

### 1.3.1 Analytical framework

As defined by [Chambers \(1988\)](#), the cost function is the minimum cost for producing a given level of output during a given period of time expressed as a function of output and factor prices. The cost function can be expressed in mathematical terms as follows:

$$c(w, y) = \min_{x \geq 0} [w \cdot x : x \in V(y)] \quad (1.1)$$

Where  $w$  is a vector of strictly positive prices,  $x$  is a vector of input quantities,  $y$  is a vector of production outputs and  $V(y)$  is the input requirement set (all input combinations producing the same output level  $y$ ). Under this setting, producers are atomistic competitors who cannot have an influence on the price of production factors, i.e. factor prices are seen as exogenous.

As mentioned at the beginning of this section, the empirical model I have chosen for representing the cost function follows a Translog approximation. The Translog cost function is a flexible form that provides a second order approximation of the production frontier evaluated in a given point. Thus, it inflicts less restrictions than commonly used specifications like the Cobb-Douglas and CES, which impose a constant elasticity of substitution. In other words, through the Translog specification it is possible to identify cross-price effects.

The Translog function considers the variable cost of production as function of input prices, output quantities and quasi-fixed factors; all these variables are expressed as logarithms. The Translog cost function is defined as:



$$\begin{aligned}
\ln(VC) = & \alpha_0 + \sum_{i=1}^n \alpha_i \ln P_i + \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n \alpha_{i,j} \ln P_i \ln P_j \\
& + \sum_{i=1}^h \beta_i \ln Q_i + \frac{1}{2} \sum_{i=1}^h \sum_{j=1}^h \beta_{i,j} \ln Q_i \ln Q_j \\
& + \sum_{i=1}^m \gamma_i \ln Z_i + \frac{1}{2} \sum_{i=1}^m \sum_{j=1}^m \gamma_{i,j} \ln Z_i \ln Z_j \\
& + \sum_{i=1}^n \sum_{j=1}^h \eta_{i,j} \ln P_i \ln Q_j \\
& + \sum_{i=1}^n \sum_{j=1}^m \theta_{i,j} \ln P_i \ln Z_j \\
& + \sum_{i=1}^h \sum_{j=1}^m \zeta_{i,j} \ln Q_i \ln Z_j
\end{aligned} \tag{1.2}$$

Where  $P_i$ ,  $Q_i$  and  $Z_i$  respectively correspond to the  $i$ -th element of the vectors of prices, output quantities and quasi-fixed factors. In order to account for theoretical properties characterising a cost function, the parameters of the Translog function have to be constrained as follows:

$$\begin{aligned}
\sum_{i=1}^n \alpha_i &= 1 \\
\sum_{j=1}^h \beta_{i,j} &= 0 ; i = 1, \dots, n \\
\sum_{i=1}^n \gamma_{i,j} &= 0 ; j = 1, \dots, m
\end{aligned} \tag{1.3}$$

A convenient property of the Translog specification is that factor demands can be expressed as input cost shares. The input cost share for the  $i$ -th input is defined as the of cost the  $i$ -th input divided by the total variable

cost. Under this approach, a cost share is a function of input prices, output quantities and quasi-fixed factors (Equation 1.4).

$$S_i = \alpha_i + \sum_{j=1}^n \alpha_{i,j} \ln P_j + \sum_{j=1}^h \beta_{i,j} \ln Q_j + \sum_{j=1}^m \gamma_{i,j} \ln Z_j ; i = 1, \dots, n \quad (1.4)$$

Price effects cannot be assessed directly from the parameters of the Translog's cost share equations. Instead, elasticities are computed using the price parameters along with the predicted values of the corresponding cost shares evaluated at their means. The formulas for computing price elasticities and cross-price elasticities are described in Equation 1.5.

$$\begin{aligned} \epsilon_{ii} &= \frac{(\alpha_{i,i} + \hat{S}_i^2 - \hat{S}_i)}{\hat{S}_i} \\ \epsilon_{ij} &= \frac{\frac{\alpha_{i,i}}{\hat{S}_i \hat{S}_j} + 1}{\hat{S}_j} ; i \neq j \\ \mu_{ij} &= \epsilon_{ij} - \epsilon_{ii} ; i \neq j \end{aligned} \quad (1.5)$$

Where  $\epsilon_{ii}$  is the derived-demand elasticity of the  $i$ -th input,  $\epsilon_{ij}$  is the cross-price elasticity of inputs  $i$  and  $j$ ; and  $\mu_{ij}$  is the Morishima elasticity of substitution for inputs  $i$  and  $j$ . Although previous studies use Allen partial elasticities of substitution, I decided to adopt the approach suggested by [Chambers \(1988\)](#) and focus instead on derived-demand and Morishima elasticities. Indeed, Chambers argues that since Allen elasticities are computed as  $\epsilon_{ij}$  divided by the cost-share of the  $j$ -th input they just disguise the actual measure of interest,  $\epsilon_{ij}$ .

### 1.3.2 Model specification

For the purpose of this analysis I consider that the irrigators' cost function is composed of three variable inputs, four types of outputs, and a set of quasi-fixed factors.

I consider groundwater, labour, and fertiliser as the variable inputs for production. Labour and fertilisers have been commonly considered as variable inputs in the water irrigation literature ([Nieswiadomy, 1988](#); [Dalton et al., 1997](#)). However, irrigation water has sometimes been assumed to be a variable input and at other times seen as a fixed factor for production. The main reason for the latter assumption is the limits imposed on irrigation water by a system of quotas; similarly, when groundwater is the main source for irrigation, the incapacity to access additional wells can also be considered an important constraint for production ([Moore and Negri, 1992](#); [Moore et al., 1994a](#); [Moore and Dinar, 1995](#)). However, and despite the fact that groundwater is managed through a system of quotas in Mexico, I have reasons to believe that groundwater can be considered as a variable input for production. The first reason is that the maximum limits established by the water quotas do not reflect the scarcity of resource. Hence, irrigators rarely have to adjust their consumption patterns to meet the quota. Following an extensive analysis of irrigation activities in Mexico, [Shah et al. \(2004\)](#) conclude that quotas established by the concessions do not act as an instrument for controlling water extraction. According to this study, the rules to define the maximum extraction limits specified in the concessions are a function of the characteristics of the water pump and in some cases of the average consumption of previous years. Hence, the limits of these quotas are not designed to influence a lower consumption, instead they just formalise the actual con-

sumption. The second reason is the inadequate pricing system embedded in the concessions. In practice, if irrigators go beyond the limit defined by their quotas, they jump to a higher price block (below the maximum limit of the quota the price per cubic meter is 0). However, the price of a cubic meter of water in this block is so low that it is hard to believe that this mechanism will make irrigators stick to the quota established in their concession. This idea is consistent with some of the comments made by the farmers included in the survey I used as main data source for the analysis. Finally, additional evidence exists that further suggests that the quotas are not respected. Due to the lack of law enforcement in Mexico, access to illegal wells seems to be a common practice. [Scott and Shah \(2004\)](#) affirm that despite the fact that official data shows a decrease in the number of wells since 2000, apparently an increasing number of wells continue to be sunk.

Within the context of the analysis I assume that input prices are exogenous. Both the price of labour ( $P_{Labour}$ ) and the price of fertiliser ( $P_{fertiliser}$ ) are driven by local markets, thus it is plausible to consider that individual producers do not have a significant influence on them. Considering the inadequate water pricing scheme defined by the concessions, the actual price of groundwater can be seen as the price of electricity used to pump groundwater. Indeed, when the quota's constraint is not binding, the price of groundwater is equal to zero; yet, irrigators have to pay for the energy used by the pump to extract the groundwater. Almost all pumps being electric, the price of electricity can then be considered as the actual price for every additional cubic meter of groundwater consumed. The electricity tariff for legal irrigators does not vary across regions in Mexico. Nevertheless, the price paid by each irrigator differs according to geographic characteristics regarding the height needed to reach the water table, as well as some technical characteristics of

the pumping system (see Table 1.7). This relationship is identified by the following equation:

$$P_{Water,i} = F \cdot S \cdot \theta \cdot P_e \quad (1.6)$$

Where  $P_{Water}$  is the price of groundwater,  $F$  is the maximum flow rate,  $S$  is the static head,  $\theta$  is a constant accounting for gravity and  $P_e$  is the price of electricity. This price is measured for every  $i$ . Both the maximum flow rate and the static head (height) are characteristics of the pipe; they are expressed respectively in  $\frac{\text{litres}}{\text{second}}$  and *metres*. Gravity is a constant taking a value equal to  $9.81 \frac{m}{s^2}$  and the price of electricity is expressed in Mexican pesos per Kw/h. Although the price of Kw/h is defined by Mexican authorities (thus not influenced by the users), the characteristics of the pipe depend on the type of irrigation technology used. Hence, by adopting a more water efficient technology, water users may be able to influence the price of groundwater in the long term.

Production output is grouped in four types of agricultural products. These groups are Alfalfa and Forages ( $Q_{A\&F}$ ), Fruits ( $Q_{Fruits}$ ), Grains ( $Q_{Grains}$ ), and Vegetables ( $Q_{Vegetables}$ ). Table 1.5 presents the shares of farmers producing each type of output across regions. As can be seen from this table, not all farmers produce the four types of outputs. For this reason, outputs enter the econometric following the expression  $\ln(Q_k + 1)$ ; where  $Q$  refers to the quantity of the  $k$ -th output. It should be noted that the inclusion of outputs in the specification of costs functions has been criticised in the literature since, depending on the type of economic activity, the quantity of output may be endogenous (Christensen et al., 1973; Fuss, 1977). In the case of agricultural activities, the fact that the amount of output is decided a long time before the actual production begins and is further affected by different

climatic events could limit this potential issue. In addition to the latter, Mexican agricultural markets tend to be competitive, forcing local producers to meet the market demand. The latter has been accentuated through the consolidation of the North American Free Trade Agreement (NAFTA) and an increasing number of agricultural exports (Romero, 2009). I thus assume that the amount of output is exogenous, while acknowledging that this may be a strong assumption framed within the short-run nature of the analysis.

**Table 1.5** – Share of producers across regions by type of output

| Region          | Alfalfa and forages | Fruits  | Grains  | Vegetables |
|-----------------|---------------------|---------|---------|------------|
| Aguascalientes  | 20.66%              | 4.08%   | 12.44%  | 1.50%      |
| Baja California | 9.92%               | 32.65%  | 1.00%   | 27.00%     |
| Nuevo Leon      | 5.79%               | 6.12%   | 11.94%  | 8.50%      |
| Puebla          | 14.05%              | 0.00%   | 21.39%  | 9.00%      |
| San Luis Potosi | 11.57%              | 0.00%   | 6.47%   | 6.50%      |
| Sonora          | 13.22%              | 36.73%  | 8.46%   | 11.00%     |
| Zacatecas       | 24.79%              | 20.41%  | 38.31%  | 36.50%     |
| Grand Total     | 100.00%             | 100.00% | 100.00% | 100.00%    |

**Source:** INECC, 2009

The set of quasi-fixed factors considers some inputs that are directly involved in the production process, as well as environmental and geographic factors that directly or indirectly influence irrigation farming activities.

Physical and environmental conditions have an important influence on the way in which irrigation activities are carried out. For instance, they can affect the choice of irrigation technology and probably the allocation of production inputs. For this reason, the model includes the total amount of rain (*RAIN*) and average temperature (*TEMPERATURE*) during 2009. To account for differences in the topography, the model also includes the slope (*SLOPE*) of the terrain expressed as the percentage of increase in the terrain<sup>5</sup> around

<sup>5</sup> A flat surface is 0 percent, a 45 degree surface is 100 percent, and as the surface

the production units. In addition, and to account for soil characteristics, I include into the model two dummy variables indicating the type of soil: clay ( $CLAY_{Dummy}$ ) and sandy ( $SANDY_{Dummy}$ )<sup>6</sup>. Throughout the literature, these variables are commonly accepted as physical factors influencing the demand of water for irrigation. Studies like [Nieswiadomy \(1988\)](#), [Moore and Negri \(1992\)](#), [Moore et al. \(1994b\)](#), [Pattanayak and Kramer \(2001\)](#), [Bell \(2007\)](#) and [Tchale and Sauer \(2007\)](#) used one or more of these variables to control for environmental conditions.

Mexican authorities have defined water availability zones all over the country. These zones are the basis for defining concession fees across water users. This classification ranks municipalities from 1 to 9, where a municipality ranked 9 is considered to be suffering from extreme water stress. I used this variable ( $AVAILABILITY$ ) to control for additional spatial characteristics not captured through the other environmental variables.

The amount of land used for agricultural activities is usually considered as one of the most relevant fixed factors for production. However, farmers have different combinations of irrigation systems, sometimes even for the same crop. For this reason, and in order to further capture the effect of technology, I decided to use the total amount of hectares having water saving technology ( $HECTARES - HT$ )<sup>7</sup>. For the latter, I consider micro-sprinklers and drip systems as water saving technology. In addition to land, I decided to control for the number of wells used by each producer ( $WELLS$ ). This number is defined by the concession.

The access to markets is without any doubt an important factor for any

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becomes more vertical, the percent rise and becomes increasingly larger.

<sup>6</sup> The base category being “loamy” soil.

<sup>7</sup> Technologies different from flooding methods

economic activity. It is particularly important for accessing input and output markets. To account for this factor, I control for the distance (*DISTANCE*) to the closest population centre with more than 25,000 inhabitants. Places having at least this number of inhabitants are officially considered in Mexico as urban areas. These places usually host dynamic labour and factor markets as well as the headquarters of authorities. Considering the lack of surveillance and law enforcement that characterised Mexico, the proximity to authorities may have an additional effect on the adequate use of water resources as established by the concessions. This variable has also been used by [Muñoz et al. \(2006\)](#).

The lack of adequate monitoring and control is considered to be one of the most relevant factors promoting inefficient use of groundwater. For this reason I consider important to control for whether the producers have been previously fined or not (*FINED<sub>Dummy</sub>*).

Finally, management skills and experience in agricultural activities can influence the allocation of production factors as well as the choice of technology. To account for these managerial characteristics, I have used as proxies the number of years of education (*EDUCATION*) and the number of years carrying out agricultural activities (*TIME*).



### 1.3.3 Estimation method

Throughout the economic literature Translog cost functions have been estimated following two different specifications. The first specification estimates the parameters of a Translog cost function by only focusing on the system of cost shares described by Equation 1.4. This is the model specification used by [Fuss \(1977\)](#), [Nieswiadomy \(1988\)](#), and [Dalton et al. \(1997\)](#). The second specification takes into account both the system of cost shares in Equation 1.4 and the cost function defined in Equation 1.2. This model specification can be found in [Christensen et al. \(1973\)](#) and more recently in [Grisley and Gitu \(1985\)](#), [Behar \(2004\)](#), and [McLaren and Zhao \(2009\)](#). In practice, the main benefit from the latter specification is the possibility to recover certain parameters that are not included in the system of equations (like the quadratic forms of the output variables). Since the parameters included in the cost function are not relevant to address the main research questions of this study, I opt to use only the system of cost shares (Equation 1.7). I use this system to estimate the parameters of the cost function through the set of covariates previously described. I achieve the latter by exploiting the variation of input prices, output quantities, and semi-fixed factor across space. Table 1.7 presents descriptive statistics of input prices, technology, outputs, pumping height, and rain availability across regions.

The system is composed by three equations corresponding to the cost shares of groundwater  $S_1$ , labour  $S_2$ , and fertiliser  $S_3$ . Each equation includes: the prices of groundwater  $P_1$ , labour  $P_2$ , and fertilisers  $P_3$ ; the quantities for each group of four different outputs  $Q_j$ ; each element of the set containing ten continuous quasi-fixed inputs  $Z_j$ ; and the three dummy variables - two of which account for soil types and the remaining one accounting for whether

the producer has been fined before - represented by  $D_j$ .

$$\begin{aligned}
 S_1 &= \alpha_1 + \sum_{j=1}^3 \alpha_{1,j} \ln(P_j) + \sum_{j=1}^4 \beta_{1,j} \ln(Q_j) + \sum_{j=1}^{10} \gamma_{1,j} \ln(Z_j) + \sum_{j=1}^4 \delta_{1,j} D_j + \epsilon_1 \\
 S_2 &= \alpha_2 + \sum_{j=1}^3 \alpha_{2,j} \ln(P_j) + \sum_{j=1}^4 \beta_{2,j} \ln(Q_j) + \sum_{j=1}^{10} \gamma_{2,j} \ln(Z_j) + \sum_{j=1}^4 \delta_{2,j} D_j + \epsilon_2 \\
 S_3 &= \alpha_3 + \sum_{j=1}^3 \alpha_{3,j} \ln(P_j) + \sum_{j=1}^4 \beta_{3,j} \ln(Q_j) + \sum_{j=1}^{10} \gamma_{3,j} \ln(Z_j) + \sum_{j=1}^4 \delta_{3,j} D_j + \epsilon_2
 \end{aligned} \tag{1.7}$$

In order to comply with the assumptions embedded in the theory of the firm, the parameters in Equation 1.7 have to be further constrained during the estimation procedure to account for the symmetry of price effects,  $\alpha_{i,j} = \alpha_{j,i}$  for  $i \neq j$ . Moreover, in addition to this constraint, to account for linear homogeneity in factor prices the parameters of the model should respect the following restrictions:

$$\begin{aligned}
 \sum_{i=1}^3 \alpha_i &= 1 \\
 \sum_{j=1}^4 \beta_{i,j} &= 0 ; i = 1, 2, 3 \\
 \sum_{i=1}^3 \gamma_{i,j} &= 0 ; j = 1, \dots, 10 \\
 \sum_{i=1}^3 \delta_{i,j} &= 0 ; j = 1, 2, 3, 4
 \end{aligned} \tag{1.8}$$

To estimate the parameters in Equation 1.7, it is necessary to address a problem concerning the singularity of the covariances matrix. This problem is due to the fact that share equations sum up to 1 (Nieswiadomy, 1988). In the literature, this issue is usually solved through a series of constraints across the parameters of the model. This constraint is applied by removing one of the share equations from the system, while dividing the remaining  $n-1$  input prices by the input price corresponding to the cost share that has been removed; this price is usually known as the numeraire. The parameters of the remaining system composed by the  $n-1$  cost share equations can then be estimated through the method of seemingly unrelated equations (SURE) using a maximum-likelihood iteration procedure. The estimates from this procedure are invariant to the equation removed (Christensen et al., 1973; Fuss, 1977; Nieswiadomy, 1988).

The system of cost shares taking into account all these constraints is described by Equation 1.9.

$$\begin{aligned}
 S_1 &= \alpha_1 + \sum_{j=1}^3 \alpha_{1,j} \ln(P_j/P_3) + \sum_{j=1}^4 \beta_{1,j} \ln Q_j + \sum_{j=1}^{10} \gamma_{1,j} \ln Z_j + \sum_{j=1}^4 \delta_j D_j + \epsilon_1 \\
 S_2 &= \alpha_2 + \sum_{j=1}^2 \alpha_{2,j} \ln(P_j/P_3) + \sum_{j=1}^4 \beta_{2,j} \ln Q_j + \sum_{j=1}^{10} \gamma_{2,j} \ln Z_j + \sum_{j=1}^4 \delta_j D_j + \epsilon_2
 \end{aligned}
 \tag{1.9}$$

As can be seen from Equation 1.9, I considered the price of fertiliser as the numeraire. The parameters of  $S_3$  can be recovered using the constraints given by Equation 1.8.

Table 1.6 – Description of variables used for the econometric model

| Tag              | Variable                             | Units           | Mean   | S.D.    | Min     | Max     | N   |
|------------------|--------------------------------------|-----------------|--------|---------|---------|---------|-----|
| $P_{Water}$      | Price of groundwater                 | MEX\$ per $m^3$ | 13.8   | 21.24   | 0.023   | 131.84  | 432 |
| $P_{Labour}$     | Price of Labour                      | MEX\$ per day   | 119.3  | 12.56   | 100     | 150     | 440 |
| $P_{Fertilizer}$ | Price of fertilizer                  | MEX\$ per Tonne | 6381.5 | 1450.52 | 4021.66 | 8475.72 | 440 |
| $Q_{A\&F}$       | Quantity of Alfalfa and Forages      | Tonnes          | 259.1  | 923.57  | 0       | 12000   | 440 |
| $Q_{Fruits}$     | Quantity of Fruits                   | Tonnes          | 50.7   | 303.07  | 0       | 4950    | 440 |
| $Q_{Grains}$     | Quantity of Grains                   | Tonnes          | 47.5   | 188.15  | 0       | 3150    | 440 |
| $Q_{Vegetables}$ | Quantity of Vegetables               | Tonnes          | 251.4  | 787.23  | 0       | 6420    | 440 |
| $RAIN$           | Yearly precipitation                 | mm              | 382.1  | 284.06  | 86.7    | 1416.2  | 440 |
| $TEMPERATURE$    | Average temperature                  | centigrades     | 17.4   | 3.44    | 10.04   | 25.45   | 440 |
| $SLOPE$          | Terrain slope                        | %               | 12.2   | 1.27    | 6       | 16      | 440 |
| $EDUCATION$      | Manager's years of education         | Years           | 8.4    | 5.66    | 0       | 23      | 439 |
| $TIME$           | Time in agricultural activities      | Years           | 25.6   | 13.29   | 0       | 65      | 440 |
| $WELLS$          | Number of wells                      | Number          | 1.8    | 2.61    | 0       | 21      | 440 |
| $HECTARES - HT$  | Area using high-tech irrigation      | Ha              | 9.5    | 20.25   | 0       | 180     | 440 |
| $FINED_{Dummy}$  | Ever been fined?, Dummy              | Yes = 1         | 0.04   | 0.20    | 0       | 1       | 440 |
| $DISTANCE$       | Distance to closest populated centre | Km              | 43.9   | 37.08   | 2.70    | 171.75  | 440 |
| $AVAILABILITY$   | Water availability zone              | Level           | 4.2    | 0.78    | 0       | 8       | 440 |
| $CLAY_{Dummy}$   | Clay soil, Dummy                     | Yes = 1         | 0.4    | 0.49    | 0       | 1       | 440 |
| $SANDY_{Dummy}$  | Sandy soil, Dummy                    | Yes = 1         | 0.4    | 0.50    | 0       | 1       | 440 |

Source: INECC, 2010; INEGI's Databank.

Table 1.7 – Differences in production characteristics across regions, mean values

| Variable                                 | Agg.    | B.C.    | N.L.    | Pue.    | S.L.P.  | Son.    | Zac.   |
|--|---------|---------|---------|---------|---------|---------|--------|
| Price of labour (MEX\$)                  | 118.907 | 132.15  | 112.82  | 122.72  | 112     | 117.34  | 114.0  |
| Price of groundwater (MEX\$)             | 10.58   | 3.39    | 11.37   | 5.26    | 7.41    | 55.21   | 5.77   |
| Price of fertilizer (MEX\$)              | 4416.66 | 8475.72 | 6528.26 | 4021.66 | 5333.33 | 6149.74 | 7000   |
| Quantity of Alfalfa and Forages (tons)   | 498.39  | 105.95  | 182.12  | 171.25  | 322.57  | 648.65  | 122.67 |
| Quantity of Fruits (tons)                | 7.27    | 137.70  | 18.87   | 0       | 0       | 139.74  | 4.02   |
| Quantity of Grains (tons)                | 55.73   | 2.04    | 143.69  | 32.32   | 15.71   | 114.16  | 23.92  |
| Quantity of Vegetables (tons)            | 4.30    | 544.91  | 883.80  | 23.77   | 234.03  | 214.09  | 65.75  |
| Cost share of groundwater                | 0.33    | 0.06    | 0.18    | 0.61    | 0.37    | 0.14    | 0.23   |
| Cost share of labour                     | 0.53    | 0.66    | 0.51    | 0.29    | 0.51    | 0.68    | 0.56   |
| Cost share of fertilizer                 | 0.12    | 0.26    | 0.30    | 0.08    | 0.11    | 0.16    | 0.19   |
| Irrigation method: gated pipes (ha)      | 5.69    | 0.23    | 0.25    | 2.03    | 5.17    | 11.84   | 4.36   |
| Irrigation method: gates (ha)            | 3.62    | 0.15    | 0.69    | 0.43    | 0.32    | 1.21    | 4.63   |
| Irrigation method: canons (ha)           | 0       | 0       | 0       | 0       | 0       | 1.39    | 0      |
| Irrigation method: sprinklers (ha)       | 5.58    | 2.96    | 4.84    | 2.58    | 7.35    | 3.98    | 1.72   |
| Irrigation method: pivot (ha)            | 0.51    | 0       | 43.87   | 0.96    | 0       | 14.60   | 0.56   |
| Irrigation method: micro-sprinklers (ha) | 0       | 0.03    | 0       | 0       | 0.71    | 0.22    | 0      |
| Irrigation method: drip (ha)             | 1.81    | 20.34   | 7.76    | 0.12    | 3.28    | 19.18   | 5.53   |
| Annual rain (mm)                         | 473.26  | 242.15  | 416.38  | 547.72  | 401.18  | 185.81  | 431.39 |
| Average temperature (centigrades)        | 18.03   | 13.51   | 15.37   | 16.68   | 18.35   | 24.23   | 17.02  |
| Pumping height (m)                       | 147.23  | 41.29   | 86.57   | 69.25   | 85.82   | 227.16  | 87.26  |

**Note:** Aguascalientes (Agg.); Baja California (B.C.); Nuevo Leon (N.L.); Puebla (Pue.); San Luis Potosi (S.L.P.); Sonora (Son.); Zacatecas (Zac.). Each cell represents the sample average within the corresponding state. **Source:** INECC, 2010; INEGI's Databank.

## 1.4 Data

The main data source for the analysis is a survey led by the National Institute of Ecology and Climate Change (*Instituto Nacional de Ecología y Cambio Climático*, INECC). This survey provides micro-data on producers in regions characterised by groundwater overdraft. The survey took place between November 2010 and January 2011. However, the information requested through its questionnaire refers to productive activities carried out in 2009. The survey collected information on the general characteristics of production units and producers, crop patterns, technology, groundwater and electricity consumption, and the perception of producers regarding water regulation. The questionnaire also included a module regarding the potential interest of producers in receiving the electricity subsidy as a lump sum rather than coupled with electricity fees. The survey was applied in seven Mexican states, from which a sample of 499 observations was collected (see Table 1.15). Due to missing information on water consumption or other key variables only 432 observations are considered in the analysis<sup>8</sup>.

The results based on this sample cannot be extrapolated at the nation level, but refer to overexploited aquifers. The selection of the states and aquifers was not random, instead it focused on those areas characterised by groundwater overdraft. States were chosen by authorities based on the number of overexploited aquifers. Within the selected states only those aquifers suffering from overdraft were considered. Nevertheless, producers within these aquifers were randomly selected from a list of irrigators provided by the Federal Commission of Electricity (CFE), Mexico's main electricity utility. It is

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<sup>8</sup> Missing information shows no specific pattern, instead it seems to follow random issues related to missing documentation during the interviews.

important to highlight that under this sampling framework all analytical results are limited to *legal* farmers, i.e. those farmers having a concession (only those farmers having a concession have access to subsidised electricity fees). For this reason, the technology used by *illegal* farmers cannot be modelled using this dataset.

The questionnaire designed by the INECC collected information on electricity facilities, but did not collect information on annual electricity consumption. Due to the latter, I matched the observations from the questionnaire to a dataset from the Electricity Federal Commission (*Comision Federal de Electricidad*, CFE), the main electricity utility in Mexico. This dataset included information for 2008 and 2009 on the type of irrigation tariffs, amount of electricity quota (Kwh), annual electricity consumption (Kwh), annual expenditure (MEX\$), and cumulated debt (MEX\$) to the CFE.

Information regarding the prices of labour and fertilisers was collected from outside sources, since it was not included in the questionnaire. Within the agricultural sector in Mexico, the daily price of labour is usually known as *jornal*. The price of a *jornal* varies among municipalities and depends on the type of crop for which the labour is used. Since the questionnaire did not contain precise information on *jornales*, this information was recovered from another survey carried out by the INECC for which data on *jornales* for a wide range of different crops was collected. Moreover, since both surveys included almost the same municipalities, it was possible to match the price of the *jornal* of each crop in the survey. The information regarding the price of fertilisers was retrieved from the Mexican Ministry of Economy through the National System of Information and Integration of Markets (SNIIM). The price of fertiliser was computed as the mean value in 2009 of the following products: diamonic phosphate, nitrate of ammonia, sulphate of ammonia,

simple superphosphate, and triple superphosphate. Prices on fertilisers are provided at the municipal level. Hence, variation of fertiliser prices follows spatial differences across municipalities.

In addition to labour and fertilisers, the importance of physical and environmental characteristics during the production process of agricultural activities is recognised throughout the literature. Precipitation, temperature and terrain slope may not only affect costs but are also key in the allocation of certain production inputs, and in the choice of irrigation technology. Moreover, these variables are highly space-dependent, i.e. they can easily change within a range of few kilometres. For this reason, I built variables capturing climatic and geographic characteristics through geographic information systems (GIS). The main advantage of GIS is their capacity to capture detailed information at really low geographical levels. To produce the information on precipitation and temperature I used the database provided by the Centre for Climatic Research from the University of Delaware<sup>9</sup>. This database includes monthly information on the maximum, minimum and average levels of rain and temperatures worldwide between 1900 and 2010. All this information is represented through a 0.5° x 0.5° grid; each cell contains the information on both precipitation and temperature all throughout the country. Using this information I calculated average and cumulated precipitation, as well as mean temperatures for 2009. Information on the terrain slope cannot be obtained from this dataset, instead it was retrieved from a digital elevation model (DEM). I considered the DEM provided by the INEGI to be the most adequate for Mexico. Through this DEM I computed the terrain slope for all the country using cells of one square kilometre.

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<sup>9</sup> <http://climate.geog.udel.edu/climate/>



I used the geographic coordinates of each observation in the sample to map its location in order to relate them to the information on environmental characteristics. In other words, every producer was represented as a point on a map; each point was then related to a particular cell containing the information on precipitation, temperature and slope.

## **1.5 Estimation results**

The results show that the consumption of groundwater responds to changes in input prices. This section presents the estimates of the econometric model including both price and cross-price elasticities for groundwater, labour, and fertiliser.

### **1.5.1 Estimates of the cost function**

The parameters of the cost function have been estimated through the method of seemingly unrelated regression equations (SURE). As can be seen from Table 1.8, in the case of the groundwater equation, both price coefficients for groundwater and labour are statistically significant. The only type of outputs being statistically significant for groundwater cost share are fruits and vegetables. The sign of the estimated parameter of fruit output is positive while the one for vegetables is negative. This suggests that the set of vegetables included in the sample are less water intensive, compared to the set of fruits which seem to need larger amounts of water during their production process. Put differently, as the ratio of the amount of vegetables to fruits increases, the groundwater share of the total cost will decrease. Regarding fixed-factors, only the coefficients of the number of hectares having water-efficient technology and manager's education are both significant and negative. These results capture the differences between producers using more

efficient irrigation technologies and small producers using flooding methods, as well as differences in terms of human capital. The results of the three cost share equations for the full model (5) are shown in Table 1.16.

**Table 1.8** – SUR regression - different specifications for the cost share of groundwater

|                  | (1)                 | (2)                 | (3)                 | (4)                 | (5)                 |
|------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| $P_{Water}$      | 0.042***<br>(5.30)  | 0.051***<br>(6.77)  | 0.047***<br>(6.19)  | 0.053***<br>(6.59)  | 0.051***<br>(6.62)  |
| $P_{Labour}$     | -0.040***<br>(4.70) | -0.048***<br>(5.99) | -0.041***<br>(5.14) | -0.050***<br>(6.08) | -0.049***<br>(6.03) |
| $P_{Fertilizer}$ | -0.002<br>(0.38)    | -0.004<br>(0.65)    | -0.007<br>(1.15)    | -0.003<br>(0.47)    | -0.002<br>(0.38)    |
| $Q_{A\&F}$       | -0.003<br>(1.08)    | -0.007*<br>(1.78)   | -0.007*<br>(1.85)   | -0.007*<br>(1.78)   | -0.006<br>(1.55)    |
| $Q_{Fruit}$      | 0.006<br>(1.53)     | 0.011**<br>(2.53)   | 0.011**<br>(2.34)   | 0.010**<br>(2.32)   | 0.009**<br>(2.05)   |
| $Q_{Grains}$     | 0.008*<br>(1.93)    | 0.001<br>(0.15)     | 0.003<br>(0.62)     | 0.003<br>(0.68)     | 0.003<br>(0.75)     |
| $Q_{Vegetables}$ | -0.010***<br>(3.81) | -0.005*<br>(1.74)   | -0.006**<br>(2.06)  | -0.006**<br>(2.00)  | -0.006**<br>(2.00)  |
| $HECTARES - HT$  |                     | -0.038***<br>(4.39) | -0.037***<br>(4.38) | -0.039***<br>(4.42) | -0.037***<br>(4.11) |
| $EDUCATION$      |                     | -0.066***<br>(3.92) | -0.063***<br>(3.83) | -0.067***<br>(4.13) | -0.065***<br>(4.09) |
| $TIME$           |                     | -0.032<br>(1.57)    | -0.028<br>(1.37)    | -0.031<br>(1.49)    | -0.030<br>(1.42)    |
| $WELLS$          |                     | -0.028<br>(1.25)    | -0.032<br>(1.43)    | -0.033<br>(1.45)    | -0.035<br>(1.55)    |
| $FINED_{Dummy}$  |                     | 0.076<br>(1.38)     | 0.084<br>(1.50)     | 0.074<br>(1.34)     | 0.071<br>(1.27)     |
| $DISTANCE$       |                     |                     | 0.042***<br>(3.50)  | 0.022<br>(1.31)     | 0.022<br>(1.30)     |
| $AVAILABILITY$   |                     |                     | 0.027<br>(0.35)     | 0.062<br>(0.74)     | 0.061<br>(0.72)     |
| $RAIN$           |                     |                     |                     | -0.082<br>(0.86)    | -0.093<br>(0.97)    |
| $TEMPERATURE$    |                     |                     |                     | -0.029<br>(0.20)    | -0.032<br>(0.21)    |
| $SLOPE$          |                     |                     |                     | 0.138<br>(1.03)     | 0.144<br>(1.08)     |
| $CLAY_{Dummy}$   |                     |                     |                     |                     | -0.047<br>(1.27)    |
| $SANDY_{Dummy}$  |                     |                     |                     |                     | -0.007<br>(0.18)    |
| Constant         | 0.429***<br>(8.56)  | 0.742***<br>(8.03)  | 0.547***<br>(3.42)  | 0.590<br>(0.73)     | 0.641<br>(0.78)     |
| Adjusted R2      | 0.38                | 0.45                | 0.46                | 0.46                | 0.47                |
| N                | 433                 | 432                 | 432                 | 432                 | 432                 |

\*  $p < 0.1$ ; \*\*  $p < 0.05$ ; \*\*\*  $p < 0.01$ **Note:** Results show the estimated coefficient from the cost share equation of groundwater; t statistics in parenthesis.

### 1.5.2 Elasticities estimates

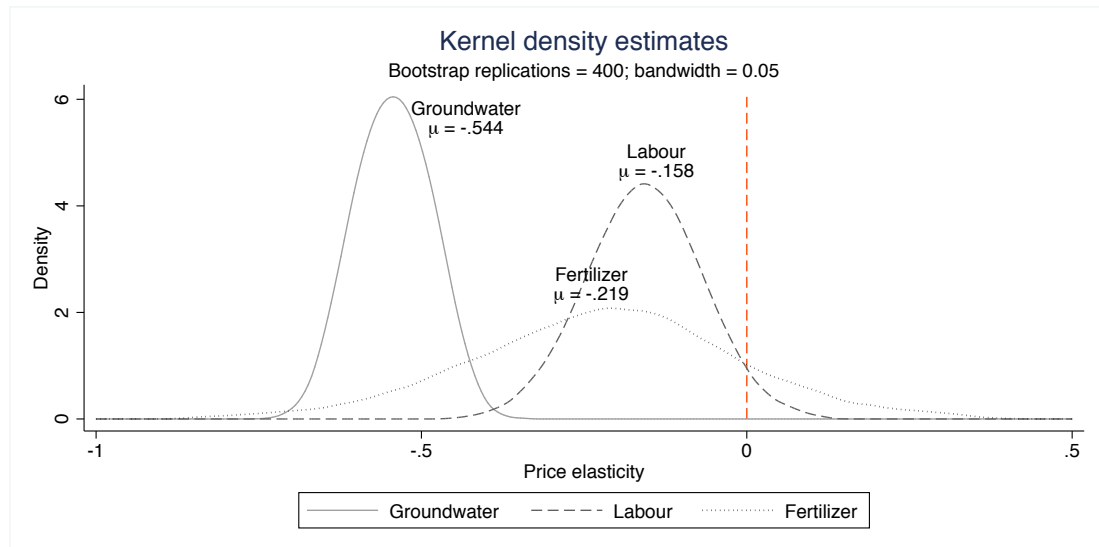
Elasticities are stochastic, thus their statistical significance (i.e. whether they are different from zero) should be analysed before making inference based on their values. Indeed, elasticities are computed using the parameters of price inputs included in the cost share equations, as well as the estimated values of the cost shares evaluated at the mean; hence, elasticities cannot be considered to be deterministic. The traditional approach to estimate the statistical properties of elasticities has relied on formulas providing a first order approximation of standard errors and the assumption of normality. However, as suggested by [Eakin et al. \(1990\)](#), there seems to be no particular reason why non-linear statistics like the ones described in Equation 1.5 follow a normal distribution. Moreover, studies like [Anderson and Thursby \(1986\)](#) and [Krinsky and Robb \(1991\)](#) further suggest that inference based on the traditional approach could be misleading. For this reason, I compute the standard errors and confidence intervals for each price and cross-price elasticity through a bootstrap re-sampling technique using the methodology proposed by [Eakin et al. \(1990\)](#). Following this methodology, I estimate the parameters of the cost share equations in 400 bootstrap samples and compute the corresponding set of elasticities. The latter provides a probability distribution for each price and cross-price elasticity.

All price elasticities are negative, but not all of them are statistically different from zero. The probability distribution for each elasticity is represented through a kernel density in Figure 1.2<sup>10</sup>. The probability mass of the three distributions concentrates on the negative side of the scale. The mean value

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<sup>10</sup> For practical reasons, all distributions in this figure have been computed using the same bandwidth, which in turn may lead to some over-smoothing. The kernel density of each elasticity, using an optimised bandwidth, is shown in the Appendix.

**Figure 1.2** – Kernel density estimates of groundwater, labour and fertiliser price elasticities - full model (5)



of the density distribution of groundwater is reached at  $-0.54$ , while for labour and fertiliser this point is reached at  $-0.15$  and  $-0.21$ , respectively. Nevertheless, the estimate for fertiliser is not statistically significantly different from 0. As can be seen from Table 1.9, these estimates are fairly consistent across the different specifications. The estimate for groundwater elasticity is higher to the that obtained in the U.S. by [Ogg and Gollehon \(1989\)](#) for western regions, which range between  $-0.34$  and  $-0.22$ ; although significantly lower than the one of [Nieswiadomy \(1988\)](#) for the High Plains of Texas equal to  $-0.95$ , and the one from [Schoengold et al. \(2006\)](#),  $-0.78$  for Kansas. Regarding previous estimates for Mexico, my estimate for groundwater price elasticity is almost three times the value obtained by [Muñoz et al. \(2006\)](#),  $-0.16$ , for 2000. Two possible reasons could explain this difference. In the first place, [Muñoz et al. \(2006\)](#) use a different definition for the price of groundwater, which is defined as the yearly electricity bill divided by the yearly consumption of water. In the second place, the sample I use for this study is composed of producers

placed in overexploited aquifers, mostly located in semi-arid regions, while [Muñoz et al. \(2006\)](#) use a sample of producers placed in different of regions in the country.

**Table 1.9** – Point estimates for cross price elasticities - full model (5)

|          | Cross-price Elasticities | Morishima Elasticities |
|----------|--------------------------|------------------------|
| WL       | 0.365***<br>(10.89)      | 0.710***<br>(17.19)    |
| LW       | 0.165***<br>(9.97)       | 0.519***<br>(6.29)     |
| FW       | 0.240***<br>(6.58)       | 0.385**<br>(2.06)      |
| WF       | 0.179***<br>(7.01)       | 0.784***<br>(14.75)    |
| FL       | -0.0341<br>(-0.17)       | 0.194<br>(0.76)        |
| LF       | -0.0115<br>(-0.17)       | 0.119<br>(0.45)        |
| <i>N</i> | 432                      | 432                    |

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

**Note:** Results show the estimated cross-price and Morishima elasticities for groundwater (W), labour (L), and fertilisers (F); t statistics in parenthesis.

The results from the estimated cross-price elasticities show that both Morishima and factor demand elasticities are positive, implying that labour and fertilisers can act as a substitute for groundwater. In other words, an increase in the price of groundwater increases the quantity of labour. For instance, an increase of 1% in the price of groundwater would increase the quantity of labour by 0.16% (LW, cross-price elasticity) and the quantity ratio of groundwater to labour by 0.51% (LW, Morishima elasticity). In the case of fertiliser, an increase of 1% in the price of groundwater would increase the quantity of fertiliser by 0.24% (FW, cross-price elasticity) and the quantity ratio of

groundwater to fertiliser by 0.38% (FW, Morishima elasticity). These results further suggest that fertiliser is a more sensitive substitute to groundwater than labour.

It should be noticed that the level of substitution of water for labour may further depend on the type of irrigation technology used. For instance, in the case of surface irrigation technologies for which flooding is a common practice, the consumption of groundwater can be significantly reduced by using labour in task like field levelling or building furrows. Sprinkler systems are more water-efficient and demand a low amount of human management, thus the level of substitutability of this technology is lower than surface irrigation methods. Similarly, drip irrigation methods being highly efficient provide even less substitutability with respect to labour. However, these technologies are more demanding in terms of capital. [Nieswiadomy \(1988\)](#) also identifies groundwater and labour as substitutes and confirms the relationship between the type of technology and the level of substitutability. Regarding fertilisers, their cross-price elasticity with respect to water seems to be lower than that of labour. Water can be substituted with fertiliser in order to increase crop yield and improve water efficiency. However, there are certain limits to this substitutability since an excessive use of fertilisers can have a negative effect on soils (e.g. acidification).

### **1.5.3 Robustness checks**

To test the robustness of the previous estimates I ran the model defined in Equation 1.9 using a different definition for the price of groundwater. More precisely, I use the same definition as [Muñoz et al. \(2006\)](#), in which bilateral is defined as the annual cost of electricity divided by the total amount of water extracted. As can be seen from Table 1.18 in the Appendix, the results

using this different definition are very close to the ones discussed in the previous section, though slightly higher: the price elasticity of groundwater based on this price definition is  $-.57$ , compared to  $-.54$ ; elasticities for labour and fertiliser are  $-.24$  and  $-.32$ , compared to  $-.15$  and  $-.21$ , respectively. In order to properly compare these two sets of estimates, I estimate confidence intervals (at 95%) for the full model using the two price definitions, Table 1.19 and Table 1.20. The results show that confidence intervals overlap, further suggesting that the two sets of elasticities are not statistically different. The same diagnosis applies to the estimates of cross-price elasticities, Table 1.21 and Table 1.22.

My definition of bilateral depends on both the price of electricity set by federal authorities and the characteristics of the pump used to extract water. Since my analysis relies on cross-sectional data, it is thus possible that the price of groundwater is correlated with unobservables that I cannot control for. To test for the latter, I ran the model in Equation 1.9 using a three-step least squares (3SLS) method using as instrument the maximum amount of electricity quota of each producer. This quota is provided by the Ministry of Agriculture (SAGARPA) and is based on the average amount of electricity consumed during the three years previous to requesting a concession. The quota allows producers to benefit from the subsidised and fixed electricity fees up to its maximal value; after this threshold producers pay a higher rate for each extra kwh. The quota is thus correlated with the electricity price, but does not directly affect the cost share of groundwater at present time. To validate the 3SLS model I ran a Hausman test comparing the estimates from this model to the ones obtained from the SUR model. The test provided a Chi-square(22) equal to 6.52; thus, I do not reject the null hypothesis of no systematic difference between the coefficients and opt to keep the SUR



model.

Finally, following [Diewert and Wales \(1987\)](#), I test the concavity of the Hessian matrix of the estimated cost function for the full model presented in Table 1.8. The statistics of the eigenvalues for the sample are presented in Table 1.23. The model satisfies the regularity condition for a significant number of observations in the sample (although not for every observation).

#### **1.5.4 Is decoupling electricity subsidies a viable policy alternative?**

The results from the previous sections show that water for irrigation does respond to changes in its price. According to these estimates, an increase of 1% in the price of groundwater could reduce the quantity extracted by approximately 0.54%. Moreover, an increase in the price of groundwater of the same magnitude can rise the quantity of labour and fertiliser by 0.1% and 0.2%, respectively. The direct policy implication from the latter is that policy reforms aiming to reduce - or even remove - the subsidy embedded in electricity fees could help to cope with groundwater overdraft.

Table 1.10 shows the expected reduction in irrigation water following the total decoupling of electricity across the observations in the sample. Electricity subsidy is estimated at approximately 80% of the current electricity fees. A full decoupling of this subsidy, considering the groundwater elasticity estimate, would translate in an average yearly reduction of 92,499 m<sup>3</sup> across the observations in the sample. On average, the biggest reductions would take place in Sonora, Nuevo Leon, and Baja California; all northern states characterised by arid climates.

Political costs and opposition from farmers and unions make removing agri-

**Table 1.10** – Expected reduction in water demand after decoupling (m<sup>3</sup>)

| Region          | Mean    | S.D.    | Min    | Max       |
|-----------------|---------|---------|--------|-----------|
| Aguascalientes  | 46,658  | 65,671  | 4,147  | 298,598   |
| Baja California | 78,563  | 122,175 | 1,184  | 855,360   |
| Nuevo Leon      | 152,345 | 192,048 | 10,368 | 972,000   |
| Puebla          | 14,518  | 33,032  | 337    | 184,032   |
| San Luis Potosi | 77,834  | 138,004 | 1,728  | 653,184   |
| Sonora          | 286,111 | 228,305 | 672    | 1,024,632 |
| Zacatecas       | 34,220  | 43,288  | 829    | 227,059   |
| Total           | 92,499  | 154,723 | 337    | 1,024,632 |

cultural subsidies a difficult task to implement. Rather than removing the subsidy and increasing the price of electricity, a more viable policy alternative could be to *decouple* the subsidy. This is a policy alternative that has been extensively discussed among environmental experts in Mexico, [Muñoz et al. \(2006\)](#). One policy option often considered is transforming the subsidy into a lump sum transfer to be used for investing in water saving technology, while facing higher electricity tariffs that better reflect the scarcity of the resource.

The survey carried out by the INECC in 2010 included questions regarding this policy alternative. More precisely, producers were asked whether they would be interested in participating in a programme from which they will be receiving the yearly amount of the subsidy they got in 2009 (expressed in Mexican pesos), so they could invest it for improving their irrigation system; or whether they would prefer to keep receiving the subsidy as part of the electricity tariffs. Only 11% of the producers surveyed were interested in this policy alternative. However, this percentage varies across the Mexican states considered in the survey.

The implementation of future reforms aiming at decoupling electricity subsidies could benefit from a better understanding of producers' interest in this type of programme. To contribute to the latter, I used the information provided in the INECC survey<sup>11</sup> to analyse the characteristics of the producers interested to participate. Thus, I ran a binary choice model that analyses the interest in *hypothetically* participating in this programme based on a set of covariates including the amount of the subsidy that producers would receive, as well as characteristics of producers and aquifers.

The dependent variable is thus defined as:

$$y = \begin{cases} 1 & \text{if producer would participate} \\ 0 & \text{if producer would not participate} \end{cases} \quad (1.10)$$

While the structure of the model is the following:

$$Pr(y_i = 1|x_i) = F(x_i'\beta) \quad (1.11)$$

Where  $F(\cdot)$  is the logit function, and  $x_i$  is a vector including the following variables: *SUBSIDY*, the transfer that the producer would receive, i.e. the decoupled subsidy (\$MEX); *INCOME*, the net income of the producer during 2009 (\$MEX); *AGE*, age of the manager or responsible of the production unit; *EDUCATION*, number of years of education of the manager or responsible of the production unit; *ACTIVITY*, the number of years that the production unit has been active; *QUALITY<sub>Dummy</sub>*, dummy that indicates whether the aquifer is suffering from salinisation or marine intrusion;

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<sup>11</sup> This is the same survey as that used for the analysis in previous sections and described in section 2.4.

*RECHARGE*, balance of water inflow/outflow in the aquifer (millions  $m^3$ ); *Price<sub>water</sub>*, price of groundwater as defined in Equation 1.6, (\$MEX per  $m^3$ ); *WATER*, the total amount of water consumed during the year ( $m^3$ ); *TECH*, the percentage of hectares using water saving technology; *USERS*, the number of users sharing the well; *SURFACE*, the total area used for production (Ha); *DISTANCE*, distance to the closest population with at least 25,000 inhabitants; *RESPECT*, scale from 1 to 10 that ranks the respect of producers towards water regulation (10 being the highest level of respect); *Dummy<sub>Centre</sub>* and *Dummy<sub>South</sub>*, dummies for northern and southern states.

The results from this model are shown in Table 1.11. The first thing to highlight is that the amount of the subsidy does not seem to influence the decision to participate, even when controlling for the net income of producers. In terms of characteristics of the producers, only age and time in agricultural activities are statistically significant. Indeed, older producers are more likely to participate, while those having a longer time in agricultural activities are less interested. The average age of the producers in the sample is 54 years old, and ranging up to 88 years old. Thus, older producers who feel more vulnerable may be interested in receiving this transfer as a source of additional income. Regarding the time in agricultural activities, for those producers who have benefited longer from the subsidy, there may be a stronger path dependency. Another important result from this analysis is the fact that those producers facing higher levels of groundwater overdraft, and in consequence a higher price for groundwater, are more likely to participate in such a programme. The latter follows from the significance and signs of the coefficients of the price of groundwater and recharge of groundwater. Finally, as indicated by regional dummies, producers in the centre of the country are more interested than producers in northern states to participate. These

regional differences can be clearly appreciated when looking at regional differences in participation rates: in the northern states of Baja California and Sonora only 1% and 4% of the producers in the survey were interested to participate, in contrast in central and southern states this percentage ranged between 12% and 20%. One possible reason for these differences is the fact that northern states already account for the largest extensions of irrigated land (see Background section); hence the preference over cheaper electricity tariffs.

It is important to highlight that this exercise has been done considering only changes at the intensive margin. Moreover, this seems to be also the case of the existing policy debates surrounding decoupling electricity subsidies. Indeed, as discussed in previous sections, evidence from other countries shows that changes in the price of groundwater or in the type of technology have an impact in the long-run on the allocation of crops. In other words, it is possible that adopting new irrigation technologies may eventually lead to more water-intensive crops.

**Table 1.11** – Results from the Logit model

|                               | (1)                | (2)                 | (3)                 | (4)                 | (5)                 |
|-------------------------------|--------------------|---------------------|---------------------|---------------------|---------------------|
| <i>Dummy<sub>Centre</sub></i> | 2.120***<br>(3.09) | 2.322***<br>(3.01)  | 3.052***<br>(3.03)  | 3.416***<br>(2.62)  | 3.551***<br>(2.82)  |
| <i>Dummy<sub>South</sub></i>  | 2.525<br>(1.30)    | 3.073<br>(1.46)     | 4.216<br>(1.61)     | 4.091<br>(1.39)     | 4.335<br>(1.57)     |
| <i>SUBSIDY</i>                | 0.040<br>(0.48)    | 0.026<br>(0.32)     | 0.039<br>(0.47)     | -0.014<br>(0.17)    | -0.019<br>(0.22)    |
| <i>INCOME</i>                 | -0.143<br>(1.29)   | -0.063<br>(0.59)    | -0.066<br>(0.63)    | -0.032<br>(0.25)    | -0.011<br>(0.07)    |
| <i>AGE</i>                    |                    | 0.039**<br>(2.53)   | 0.040**<br>(2.56)   | 0.044***<br>(2.77)  | 0.043***<br>(2.66)  |
| <i>EDUCATION</i>              |                    | -0.033<br>(0.90)    | -0.031<br>(0.82)    | -0.039<br>(0.96)    | -0.041<br>(1.05)    |
| <i>ACTIVITY</i>               |                    | -0.038***<br>(2.75) | -0.036***<br>(2.60) | -0.040***<br>(2.78) | -0.040***<br>(2.77) |
| <i>QUALITY</i>                |                    |                     | 0.379<br>(0.74)     | -0.034<br>(0.06)    | 0.029<br>(0.05)     |
| <i>RECHARGE</i>               |                    |                     | -1.326*<br>(1.91)   | -1.172*<br>(1.75)   | -1.243*<br>(1.78)   |
| <i>P<sub>Water</sub></i>      |                    |                     |                     | 0.039**<br>(2.28)   | 0.040**<br>(2.39)   |
| <i>WATER</i>                  |                    |                     |                     | -0.000<br>(0.30)    | -0.000<br>(0.25)    |
| <i>TECH</i>                   |                    |                     |                     | -0.007<br>(1.35)    | -0.007<br>(1.27)    |
| <i>USERS</i>                  |                    |                     |                     |                     | 0.003<br>(0.21)     |
| <i>SURFACE</i>                |                    |                     |                     |                     | -0.001<br>(0.08)    |
| <i>DISTANCE</i>               |                    |                     |                     |                     | -0.001<br>(0.09)    |
| <i>RESPECT</i>                |                    |                     |                     |                     | 0.191<br>(0.93)     |
| Constant                      | -2.573<br>(0.69)   | -3.518<br>(0.91)    | -4.326<br>(1.07)    | -3.405<br>(0.72)    | -5.379<br>(0.99)    |
| <i>N</i>                      | 429                | 428                 | 428                 | 420                 | 420                 |

\*  $p < 0.1$ ; \*\*  $p < 0.05$ ; \*\*\*  $p < 0.01$ **Note:** t statistics in parenthesis.

## Conclusions

The main objective of this paper is to model the behaviour of Mexican producers operating in overexploited aquifers using a structural approach. This approach allows to estimate not only the price elasticity of groundwater, but also testing for the existence of cross-price effects among groundwater and other production inputs. To this end, I use a combination of different micro-data sources to estimate a Translog cost function.

The results of the analysis show that the demand of irrigation water in the sample analysed is inelastic. According to my estimates, a 1% increase in bilateral can reduce on average groundwater extraction by 0.54%. These results are in line with previous estimates of groundwater elasticity.

My results also show that labour and fertiliser can act as substitutes for groundwater. An increase in the price of groundwater increases the quantity of both labour and fertiliser. According to my estimates, an increase of 1% in the price of groundwater would increase on average the quantity of labour by 0.16% (derived demand elasticity) and the quantity ratio of groundwater to labour by 0.51% (Morishima elasticity). In the case of fertiliser, an increase of 1% in the price of groundwater would increase the quantity of fertiliser by 0.24% (derived demand elasticity) and the quantity ratio of groundwater to fertiliser by 0.38% (Morishima elasticity).

Overall, my results show that policies aiming at reducing groundwater overdraft could use electricity price as a policy tool for reducing unsustainable consumption patterns. However, the implementation of such policies will probably face important challenges to overcome. Only 11% of the producers in the sample analysed would accept decoupling the subsidy and receiving it

as a direct transfer. The last section of this paper further analyses the characteristics of those producers potentially interested in such a policy alternative. Results show that the size of the transfer does not seem to influence participation (even after controlling for net income). Producers that have been involved in agriculture for longer, and thus benefited longer from the subsidy, are less likely to participate in this type of programmes. Probably the simplest explanation for the latter is path dependency, i.e. these producers are more used to receiving these subsidies. However, producers operating in regions with higher water stress and facing higher extraction costs would be more likely to participate. In addition, results show important regional differences. Producers in northern states closer to the U.S. border are significantly less interested in decoupling the subsidy, while for those in central states this seems to be a more appealing policy alternative. These differences could be related to the fact that northern producers face higher water stress and may have already invested in water saving technology.

There are certain caveats about the analysis worth mentioning. My analysis focuses on the direct impact of changes in electricity prices, i.e. the intensive margin. Since it does not account for potential changes in the long-run, when farmers may switch to less water-intensive crops - the extensive margin - it is likely that it underestimates the effect of changes in electricity prices. In addition, my identification strategy further relies on the assumption that output is exogenous. If this is not the case, estimates could be biased. Another potential caveat is the fact that the concavity is not satisfied for every observation in the sample. Local concavity could be further imposed to comply with this property.

Finally, this analysis provides a number of results useful for future policy actions aiming to limit groundwater overdraft. The demand for irrigation



water being inelastic it implies that changes in electricity prices cannot be the only tool promoting sustainable groundwater extraction. Indeed, in addition to reforming the existing mechanism of quotas, coping with groundwater overdraft will require greater enforcement capability. In practice, this implies investing in additional personnel, capacity building, as well as better equipment for the implementation of environmental inspections.

## 1.A Appendix: Chapter 1

Table 1.12 – Share of production units by type of activity and number of hectares by type of production method.

| Region              | Agriculture | Livestock | Forestry | Harvesting | Other | Irrigation Ha | Rainfed Ha |
|---------------------|-------------|-----------|----------|------------|-------|---------------|------------|
| Aguascalientes      | 90.30%      | 6.20%     | 0.03%    | 0.03%      | 3.44% | 29.61%        | 70.39%     |
| Baja California Sur | 39.21%      | 56.20%    | 0.02%    | 0.27%      | 4.30% | 72.86%        | 27.14%     |
| Baja California     | 70.91%      | 23.18%    | 0.16%    | 0.25%      | 5.50% | 69.03%        | 30.97%     |
| Campeche            | 72.61%      | 22.28%    | 0.09%    | 0.28%      | 4.73% | 1.94%         | 98.06%     |
| Chiapas             | 89.69%      | 7.15%     | 0.05%    | 0.08%      | 3.03% | 2.08%         | 97.92%     |
| Chihuahua           | 86.26%      | 11.02%    | 0.73%    | 0.03%      | 1.96% | 27.74%        | 72.26%     |
| Coahuila            | 77.76%      | 17.33%    | 0.03%    | 1.11%      | 3.78% | 33.89%        | 66.11%     |
| Colima              | 75.53%      | 17.18%    | 0.13%    | 0.16%      | 7.01% | 33.24%        | 66.76%     |
| Distrito Federal    | 95.96%      | 1.29%     | 0.15%    | 0.01%      | 2.59% | 6.07%         | 93.93%     |
| Durango             | 91.44%      | 5.60%     | 0.10%    | 0.02%      | 2.83% | 19.85%        | 80.15%     |
| Guamajuato          | 94.40%      | 2.67%     | 0.02%    | 0.05%      | 2.85% | 33.18%        | 66.82%     |
| Guerrero            | 93.74%      | 4.03%     | 0.06%    | 0.09%      | 2.08% | 5.80%         | 94.20%     |
| Hidalgo             | 90.15%      | 3.71%     | 0.06%    | 0.22%      | 5.87% | 16.64%        | 83.36%     |
| Jalisco             | 79.34%      | 14.21%    | 0.12%    | 0.04%      | 6.29% | 11.33%        | 88.67%     |
| Mexico              | 95.63%      | 1.22%     | 0.04%    | 0.04%      | 3.07% | 15.15%        | 84.85%     |
| Michoacan           | 89.51%      | 3.01%     | 0.14%    | 0.15%      | 7.19% | 21.54%        | 78.46%     |
| Morelos             | 91.26%      | 1.66%     | 0.05%    | 0.02%      | 7.01% | 27.91%        | 72.09%     |
| Nayarit             | 87.94%      | 7.62%     | 0.06%    | 0.05%      | 4.34% | 18.41%        | 81.59%     |
| Nuevo Leon          | 72.75%      | 22.36%    | 0.08%    | 0.08%      | 4.73% | 21.56%        | 78.44%     |
| Oaxaca              | 91.59%      | 4.61%     | 0.08%    | 0.11%      | 3.60% | 4.43%         | 95.57%     |
| Puebla              | 92.77%      | 1.05%     | 0.07%    | 0.10%      | 6.01% | 11.76%        | 88.24%     |
| Queretaro           | 92.83%      | 3.89%     | 0.12%    | 0.10%      | 3.06% | 28.80%        | 71.20%     |
| Quintana Roo        | 90.08%      | 6.09%     | 0.37%    | 0.09%      | 3.37% | 1.23%         | 98.77%     |
| San Luis Potosi     | 88.69%      | 6.49%     | 0.03%    | 0.24%      | 4.54% | 9.82%         | 90.18%     |
| Sinaloa             | 86.29%      | 8.78%     | 0.11%    | 0.08%      | 4.75% | 46.33%        | 53.67%     |
| Sonora              | 43.16%      | 52.01%    | 0.09%    | 0.05%      | 4.70% | 59.45%        | 40.55%     |
| Tabasco             | 67.68%      | 25.82%    | 0.12%    | 0.07%      | 6.30% | 0.92%         | 99.08%     |
| Tamaulipas          | 68.11%      | 26.51%    | 0.28%    | 0.16%      | 4.94% | 22.35%        | 77.65%     |
| Tlaxcala            | 90.94%      | 0.25%     | 0.02%    | 0.02%      | 8.77% | 5.23%         | 94.77%     |
| Veracruz            | 76.54%      | 16.22%    | 0.21%    | 0.11%      | 6.92% | 3.34%         | 96.66%     |
| Yucatan             | 80.06%      | 15.18%    | 0.07%    | 0.78%      | 3.92% | 7.93%         | 92.07%     |
| Zacatecas           | 89.92%      | 4.64%     | 0.01%    | 0.04%      | 5.40% | 11.42%        | 88.58%     |
| Total               | 87.41%      | 7.72%     | 0.10%    | 0.12%      | 4.64% | 17.76%        | 82.24%     |

Source: Data obtained from the Agricultural Census 2007, INEGI

**Table 1.13** – Number of production units by type of irrigation technology

| Region              | Lined<br>Canals | Earthen<br>Canals | Aspersion     | Micro-<br>aspersion | Dripping      | Other         |
|---------------------|-----------------|-------------------|---------------|---------------------|---------------|---------------|
| Aguascalientes      | 2,691           | 2,181             | 1,517         | 105                 | 228           | 759           |
| Baja California     | 1,916           | 2,920             | 205           | 29                  | 1,060         | 102           |
| Baja California Sur | 71              | 445               | 198           | 84                  | 1,218         | 712           |
| Campeche            | 56              | 648               | 228           | 80                  | 541           | 430           |
| Coahuila            | 6,478           | 10,092            | 841           | 104                 | 384           | 441           |
| Colima              | 1,589           | 3,071             | 318           | 271                 | 421           | 413           |
| Chiapas             | 3,278           | 7,406             | 1,214         | 272                 | 586           | 2,056         |
| Chihuahua           | 4,954           | 10,031            | 1,677         | 791                 | 403           | 2,746         |
| Distrito Federal    | 17              | 597               | 70            | 2                   | 41            | 660           |
| Durango             | 7,348           | 10,854            | 509           | 93                  | 154           | 1,225         |
| Guanajuato          | 11,248          | 27,675            | 3,958         | 169                 | 678           | 8,664         |
| Guerrero            | 6,238           | 15,090            | 2,443         | 312                 | 1,225         | 5,948         |
| Hidalgo             | 14,168          | 36,248            | 358           | 29                  | 472           | 3,355         |
| Jalisco             | 4,597           | 13,387            | 4,228         | 130                 | 1,869         | 3,891         |
| Mexico              | 27,347          | 49,785            | 807           | 125                 | 945           | 1,805         |
| Michoacan           | 10,852          | 45,867            | 1,930         | 329                 | 2,316         | 4,342         |
| Morelos             | 4,420           | 11,189            | 212           | 43                  | 245           | 1,535         |
| Nayarit             | 2,391           | 2,866             | 9,882         | 204                 | 764           | 1,970         |
| Nuevo Leon          | 686             | 4,136             | 1,441         | 174                 | 293           | 308           |
| Oaxaca              | 5,166           | 18,396            | 3,316         | 445                 | 630           | 5,540         |
| Puebla              | 12,705          | 38,580            | 3,209         | 114                 | 291           | 3,385         |
| Queretaro           | 3,995           | 5,900             | 773           | 33                  | 405           | 1,478         |
| Quintana Roo        | 13              | 312               | 135           | 39                  | 112           | 171           |
| San Luis Potosi     | 2,662           | 10,381            | 1,076         | 129                 | 826           | 1,508         |
| Sinaloa             | 3,385           | 27,486            | 591           | 58                  | 1,164         | 1,450         |
| Sonora              | 4,437           | 12,003            | 271           | 61                  | 494           | 636           |
| Tabasco             | 41              | 115               | 84            | 24                  | 91            | 308           |
| Tamaulipas          | 2,104           | 12,695            | 329           | 629                 | 235           | 589           |
| Tlaxcala            | 4,476           | 1,399             | 830           | 21                  | 38            | 290           |
| Veracruz            | 1,882           | 9,529             | 1,049         | 181                 | 734           | 2,448         |
| Yucatan             | 931             | 1,742             | 3,707         | 2,910               | 607           | 2,214         |
| Zacatecas           | 7,734           | 12,825            | 1,239         | 201                 | 1,411         | 2,733         |
| <b>Total</b>        | <b>159,876</b>  | <b>405,851</b>    | <b>48,645</b> | <b>8,191</b>        | <b>20,881</b> | <b>64,112</b> |

**Source:** Data obtained from the Agricultural Census 2007, INEGI

**Table 1.14** – Number of production units by type of water source.

| Region              | Reservoirs    | Deep wells     | Shallow wells | Rivers         | Springs       | Damns          | Other         |
|---------------------|---------------|----------------|---------------|----------------|---------------|----------------|---------------|
| Aguascalientes      | 203           | 4,484          | 116           | 60             | 55            | 2,389          | 42            |
| Baja California     | 70            | 2,125          | 153           | 2,141          | 28            | 363            | 52            |
| Baja California Sur | 36            | 1,842          | 225           | 17             | 217           | 155            | 100           |
| Campeche            | 23            | 1,422          | 372           | 82             | 0             | 5              | 26            |
| Coahuila            | 139           | 3,033          | 115           | 2,111          | 2,224         | 6,258          | 415           |
| Colima              | 214           | 1,789          | 52            | 2,470          | 265           | 2,136          | 35            |
| Chiapas             | 833           | 1,293          | 661           | 8,273          | 1,642         | 1,130          | 231           |
| Chihuahua           | 333           | 8,039          | 478           | 3,768          | 756           | 5,097          | 575           |
| Distrito Federal    | 29            | 67             | 77            | 42             | 20            | 66             | 1,080         |
| Durango             | 407           | 4,482          | 237           | 4,676          | 690           | 6,954          | 204           |
| Guanajuato          | 1,595         | 23,312         | 571           | 6,172          | 423           | 17,375         | 596           |
| Guerrero            | 730           | 2,628          | 1,182         | 11,482         | 4,088         | 7,797          | 1,739         |
| Hidalgo             | 1,463         | 4,751          | 188           | 8,522          | 2,681         | 27,812         | 1,763         |
| Jalisco             | 1,784         | 8,126          | 758           | 5,670          | 1,089         | 8,791          | 662           |
| Mexico              | 7,631         | 13,025         | 1,166         | 14,664         | 6,446         | 26,570         | 1,770         |
| Michoacan           | 4,695         | 11,986         | 1,765         | 20,970         | 7,640         | 15,512         | 1,116         |
| Morelos             | 1,422         | 2,749          | 105           | 6,705          | 3,706         | 1,406          | 287           |
| Nayarit             | 1,515         | 2,108          | 403           | 9,830          | 782           | 798            | 1,454         |
| Nuevo Leon          | 83            | 2,388          | 144           | 2,555          | 453           | 801            | 88            |
| Oaxaca              | 641           | 4,314          | 3,300         | 16,164         | 2,448         | 4,163          | 928           |
| Puebla              | 2,891         | 24,149         | 1,348         | 10,013         | 6,839         | 10,060         | 1,253         |
| Queretaro           | 1,101         | 5,183          | 336           | 1,242          | 604           | 3,852          | 107           |
| Quintana Roo        | 11            | 693            | 46            | 7              | 3             | 2              | 22            |
| San Luis Potosi     | 420           | 7,133          | 920           | 2,395          | 1,989         | 1,838          | 924           |
| Sinaloa             | 810           | 1,782          | 385           | 2,548          | 65            | 26,610         | 231           |
| Sonora              | 262           | 3,734          | 1,485         | 2,308          | 265           | 7,697          | 168           |
| Tabasco             | 152           | 209            | 58            | 156            | 10            | 11             | 69            |
| Tamaulipas          | 109           | 1,445          | 204           | 4,990          | 895           | 7,478          | 151           |
| Tlaxcala            | 351           | 3,553          | 98            | 2,264          | 105           | 494            | 17            |
| Veracruz            | 442           | 1,824          | 308           | 9,689          | 1,288         | 1,150          | 590           |
| Yucatan             | 28            | 8,008          | 2,484         | 0              | 8             | 12             | 234           |
| Zacatecas           | 580           | 14,757         | 674           | 815            | 853           | 6,594          | 136           |
| <b>Total</b>        | <b>31,003</b> | <b>176,433</b> | <b>20,414</b> | <b>162,801</b> | <b>48,577</b> | <b>201,376</b> | <b>17,065</b> |

**Source:** Data obtained from the Agricultural Census 2007, INEGI

**Table 1.15** – Distribution of surveys by state

| <b>State Name</b> | Number<br>of<br>Surveys | Percentage    |
|-------------------|-------------------------|---------------|
| Aguascalientes    | 48                      | 9.6%          |
| Baja California   | 104                     | 20.8%         |
| Nuevo Leon        | 47                      | 9.4%          |
| Puebla            | 64                      | 12.8%         |
| San Luis Potos.   | 31                      | 6.2%          |
| Sonora            | 76                      | 15.2%         |
| Zacatecas         | 129                     | 25.9%         |
| <b>Total</b>      | <b>499</b>              | <b>100.0%</b> |

**Source:** INECC, 2010.

**Table 1.16** – SUR regression - full model for the three cost shares

|                  | CS - Groundwater    | CS - Labour         | CS - Fertiliser     |
|------------------|---------------------|---------------------|---------------------|
| $P_{Water}$      | 0.051***<br>(6.62)  | -0.049***<br>(6.03) | -0.002<br>(0.38)    |
| $P_{Labour}$     | -0.049***<br>(6.03) | 0.161***<br>(4.23)  | -0.112***<br>(3.06) |
| $P_{Fertilizer}$ | -0.002<br>(0.38)    | -0.112***<br>(3.06) | 0.114***<br>(3.26)  |
| $Q_{A\&F}$       | -0.006<br>(1.55)    | 0.015***<br>(3.75)  | -0.008***<br>(4.06) |
| $Q_{Fruit}$      | 0.009**<br>(2.05)   | -0.007<br>(1.26)    | -0.002<br>(0.58)    |
| $Q_{Grains}$     | 0.003<br>(0.75)     | -0.005<br>(1.31)    | 0.002<br>(0.77)     |
| $Q_{Vegetables}$ | -0.006**<br>(2.00)  | -0.003<br>(0.93)    | 0.008***<br>(2.60)  |
| $HECTARES - HT$  | -0.037***<br>(4.11) | 0.047***<br>(4.81)  | -0.009<br>(1.54)    |
| $EDUCATION$      | -0.065***<br>(4.09) | 0.038**<br>(2.33)   | 0.027***<br>(2.74)  |
| $TIME$           | -0.030<br>(1.42)    | 0.032*<br>(1.95)    | -0.002<br>(0.14)    |
| $WELLS$          | -0.035<br>(1.55)    | -0.007<br>(0.23)    | 0.042**<br>(2.10)   |
| $FINED_{Dummy}$  | 0.071<br>(1.27)     | -0.153***<br>(2.69) | 0.083*<br>(1.65)    |
| $DISTANCE$       | 0.022<br>(1.30)     | -0.041***<br>(2.64) | 0.019<br>(1.47)     |
| $AVAILABILITY$   | 0.061<br>(0.72)     | -0.026<br>(0.41)    | -0.034<br>(0.71)    |
| $RAIN$           | -0.093<br>(0.97)    | 0.074<br>(0.80)     | 0.019<br>(0.31)     |
| $TEMPERATURE$    | -0.032<br>(0.21)    | 0.073<br>(0.59)     | -0.041<br>(0.44)    |
| $SLOPE$          | 0.144<br>(1.08)     | -0.366***<br>(2.62) | 0.222*<br>(1.95)    |
| $CLAY_{Dummy}$   | -0.047<br>(1.27)    | 0.043<br>(1.37)     | 0.004<br>(0.16)     |
| $SANDY_{Dummy}$  | -0.007<br>(0.18)    | 0.019<br>(0.59)     | -0.012<br>(0.47)    |
| Constant         | 0.641<br>(0.78)     | 1.222<br>(1.50)     | -0.863<br>(1.60)    |
| Adjusted R2      | 0.47                | 0.40                | 0.28                |
| N                | 432                 | 432                 | 432                 |

\*  $p < 0.1$ ; \*\*  $p < 0.05$ ; \*\*\*  $p < 0.01$

**Table 1.17** – Point estimates for price elasticities

|            | (1)                   | (2)                   | (3)                   | (4)                   | (5)                   |
|------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Water      | -0.581***<br>(-17.47) | -0.545***<br>(-17.77) | -0.559***<br>(-17.95) | -0.538***<br>(-16.65) | -0.545***<br>(-17.40) |
| Labour     | -0.186**<br>(-2.12)   | -0.179***<br>(-2.82)  | -0.199***<br>(-3.17)  | -0.154**<br>(-2.28)   | -0.154**<br>(-2.27)   |
| Fertilizer | -0.255<br>(-1.11)     | -0.268<br>(-1.54)     | -0.275<br>(-1.56)     | -0.209<br>(-1.13)     | -0.205<br>(-1.10)     |
| <i>N</i>   | 433                   | 432                   | 432                   | 432                   | 432                   |

*t* statistics in parentheses

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

**Table 1.18** – Point estimates for price elasticities - alternative definition for the price of groundwater

|            | (1)                   | (2)                   | (3)                   | (4)                   | (5)                   |
|------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Water      | -0.567***<br>(-28.45) | -0.575***<br>(-30.41) | -0.574***<br>(-30.96) | -0.573***<br>(-30.38) | -0.574***<br>(-30.58) |
| Labour     | -0.237***<br>(-3.46)  | -0.249***<br>(-3.68)  | -0.244***<br>(-3.46)  | -0.240***<br>(-3.43)  | -0.240***<br>(-3.43)  |
| Fertilizer | -0.310<br>(-1.59)     | -0.341*<br>(-1.71)    | -0.329<br>(-1.60)     | -0.320<br>(-1.57)     | -0.318<br>(-1.56)     |
| <i>N</i>   | 439                   | 438                   | 438                   | 438                   | 438                   |

*t* statistics in parentheses

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

**Table 1.19** – Confidence interval for price elasticities - full model

|            | $\beta$   | S.E.  | <i>t</i> | 95% C.I.       |
|------------|-----------|-------|----------|----------------|
| Water      | -0.545*** | 0.035 | -15.489  | -0.613, -0.476 |
| Labour     | -0.154**  | 0.076 | -2.031   | -0.302, -0.005 |
| Fertilizer | -0.205    | 0.199 | -1.033   | -0.595, 0.184  |

*t* statistics in parentheses

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$



**Table 1.20** – Confidence intervals for price elasticities - alternative definition for the price of groundwater - full model

|            | $\beta$   | S.E.  | $t$     | 95% C.I.       |
|------------|-----------|-------|---------|----------------|
| Water      | -0.574*** | 0.018 | -31.529 | -0.610, -0.539 |
| Labour     | -0.240*** | 0.073 | -3.280  | -0.383, -0.096 |
| Fertilizer | -0.318    | 0.212 | -1.505  | -0.733, 0.096  |

$t$  statistics in parentheses

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

**Table 1.21** – Confidence intervals for cross-price elasticities - full model

| C-P Elasticity | $\beta$  | S.E.  | $t$    | 95% C.I.     |
|----------------|----------|-------|--------|--------------|
| WL             | 0.365*** | 0.035 | 10.458 | 0.297,0.434  |
| LW             | 0.165*** | 0.018 | 9.115  | 0.130,0.201  |
| FW             | 0.240*** | 0.033 | 7.244  | 0.175,0.304  |
| WF             | 0.179*** | 0.025 | 7.089  | 0.130,0.229  |
| FL             | -0.034   | 0.210 | -0.163 | -0.445,0.377 |
| LF             | -0.012   | 0.071 | -0.162 | -0.151,0.128 |

| Morishima | $\beta$  | S.E.  | $t$    | 95% C.I.     |
|-----------|----------|-------|--------|--------------|
| WL        | 0.710*** | 0.046 | 15.404 | 0.619,0.800  |
| LW        | 0.519*** | 0.093 | 5.575  | 0.337,0.702  |
| FW        | 0.385**  | 0.195 | 1.976  | 0.003,0.766  |
| WF        | 0.784*** | 0.053 | 14.671 | 0.679,0.889  |
| FL        | 0.194    | 0.270 | 0.719  | -0.334,0.722 |
| LF        | 0.119    | 0.284 | 0.421  | -0.437,0.676 |

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

**Table 1.22** – Confidence intervals for cross-price elasticities - alternative definition for the price of groundwater - full model

| C-P Elasticity | $\beta$  | S.E.  | $t$    | 95% C.I.      |
|----------------|----------|-------|--------|---------------|
| WL             | 0.433*** | 0.017 | 25.367 | 0.400, 0.466  |
| LW             | 0.195*** | 0.012 | 16.205 | 0.171, 0.219  |
| FW             | 0.187*** | 0.018 | 10.250 | 0.151, 0.223  |
| WF             | 0.141*** | 0.013 | 10.685 | 0.115, 0.167  |
| FL             | 0.131    | 0.212 | 0.619  | -0.285, 0.548 |
| LF             | 0.045    | 0.073 | 0.616  | -0.098, 0.187 |
| Morishima      | $\beta$  | S.E.  | $t$    | 95% C.I.      |
| WL             | 0.769*** | 0.020 | 39.262 | 0.731, 0.808  |
| LW             | 0.673*** | 0.076 | 8.877  | 0.524, 0.821  |
| FW             | 0.460**  | 0.213 | 2.162  | 0.043, 0.876  |
| WF             | 0.761*** | 0.025 | 30.545 | 0.712, 0.810  |
| FL             | 0.363    | 0.284 | 1.279  | -0.193, 0.919 |
| LF             | 0.371    | 0.285 | 1.304  | -0.187, 0.929 |

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

**Table 1.23** – Statistics of eigenvalues of the Hessian matrix

|      | EV-1         | EV-2         | EV-3        |
|------|--------------|--------------|-------------|
| Min  | -0.35912195  | -0.12639196  | -2.769E-08  |
| Mean | -0.156138777 | -0.011623139 | 0.074048839 |
| Max  | 1.577E-08    | 0.06474746   | 0.25572057  |



## Chapter 2

# The geography of illegal groundwater extraction in Mexico

## 2.1 Introduction

Water is still illegally withdrawn in Mexico in spite of the existence of both a regulatory framework and enforcement mechanisms.

Water illegally withdrawn for irrigation deserves special attention, since agriculture consumes more than 70% of the water available in the country. Although Mexican authorities have attempted to control illegal water extraction, a series of constraints have hindered these efforts. Some of these constraints include a limited enforcement capacity of regional authorities and high monitoring costs. The main objective of this paper is to analyse the effects of enforcement actions on illegal groundwater extraction in Mexico. The analysis focuses on the effects of environmental inspections - as a deterrence mechanism - on the number of illegal water users in each municipality.

Water stress is an increasing concern in Mexico. Since 1950, water availability has decreased by 75% (OECD, 2013). This has been driven by a fast population growth and further accentuated by a spatial mismatch between water supply and demand. Historical processes and the increasing integration to north american markets have resulted in the concentration of both population and economic activities in areas with limited water supplies. In 2012, the Valley of Mexico – a region mainly comprising Mexico City - accounted for almost 25% of national GDP, 20% of the country population, but only 0.74% of the total supply of renewal water (CONAGUA, 2014). In this regard, and although securing the provision of pipe water has been a major challenge in certain regions of the country, Mexico has taken important steps forward. For instance, in the Distrito Federal more than 95% of the population have benefited from this service since 1995<sup>1</sup>, while in states

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<sup>1</sup> INEGI Data Bank; accessed in March 2016.

like Oaxaca access to pipe water increased from 56% in 1990 to 76% in 2006. These improvements have not come without financial costs. Indeed, the cost of providing access to pipe water is estimated at US\$199 per person for urban areas and US\$228 per person for rural areas connected to the network (OMM, 2008).

The number of Mexican aquifers classified as overexploited or suffering from salinisation problems has significantly increased in the past decades. Mexican authorities consider an aquifer to be overexploited when the amount of water extracted is higher than the amount of water filtering in and recharging the aquifer within a given period of time. According to the Mexican National Water Commission (CONAGUA), in 2013 there were 101 (out of 653) aquifers in the country classified as overexploited; compared to only 32 in 1975 (CONAGUA, 2014). Moreover, during the same year, 76 additional aquifers were considered to be in risk of overdraft. This is an issue that should not be ignored, since some aquifers not considered to be overexploited can also suffer from salinisation and pollution problems, and an overall decrease in water quality. Custodio and Botín (2000) suggest that, in some cases, even moderate extraction rates can affect the balance of the aquifer and deteriorate water quality. By 2013, when considering both exploited and non-exploited aquifers, there were 16 aquifers suffering from seawater intrusion and 32 suffering from salinisation problems (CONAGUA, 2014).

The sustainability of groundwater is key for granting water security to the Mexican population. Overexploited aquifers in Mexico supply 50% of all the groundwater consumed in the country (CONAGUA, 2014). Moreover, in 2010, 70% of the water consumed in Mexican cities came from groundwater reservoirs, making aquifers the main source of freshwater for 75 million people (CONAGUA, 2010). The latter stresses the relevance of water security, and

explains why curbing groundwater overdraft has become a key topic in the agenda of Mexican authorities.

The sustainability of water resources is further threatened by climate change. Indeed, climate change is expected to have significant and negative impacts on Mexico. However, the extent of these impacts will be different across regions within the country. Recent projections suggest that by the end of the century temperatures may increase between 1 and 4 degrees Celsius, while rainfall could decrease by 11%. Moreover, these projections further suggest that effects will be harder in northern and northwestern areas of Mexico, which are characterised by arid climates ([Estrada et al., 2013](#)). Higher temperatures and rainfall shortages will impose additional pressure to hydric resources, which in turn will further reduce environmental quality and increase economic costs associated to adaptation.

Adequate regulation and effective implementation of laws governing hydric resources will be key for water sustainability. Imposing the legal framework governing water resources has been one of the most important challenges faced by Mexican authorities during the last decades. Despite being compulsory for every agricultural, industrial, and municipal water user to have a concession, an important number of these users operate without.

Unauthorised water extraction is particularly frequent among agricultural users. Considering that irrigators are the most intensive users of groundwater in the country, reducing unauthorised extraction within the agricultural sector is key for limiting groundwater overdraft. In 2009, the share of irrigators without a valid concession was close to 25% at the national level<sup>2</sup>.

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<sup>2</sup> This value is computed based on the number of users having non-preferential electricity fees. The following section details the way in which illegal users can be identified and counted.

However, at the subnational level, this value ranged between 8% and 60% across Mexican states, and from 0% to 100% across municipalities. Indeed, illegal water extraction is a recurrent problem, specially in semi-arid regions.

Illegal extraction not only comprises water users without a valid permit or concession, but also those consuming water volumes above the maximum limits allowed or withdrawing water from unauthorised sources. Due to high administrative costs (including inspection costs) and lack of personnel, Mexican authorities cannot verify that all water users comply with the conditions imposed by concessions. Moreover, it is common knowledge that not every concession holder has a water metering unit; and even if they do, in some cases the metering units are trafficked ([Scott and Shah, 2004](#)).

The lack of compliance with environmental regulation among groundwater users is far from being an exclusive problem of Mexico. Southern European countries also struggle to enforce both the use of concessions and sustainable extractions patterns. [De Stefano and Lopez-Gunn \(2012\)](#) point out that in Spain illegal groundwater users could represent up to 45% of the total number of users. According to these authors, in the Italian regions of Abruzzo, Molise, Puglia, Campania, Basilicata, Calabria, Sicily and Sardinia only half of the total hectares are legally irrigated; while in Malta illegal extraction represents 1.2 times legal consumption.

Monitoring and enforcement efforts from environmental authorities are key drivers for compliance. Analyses at the plant level in the U.S. indicate that inspections carried out by EPA<sup>3</sup> have played an important role for improving environmental compliance ([Magat and Viscusi, 1990](#); [Earnhart, 2004a,b](#); [Glicksman and Earnhart, 2007](#); [Gray and Shimshack, 2011](#)). Moreover, ev-

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<sup>3</sup> Environmental Protection Agency.



idence from the United States further suggests that the deterrence effect of inspection is not limited to firms that have been previously inspected. Indeed, neighbouring firms or firms within the same sector can improve their environmental performance due to the perception of a higher likelihood of future visits ([Shimshack and Ward, 2005](#); [Thornton et al., 2005](#); [Gray and Shadbegian, 2007](#)).

Results of empirical studies analysing environmental compliance in Mexico are consistent with findings from the United States. [Dasgupta et al. \(2000\)](#) analyse firms engaged in industrial activities (food, chemicals, metals, and non-methallic sectors) and shows that regulatory pressure has an effect on environmental compliance: plants that have been visited by the environmental authorities and/or have been fined are cleaner than their counterparts. In a more recent study, [Escobar and Chavez \(2013\)](#) analyse the effects of the Federal Industrial Inspection Program operated by the Mexican Environmental Attorney (PROFEPA) across industrial firms between 2000 and 2008. Results not only show that inspections tend to be more frequent in densely-populated municipalities with low-income levels, but also that inspections triggered by local complaints tend to have a bigger effect on firms' environmental compliance levels. Regarding the effects of previous fines, results also show that they are significant but really small.

In this paper, I seek to analyse the deterrence effect of environmental inspections on the number of illegal water users. To this end, I control for socio-economic characteristics, as well as for territorial policies such as prohibition zones and closed aquifers. For the latter, I build a series of indicators using official data sources and geographic information systems (GIS). With regard to my empirical strategy, I estimate the effect of environmental inspections through an instrumental variable approach. My results show that

one additional inspection during the previous year can reduce the average number of illegal water users in each municipality by 1% to 3%. Although this effect appears to be strong, the effectiveness of environmental inspections as a mechanism for achieving water sustainability is hindered by the low frequency of inspections across the country. Indeed, the average number of inspections per year across Mexican municipalities was 2 in the period of the analysis (2007-2009).

The contribution of this paper is twofold. Firstly, to my knowledge, it is the first study using rigorous econometric techniques for the analysis of illegal groundwater extraction. Moreover, to my knowledge, this study is the first one analysing the effects of environmental inspection outside industrial and manufacturing activities in Mexico. Secondly, due to the increasing importance of illegal water extraction within the agenda of environmental authorities in Mexico, my results provide direct guidance for enhancing policy strategies aiming to both curb the number of unauthorised water user and reduce groundwater overdraft.

## 2.2 Background

Weak institutions and limited implementation capacity have both contributed to illegal groundwater extraction in Mexico. During the last 30 years Mexico has built formal institutions governing water resources in the country. The latter included the creation of a legal framework and an agency in charge of both regulating and managing water. Along these efforts Mexico has also engaged in an ambitious decentralisation process that aimed to increase water governance by granting fiscal and regulatory responsibilities to regional water agencies. Although the objective of this process was well-intended, its implementation has been hindered by the lack of financial resources and limited implementation capacity. This has resulted in weak legal enforcement and an inefficient use of water across the country.

Governing groundwater reservoirs has been particularly challenging for both central and regional governments. The very particular attributes characterising groundwater create important regulatory challenges. Contrary to surface water, which may require important investments mainly associated to its distribution, in some Mexican regions producers can access groundwater by building wells that require a small capital investment. Low access costs along with the benefits from using groundwater for irrigation have translated into an increasing number of unauthorised wells<sup>4</sup>. Regulatory efforts are further challenged by the fact that a large number of water users is scattered across large extensions of land. Thus, verifying the compliance of users can be very costly. As a consequence, a number of producers does not respect extrac-

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<sup>4</sup> In addition to the latter, and also in contrast to surface water, groundwater levels are not easily identified. The lack of visibility characterising groundwater makes it harder for users to see the effects of their activities on the resource, thus making them less willing to accept or engage in actions that internalise social costs.

tion limits or even lacks a concession (permit) to extract groundwater. This type of producers is present all across the country showing a complex spatial pattern: they are present in regions with different levels of water availability and income; tend to cluster without respecting administrative boundaries; and can be close or remote from important populated centres.

The following paragraphs provide an overview of the main institutions governing groundwater extraction, the main policy tools regulating the resource, and a description of the main trends of illegal groundwater extraction in the country.

### **2.2.1 Institutions governing groundwater in Mexico**

During the last three decades, Mexico has carried out an important number of reforms aiming to improve water governance. At the core of these reforms lays the creation of the Mexican Water Law (LAN). The LAN is the main legal framework regulating water in Mexico. It establishes that all water resources belong to the Mexican State. This implies that water users do not have property rights over the resource; instead, they can only use and extract the resource under certain legal constraints. The LAN defines these constraints, as well as the rights, obligations, and sanctions concerning all water users in Mexico.

The LAN further defines the National Water Commission (CONAGUA) as the agency in charge of managing and preserving national waters. Among the different stakeholders involved in the management of water resources in Mexico, CONAGUA has the most important role. Created in 1989, CONAGUA is a decentralised agency under the mandate of the Ministry of Environment. CONAGUA is in charge of the management of all water resources in the

country. Its main duties include: the development of national water policy, managing water concessions and wastewater discharges, planning irrigation and developing water systems, as well as managing investments in the water sector.

Being a federal agency, CONAGUA's jurisdiction extends to all the country. CONAGUA's headquarters are based in Mexico City, but it manages water resources at the regional level through 13 River Basin Organisations (RBO). In 2004, a reform of the LAN granted RBOs with administrative, fiscal, and monitoring responsibilities. Nevertheless, some critics argue that the decentralisation process was not properly implemented, suggesting that regional water agencies lack the resources and capacity to ensure compliance with the water legislation ([Wilder and Romero-Lankao, 2006](#); [Wilder, 2010](#)).

CONAGUA's headquarters are in charge of defining water policy and development plans at the national level. This includes defining the fiscal framework concerning water concessions and discharge fees. Furthermore, CONAGUA's headquarters are responsible for the coordination with national and international banking institutions regarding the credits for developing water projects in the country.

River Basin Organisations are in charge of the implementation of the LAN at the regional level. Their duties include: the promotion of sustainable water use, prevention of water-related natural disasters, verifying water availability, collecting fiscal revenues from water concessions and discharge fees; granting concessions and permits; ensuring the preservation of groundwater resources as well as the quality of superficial waters. These duties are geographically delimited by Hydrological Administrative Regions (HAR). HARs' borders may account for more than one state. However, in order to facilitate the

coordination across different levels of government, all HARs respect municipal borders. Since RBOs are based in 13 out of the 31 Mexican states, CONAGUA is represented in the remaining states through Local Offices.

CONAGUA's activities are funded through direct transfers from the federal government as well as with the money collected through concessions and fees. Part of this money is then redistributed back to state governments through different programmes that promote the efficient use of water and support the development of local communities.

At the sub-national level, besides the activities carried out by the RBOs, state governments are also involved in the management of water resources. State congresses define the tariffs to be paid for water and sanitation services, while local governments (municipalities) are the ones in charge of providing these services. States are also in charge of establishing state water plans.

### **2.2.2 Policy instruments for managing water resources**

Water management in Mexico mainly relies on a regulatory system based on quotas and enforcing mechanisms. Quotas are defined through concessions, which are only available in regions where water is abundant. In addition to setting consumption limits and volumetric prices, the information conveyed by concessions is a key input for defining water policy in the country since it provides information on the availability of water supplies. With regard to monitoring mechanisms, the main policy tool is the water inspection programme lead by CONAGUA. The main objective of this programme is to make sure that all water users respect the LAN. When water users do not comply with the LAN, CONAGUA launches administrative procedures that can lead to financial and non-financial penalties, including the invalidation

of concessions.

Agricultural users can obtain a concession through a costless administrative procedure. Producers can go to CONAGUA's regional offices in order to request a concession. Offices are based in capital cities across the country, as well as in one or two secondary cities. However, since 2011, concessions can also be requested through a web-based service. In either case, producers have to fill in a form that requests information on the basic characteristics of the production unit, such as irrigated surface, amount of water demanded, irrigation infrastructure, etc. Producers also have to indicate the desired length of the concession, which can last between 5 and 30 years. In addition to this information, producers have to provide CONAGUA with a number of documents including: an environmental impact assessment (if the irrigated surface is bigger than 100 Ha.); technical documents that justify the amount of water requested; documents proving property rights over the land where extraction is to take place; and a plan describing the infrastructure in the place of extraction. After the request has been filed, CONAGUA has 60 days to answer; the concession starts the day CONAGUA provides a formal and positive answer.

Until 2013 concessions were only required in prohibition zones<sup>5</sup>. Outside these zones, any citizen was free to drill a well to extract groundwater. What was not a prohibition zone was then considered to be a free-access zone<sup>6</sup>. Prohibition zones started in 1947, with the overall aim to reduce groundwater withdrawals. The latest zone was established in 2007; by this year there were a total of 146 prohibition zones (CONAGUA, 2014). There are three types of prohibition zones:

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<sup>5</sup> Known in Spanish as "Zonas de veda"

<sup>6</sup> Known in Spanish as "Zona de libre alumbramiento".

- Type I: Zones where further extraction is not possible without endangering the sustainability of the aquifer or leading to its depletion;
- Type II: Zones where extraction is allowed for domestic use only;
- Type III: Zones with capacity for limited extraction for domestic, industrial, irrigation, and other uses.

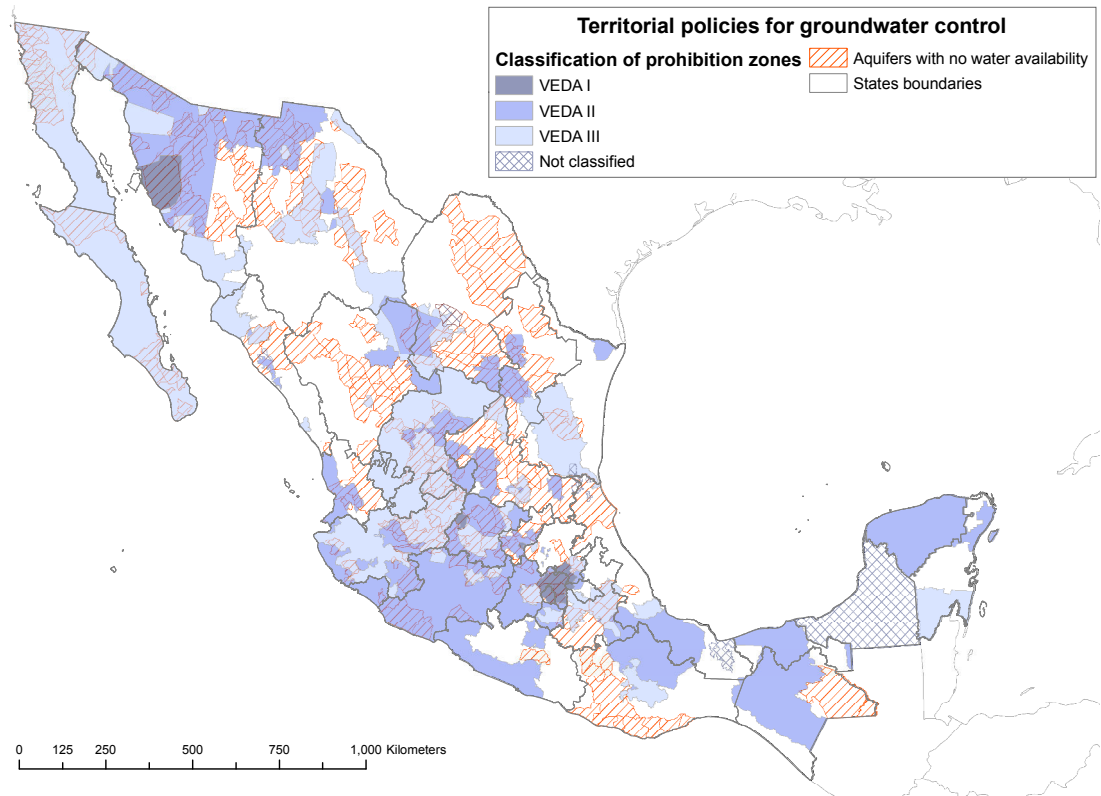
In 2013, following a presidential decree, the whole country was classified as a prohibition zone. In other words, today, independently of their location, every producer extracting groundwater is required by law to have a valid concession.

CONAGUA does not provide additional concessions in regions suffering from groundwater overdraft. In addition to prohibition zones of Type I, no further concessions are allowed in those aquifers considered to be suffering from groundwater overdraft. These aquifers are commonly referred to as *closed*. In 2013, there were 66 closed aquifers (CONAGUA, 2014). Figure 2.1 shows both prohibition zones and closed aquifers. As can be seen from this figure, closed aquifers and prohibition zones of Type III sometimes overlap. In these cases it would seem logical that the ban imposed by closed aquifers should overrule what is established by prohibition zones. This map also highlights a key challenge in terms of governance. Since neither prohibition zones nor closed aquifers coincide with administrative boundaries it could be difficult for water users to know whether they are based in one of these areas.

Concessions price water through a volumetric scheme. Once a concession is granted, water users have to pay an initial fixed charge. This charge depends on the type of water user. Water consumed within the maximum limits of a concession is charged according to the type of user and the water availability in the corresponding municipality. Mexico is divided into 9 availability zones,



**Figure 2.1** – Zones with water bans in place and aquifers with no water availability, 2007



**Source:** Maps for both prohibition zones and aquifers were provided by CONAGUA.

the charges corresponding to each zone are established by the Law of Federal Duties (LFD). Thus, in order to implement this pricing scheme, all concession holders must have a working water meter.

Water users engaged in agricultural activities receive a preferential treatment. In the first place, agricultural users are not charged with the initial fixed fee for obtaining a concession. In the second place, for these users, volumetric pricing is not fully implemented. Indeed, water is priced \$0 for any amount consumed below the maximum quota; above the maximum quota, water is priced with a flat rate. Moreover, this rate is the lowest among water

users and does not change across the country. For instance, in 2008, agricultural users were charged MEX\$ 0.0001173 per cubic meter, while households' water consumption was priced MEX\$ 0.03799 per cubic meter ([Cob and Romero, 2011](#)). Another important issue to note is that CONAGUA sets the maximum water quota based on the information provided by the users on the expected average consumption. This implies that concessions do not promote a more efficient water consumption, instead they just formalise expected water demand. This has also been pointed out by [Shah \(2008\)](#), who after analysing a sample of water users in arid regions further suggests that quotas are rarely exceeded. In summary, concessions and the amounts of water consumed below the maximum quota are free of charge for agricultural users.

CONAGUA is responsible for ensuring that water users respect the LAN. The Water Inspections Programme is CONAGUA's main policy tool for verifying compliance. Since its creation, CONAGUA has been allowed to carry out inspections, but it was not until the last decade when it managed to consolidate these activities. RBOs and local offices implement inspections according to their financial capacity and priorities. Some of the main challenges faced by CONAGUA have been related to the limited capacity of basin councils and regional offices to carry out inspections. The latter included unskilled personnel and the lack of adequate equipment ([CONAGUA, 2012b](#)). River basin organisations coordinate with their corresponding regional offices in order to allocate their resources (human resources and equipment) for inspecting those sectors and locations that deserve special attention<sup>7</sup>. All economic sectors are considered in the inspections programme, but priority is given to those

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<sup>7</sup> Inspections are classified by CONAGUA according to the use given to water resources: extraction of national groundwater and superficial water; use of water bodies for discharges; extraction of minerals; and use of federal zones.

with a high water consumption, such as agriculture. In 2013, almost 60% of the inspections focused on the agricultural sector, paying special attention to groundwater users ([CONAGUA, 2013](#)).

How likely is it for a farmer to receive a visit from CONAGUA? Table 2.1 shows the frequency of water inspections across states in 2007. The frequency of inspections is computed as the ratio of inspections over the number of production units involved in agricultural and forestry activities. These computations show that only for the northern states of Baja California and Baja California Sur does the frequency of inspections (i.e. the probability of being inspected) is exceed 1%. In states like Puebla, Veracruz, or Oaxaca this probability is equal or lower to 0.02%. It is important to highlight that these computations should be taken with a pinch of salt. First, the universe of producers considered by CONAGUA for the inspections programme is not clear and it may be smaller than the one considered by the census. In other words, it is possible that these computations underestimate the frequency of inspections. In spite of the latter, this number helps to put things in perspective by highlighting the small number of visits compared to the total number of producers that may be considered by the authorities. Second, another important and misleading issue is the fact that the likelihood of being visited presented in this table assumes that production units are independently and randomly selected. As will be discussed in the following sections, the latter does not hold in practice, since the selection process followed by authorities that gives bigger weights to certain places or groups of producers based on the levels of water stress and costs associated to inspections.

Inspections can lead to financial and non-financial sanctions. When inspections identify non-compliance with existing regulation, CONAGUA initiates administrative procedures against the corresponding water users. During

**Table 2.1** – Likelihood of being inspected by CONAGUA in 2007

| State               | Number of agricultural production units | Inspections in the agricultural sector | Frequency of inspections |
|---------------------|---|--|--------------------------|
| Aguascalientes      | 18,986                                  | 35                                     | 0.19%                    |
| Baja California     | 7,628                                   | 96                                     | 1.26%                    |
| Baja California Sur | 5,907                                   | 77                                     | 1.30%                    |
| Campeche            | 41,497                                  | 71                                     | 0.17%                    |
| Chiapas             | 406,599                                 | 84                                     | 0.02%                    |
| Chihuahua           | 87,355                                  | 63                                     | 0.07%                    |
| Coahuila            | 37,224                                  | 139                                    | 0.37%                    |
| Colima              | 12,565                                  | 55                                     | 0.44%                    |
| Distrito Federal    | 11,881                                  | 113                                    | 0.95%                    |
| Durango             | 67,221                                  | 52                                     | 0.08%                    |
| Estado de Mexico    | 345,299                                 | 53                                     | 0.02%                    |
| Guanajuato          | 152,965                                 | 116                                    | 0.08%                    |
| Guerrero            | 275,899                                 | 110                                    | 0.04%                    |
| Hidalgo             | 205,774                                 | 40                                     | 0.02%                    |
| Jalisco             | 127,932                                 | 163                                    | 0.13%                    |
| Michoacan           | 192,863                                 | 152                                    | 0.08%                    |
| Morelos             | 42,888                                  | 81                                     | 0.19%                    |
| Nayarit             | 64,870                                  | 41                                     | 0.06%                    |
| Nuevo Leon          | 34,171                                  | 59                                     | 0.17%                    |
| Oaxaca              | 354,201                                 | 50                                     | 0.01%                    |
| Puebla              | 376,860                                 | 79                                     | 0.02%                    |
| Queretaro           | 48,509                                  | 35                                     | 0.07%                    |
| Quintana Roo        | 26,781                                  | 38                                     | 0.14%                    |
| San Luis Potosi     | 155,024                                 | 95                                     | 0.06%                    |
| Sinaloa             | 72,999                                  | 34                                     | 0.05%                    |
| Sonora              | 32,063                                  | 238                                    | 0.74%                    |
| Tabasco             | 90,124                                  | 33                                     | 0.04%                    |
| Tamaulipas          | 54,807                                  | 124                                    | 0.23%                    |
| Tlaxcala            | 71,371                                  | 21                                     | 0.03%                    |
| Veracruz            | 441,034                                 | 99                                     | 0.02%                    |
| Yucatan             | 68,879                                  | 92                                     | 0.13%                    |
| Zacatecas           | 137,762                                 | 101                                    | 0.07%                    |

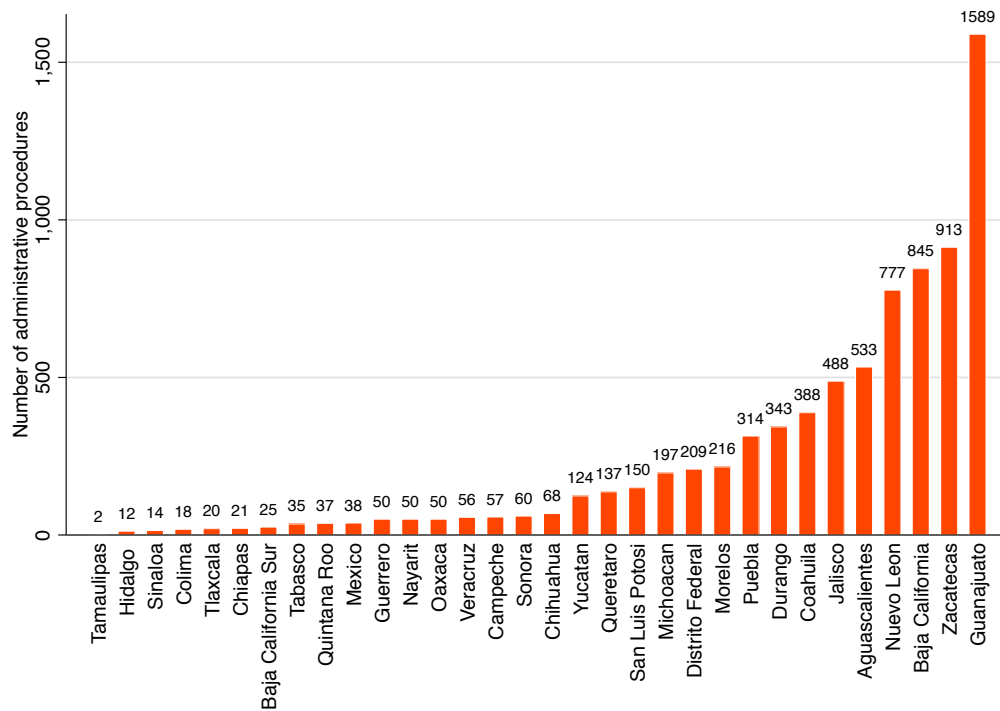
**Source:** The source of the number of agricultural production units is the Mexican agricultural census 2007 produced by INEGI. Information on the number of inspections was obtained from the public archive of CONAGUA's Subdirección General de Administración del Agua. The number of agricultural production units includes those involved in forest-related activities. The frequency of inspections is computed as the ratio of the number of inspections over the number of production units.

an administrative procedure, water users can contest the charges made by CONAGUA. If water users prove that they were actually complying with the current regulation when the inspection took place, or if they show that the inspection was not executed according to the law, the administrative procedure stops. At the end of an administrative procedure CONAGUA decides whether the actions identified during the inspection deserve a financial or non-financial penalty, or both. During 2012, 45% of the visits identified actions that did not comply with the current regulation (CONAGUA, 2012a). Within this set of actions, the highest share of infractions was related to users that did not respect the conditions set by their concession, such as extracting more water than the maximum quota or not having a water meter (18%); this was followed by the lack of a title or concession for consuming or extracting water (16%), and drilling wells without a permit (15%). It is important to note that only one-third of the administrative procedures initiated by CONAGUA actually led to a sanction. With regard to these sanctions, 34% included a financial penalty, 42% a non-financial penalty, and 24% implied both types of penalties. It is also important to note that the number of administrative procedures significantly differs across Mexican states.

Figure 2.2 presents the total number of procedures due to the lack of a valid concession or a licence for waste water discharges. The number of administrative procedures related to these faults ranges from 2 in Tamaulipas to 1,589 in Guanajuato. These differences could be partially explained by the differences in the number of water users, but they could also be related to other factors such as the number and effectiveness of inspections, the capacity of regional authorities, etc. Moreover, since the existing legislation applies uniformly across the country, it is possible that in some states producers find it easier to comply. At present, the public information regarding the number

of administrative procedures is very limited. This is also the case for the total amount of sanctions paid, which is not available in public registries. The only public source that provides detailed information on the types of sanctions and their corresponding fines is the LAN. Although this information does not reflect the actual financial costs of non-compliance, it does help to understand the potential deterrence effect associated to inspections.

**Figure 2.2** – Number of administrative procedures initiated by CONAGUA due to the lack of a valid concession or a licence for waste water discharges



Source: CONAGUA (2012a)

Table 2.2 presents the actions and corresponding penalties for water users that do not comply with the LAN. The fractions of Article 119 of the LAN define the types of faults that can be attributed to water users, while Articles 120 and 122 describe their corresponding penalties. Fines range between US\$

768 and US\$ 76,842<sup>8</sup>, and can be accumulated due to multiple faults. For instance, extracting water without a valid concession implies a sanction of at least US\$ 5,763; this represents an important amount of money in a country where the average household net-adjusted disposable income per capita is USD 13,085 a year<sup>9</sup>. In addition to providing a financial penalty, inspections could also lead to the full closure of wells. Indeed, in 18 out of the 24 faults defined by Article 119, CONAGUA is entitled to closure wells or any other extraction source on top of providing a financial penalty. Article 121 of the LAN further stipulates that the type of sanction will depend on the extent of the fault, the socio-economic condition of the infractor, premeditation, and recidivism. Based on the limited information available it seems that although the likelihood of being inspected is low, inspections act as a threat that is backed by important sanctions.

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<sup>8</sup> Current US dollars in February 2016.

<sup>9</sup> OECD estimates, <http://stats.oecd.org>; access date: February, 2016.

**Table 2.2** – Faults defined by the fractions of article 119 and their corresponding sanctions included in Articles 120 and 122 of the LAN

| <b>Fraction</b> | <b>Description</b>   | <b>Range of fines</b>              | <b>Closure</b> |
|-----------------|--|------------------------------------|----------------|
| I               | Illegal waste water discharges   | Between US\$ 4,611 and US\$ 19,211 | Yes            |
| II              | Exploit, use or benefit from national waters without complying with Mexican Official Norms                             | Between US\$ 5,763 and US\$ 76,842 | Yes            |
| III             | Exploit, use or benefit from national waters above the maximum quota stipulated by the public registry of water rights | Between US\$ 5,763 and US\$ 76,842 | Yes            |
| IV              | Use or benefit from basin, channels, federal zones, and protected areas without a valid concession                     | Between US\$ 5,763 and US\$ 76,842 | Yes            |
| V               | Modify hydraulic infrastructure without authorisation  | Between US\$ 5,763 and US\$ 76,842 | Yes            |
| VI              | Do not adapt existing infrastructure to comply with norms and regulation in order to limit negative externalities      | Between US\$ 4,611 and US\$ 19,211 | No             |
| VII             | Lack of or alteration of water metering devices  | Between US\$ 5,763 and US\$ 76,842 | Yes            |
| VIII            | Exploit, use, or benefit from national waters without the corresponding title  | Between US\$ 5,763 and US\$ 76,842 | Yes            |
| IX              | Build infrastructure for extracting groundwater in close aquifers or in regions where concessions are banned           | Between US\$ 5,763 and US\$ 76,842 | Yes            |
| X               | Block or interfere inspections   | Between US\$ 768 and US\$ 5,763    | No             |
| XI              | Do not provide required information to CONAGUA   | Between US\$ 768 and US\$ 5,763    | Yes            |
| XII             | Use higher water flows than those of waste water discharges in order to comply with existing norms                     | Between US\$ 4,611 and US\$ 19,211 | Yes            |
| XIII            | Supply water for human consumption without complying with quality standards  | Between US\$ 5,763 and US\$ 76,842 | Yes            |
| XIV             | Dump pollutants into superficial and ground-water bodies   | Between US\$ 5,763 and US\$ 76,842 | Yes            |

*Continued on next page*



Table 2.2 – *Continued from previous page*

| <b>Fraction</b> | <b>Description</b>   | <b>Range of fines</b>              | <b>Closure</b> |
|-----------------|--|------------------------------------|----------------|
| XV              | Do not comply with obligations stipulated in a concession or a waste water discharge permit  | Between US\$ 5,763 and US\$ 76,842 | Yes            |
| XVI             | Do not request the inscription into the public registry of water rights  | Between US\$ 768 and US\$ 5,763    | No             |
| XVII            | Causing environmental damage on water bodies   | Between US\$ 5,763 and US\$ 76,842 | Yes            |
| XVIII           | Wasting water in contravention of the LAN and related regulation   | Between US\$ 4,611 and US\$ 19,211 | No             |
| XIX             | Not blocking wells or adjusting extraction capacity following a change in the concession   | Between US\$ 4,611 and US\$ 19,211 | Yes            |
| XX              | Modify or bypass natural water flows, rivers, or currents without official authorisation   | Between US\$ 5,763 and US\$ 76,842 | Yes            |
| XXI             | Do not inform CONAGUA about changes in infrastructure that affect water consumption capacity   | Between US\$ 768 and US\$ 5,763    | No             |
| XXII            | Stop tracking water consumption according to what is stipulated in the LAN   | Between US\$ 768 and US\$ 5,763    | Yes            |
| XXIII           | Exploit, use or benefit from national goods defined by articles 113 and 113bis (different types of water resources) without a valid concession                   | Between US\$ 5,763 and US\$ 76,842 | Yes            |
| XXIV            | Exploit, use or benefit from national goods defined by articles 113 and 113bis (different types of water resources) above the limits specified by the concession | Between US\$ 5,763 and US\$ 76,842 | No             |

**Source:** Text translated and simplified by the author. The amount of fines was originally defined in terms of number of days of minimum wage. To express the range of fines in US dollars I used the exchange rate and minimum wage valid in February 2016. In the last column of the table, *closure* refers to the partial, complete, temporary, or permanent closure of wells or installations used for extracting water.

### 2.2.3 Agricultural subsidies and environmental compliance

Inspections and sanctions are not the only mechanism promoting the adoption of concessions. Indeed, there are strong economic incentives following the provision of agricultural subsidies that influence the decision to request a concession. Despite the fact that the marginal price of water for irrigation is practically zero, farmers have to pay for extraction costs, which are mainly defined by the price of the fuel used to pump water out of the ground. In the case of Mexico, 93% of agricultural users rely on electric water pumps (CONUEE, 2011). Hence, the consumption of water for irrigation is sensitive to changes and distortions in electricity prices.

Irrigation activities benefit from highly subsidised electricity tariffs. Enforcing the adoption of concessions, in particular those concerning agriculture, has been one of the most important challenges for establishing an integrated water management framework in Mexico. For this reason, since 2003 authorities have prompted the adoption of concessions through conditioning the access to subsidised electricity fees. This policy also aimed to promote the competitiveness of the agricultural sector, which in practice implied having two different groups of electricity tariffs for irrigation. The first group corresponds to those tariffs accessible for concession holders; these tariffs are coded 9CU (day tariff) and 9N (night tariff). The second group of tariffs is available for those irrigators without a concession, it includes tariffs 09 and 9M. Tariffs in the first group, i.e. those for concession holders, are not only significantly lower, but they have also followed a slow progression during the last ten years, Table 2.3. In 2015, tariffs for irrigators without a concession were MEX\$ 297.23 (09) and MEX\$ 313.64 (9-M) cents per Killowatt-hour, while tariffs for concession holders were MEX\$ 57.70 and MEX\$ 47.22 cents

per Killowatt-hour. In other words, not having a concession implies paying electricity fees five times more expensive.

**Table 2.3** – Evolution of electricity tariffs for irrigation

| Year | Tariff 9 | Tariff 9M | Tariff 9CU | Tariff 9N |
|------|----------|-----------|------------|-----------|
| 2003 | 55.22    | 39.30     | 33.09      | 9.58      |
| 2004 | 42.01    | 48.07     | 39.84      | 34.26     |
| 2005 | 50.62    | 60.22     | 43.54      | 37.06     |
| 2006 | 66.13    | 76.95     | 40.19      | 34.94     |
| 2007 | 99.33    | 94.97     | 43.27      | 36.01     |
| 2008 | 98.01    | 116.88    | 46.87      | 38.15     |
| 2009 | 117.79   | 40.95     | 48.52      | 40.87     |
| 2010 | 154.95   | 107.36    | 41.25      | 39.93     |
| 2011 | 149.39   | 138.14    | 53.99      | 45.05     |
| 2012 | 208.18   | 164.00    | 56.62      | 47.97     |
| 2013 | 288.24   | 115.77    | 49.78      | 48.77     |
| 2014 | 358.24   | 195.85    | 55.03      | 41.87     |
| 2015 | 297.23   | 313.64    | 57.70      | 47.22     |

**Source:** Energy Information System, Mexican Ministry of Energy, 2015.

This pricing scheme has created a water governance setting in which illegal extraction is not only tolerated but, until recently, rewarded. Previous studies suggest that the group of tariffs for concession holders receives a subsidy up to 83% of electricity production costs (Muñoz et al., 2006; Cob and Romero, 2011). Moreover, these studies also show that tariffs for irrigators without a concession also benefit from a subsidy that could have reached two-thirds of electricity production costs.

The difference between groups of electricity fees creates a very strong incentive for irrigators to request a concession. Agricultural producers with a concession will certainly opt to request tariffs 9CU and 9N, which provide lower electricity prices. Hence, it can be assumed that those producers that have requested fees 9 and 9N lack a valid concession<sup>10</sup>. This is how I identify

<sup>10</sup> It is important to note that there is no information on whether water users lacking a concession pay or not their electricity fees. Assuming that producers will always opt for

farmers irrigating without a valid concession. These producers are incurring into an illegal activity, and for the purposes of this paper are considered as illegal water users (IWU)<sup>11</sup>.

#### **2.2.4 The geography of illegal water extraction in Mexico**

Mexico is characterised by important regional socio-economic disparities. This is mainly driven by a high concentration of economic activity in central areas of the country. Indeed, the central states of the Distrito Federal and Mexico (see Figure 3.7 for a map of Mexico's political division) accounted together for almost one-quarter of the national GDP in 2011, Table 2.4. Economic activity is further concentrated in the states of Nuevo Leon (8%) and Jalisco (6.7%). A similar trend regards the distribution of the population across the country. In 2010, more than 20% of the population resided in the states of the Distrito Federal and Mexico, representing close to 24 million people.

Agriculture represents a small share of regional economies. Overall Mexico has completed the structural transformation of its economy. In 2011, agriculture only accounted for 3.5% of the national GDP, while services accounted for two-thirds. At the regional level, only in the states of Nayarit, Durango, and Michoacan does agriculture represent more than 10% of the state's economy, Table 2.4. In contrast, and not surprisingly, agriculture represents less than 1% in the economy of states like the Distrito Federal (0.1%) and Nuevo Leon (0.7%).

Deprivation levels are higher in southern parts of Mexico. In 2010, the south-

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the cheaper implicitly considers that they do.

<sup>11</sup>Although this term could account for different types of water users, within the context of my analysis it exclusively refers to irrigators extracting groundwater.

ern states of Oaxaca, Guerrero, and Chiapas were all characterised by a "very high" level of deprivation according to estimates from the National Committee for Social Development Policy Evaluation (CONEVAL)<sup>12</sup>. Deprivation was the lowest in central and northern states like the Distrito Federal, Nuevo Leon, Coahuila, and Baja California, Table 2.4.

The distribution of IWU cannot be easily associated with regional socio-economic patterns. Illegal water users can be found in every Mexican state<sup>13</sup>. However, some states are characterised by higher concentrations of IWU than others. In 2009, the rate of IWU across Mexican states ranged from 8% in Aguascalientes to 60% in the state of Mexico, Figure 2.3. In addition to highlighting differences across states, this figure also shows that within some "macro" regions IWU rates tend to be similar to each other. For instance, the lowest rates in the country can be found in a group of states close to the U.S. border, composed by Baja California Sur, Baja California, Sonora and Chihuahua. In contrast, the highest rates of IWU can be found in two clusters of states in the south-east and south-west parts of the country. The south-west cluster includes the states of Guerrero, Morelos, and Mexico; the south-east cluster is composed by Tabasco, Campeche, and Quintana Roo. A key thing to notice is that the north side of the country is characterised by arid and semi-arid weather, having the lowest supply of water in Mexico; while the south of Mexico is characterised by a tropical weather, and accounts for the largest supply of water (see Figure 2.9 and Figure 2.8).

Illegal water extraction further varies within states showing complex patterns. Figure 2.4 shows the distribution of IWU rates across municipalities.

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<sup>12</sup> Deprivation is measured through an index that takes into account access to basic services, education, and financial resources of the population in each state.

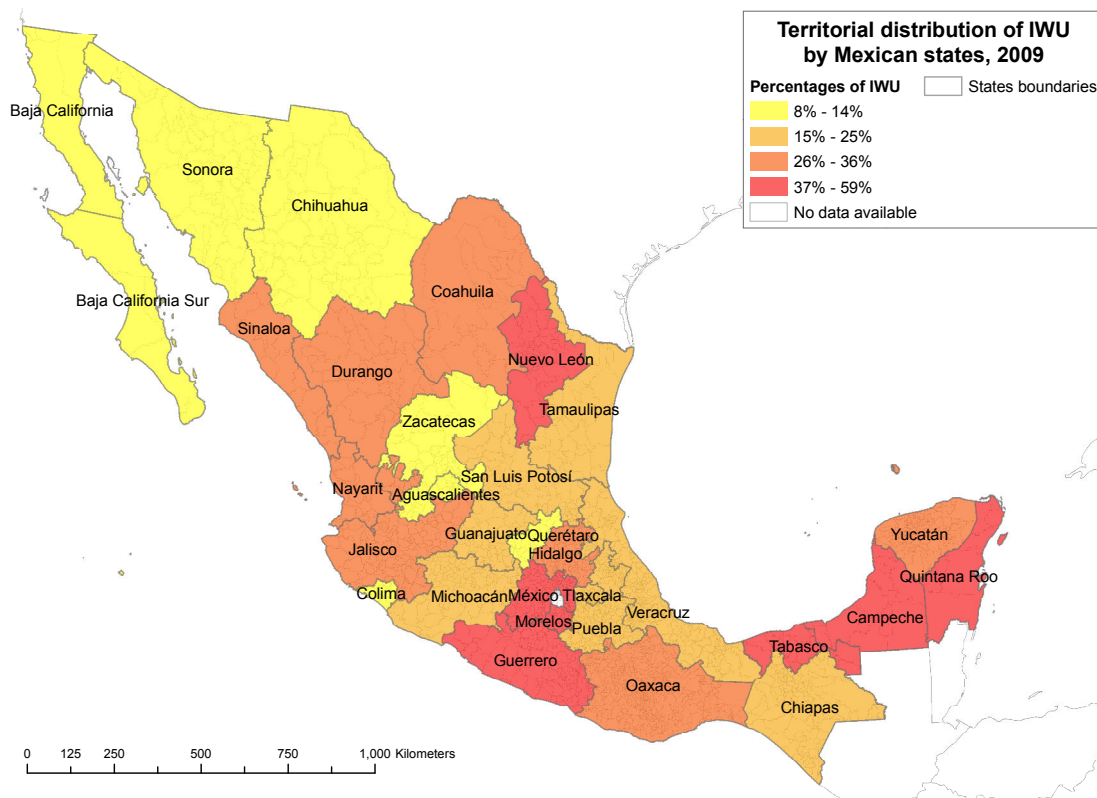
<sup>13</sup> Mexico is a federation composed by 31 states and a Federal District (Mexico City).

**Table 2.4** – Socio-economic characteristics of Mexican states

| State               | Share of national GDP, 2011 | Share of GVA in Agriculture, 2011 | Share of total population, 2010 | Deprivation level, 2010 |
|---------------------|-----------------------------|-----------------------------------|---------------------------------|-------------------------|
| Aguascalientes      | 1.20%                       | 4.20%                             | 1.10%                           | Very low                |
| Baja California     | 3.00%                       | 3.30%                             | 2.80%                           | Very low                |
| Baja California Sur | 0.60%                       | 5.20%                             | 0.60%                           | Low                     |
| Campeche            | 3.00%                       | 1.10%                             | 0.70%                           | High                    |
| Coahuila            | 3.30%                       | 2.70%                             | 2.40%                           | Very low                |
| Colima              | 0.60%                       | 5.70%                             | 0.60%                           | Very low                |
| Chiapas             | 1.90%                       | 9.20%                             | 4.30%                           | Very high               |
| Chihuahua           | 3.10%                       | 6.50%                             | 3.00%                           | Low                     |
| Distrito Federal    | 17.80%                      | 0.10%                             | 7.90%                           | Very low                |
| Durango             | 1.20%                       | 10.70%                            | 1.50%                           | Medium                  |
| Guanajuato          | 4.10%                       | 4.00%                             | 4.90%                           | Medium                  |
| Guerrero            | 1.50%                       | 7.00%                             | 3.00%                           | Very high               |
| Hidalgo             | 1.50%                       | 4.30%                             | 2.40%                           | High                    |
| Jalisco             | 6.70%                       | 6.70%                             | 6.50%                           | Very low                |
| Mexico              | 9.80%                       | 1.30%                             | 13.50%                          | Low                     |
| Michoacán           | 2.40%                       | 10.70%                            | 3.90%                           | High                    |
| Morelos             | 1.20%                       | 3.60%                             | 1.60%                           | Medium                  |
| Nayarit             | 0.60%                       | 11.00%                            | 1.00%                           | Low                     |
| Nuevo León          | 8.00%                       | 0.70%                             | 4.10%                           | Very low                |
| Oaxaca              | 1.50%                       | 9.70%                             | 3.40%                           | Very high               |
| Puebla              | 3.60%                       | 3.90%                             | 5.10%                           | High                    |
| Queretaro           | 1.90%                       | 2.60%                             | 1.60%                           | Low                     |
| Quintana Roo        | 1.50%                       | 0.90%                             | 1.20%                           | Low                     |
| San Luis Potosí     | 1.90%                       | 3.90%                             | 2.30%                           | High                    |
| Sinaloa             | 2.00%                       | 9.00%                             | 2.50%                           | Low                     |
| Sonora              | 2.60%                       | 8.00%                             | 2.40%                           | Very low                |
| Tabasco             | 2.80%                       | 1.50%                             | 2.00%                           | Medium                  |
| Tamaulipas          | 3.20%                       | 3.60%                             | 2.90%                           | Very low                |
| Tlaxcala            | 0.50%                       | 3.30%                             | 1.00%                           | Medium                  |
| Veracruz            | 4.60%                       | 5.90%                             | 6.80%                           | High                    |
| Yucatán             | 1.50%                       | 4.10%                             | 1.70%                           | High                    |
| Zacatecas           | 0.80%                       | 9.40%                             | 1.30%                           | Medium                  |

**Source:** Calculations for the share of GDP, GVA in agriculture, and population made by the author using information from INEGI's State and Municipal Database System: <http://sc.inegi.org.mx/cobdem/>. Information on deprivation levels was obtained from the National Committee for Social Development Policy Evaluation (CONEVAL): <http://www.coneval.gob.mx/>; all data extracted on February 2016.

**Figure 2.3** – Percentage of illegal water users across Mexican states, 2009



**Source:** Map produced by the author using the official map layers provided by INEGI. This map has been produced using a quantile distribution for creating the classes grouping the values of IWU rates.

Although this figure does not show a clear spatial pattern, there are certain features worth noting:

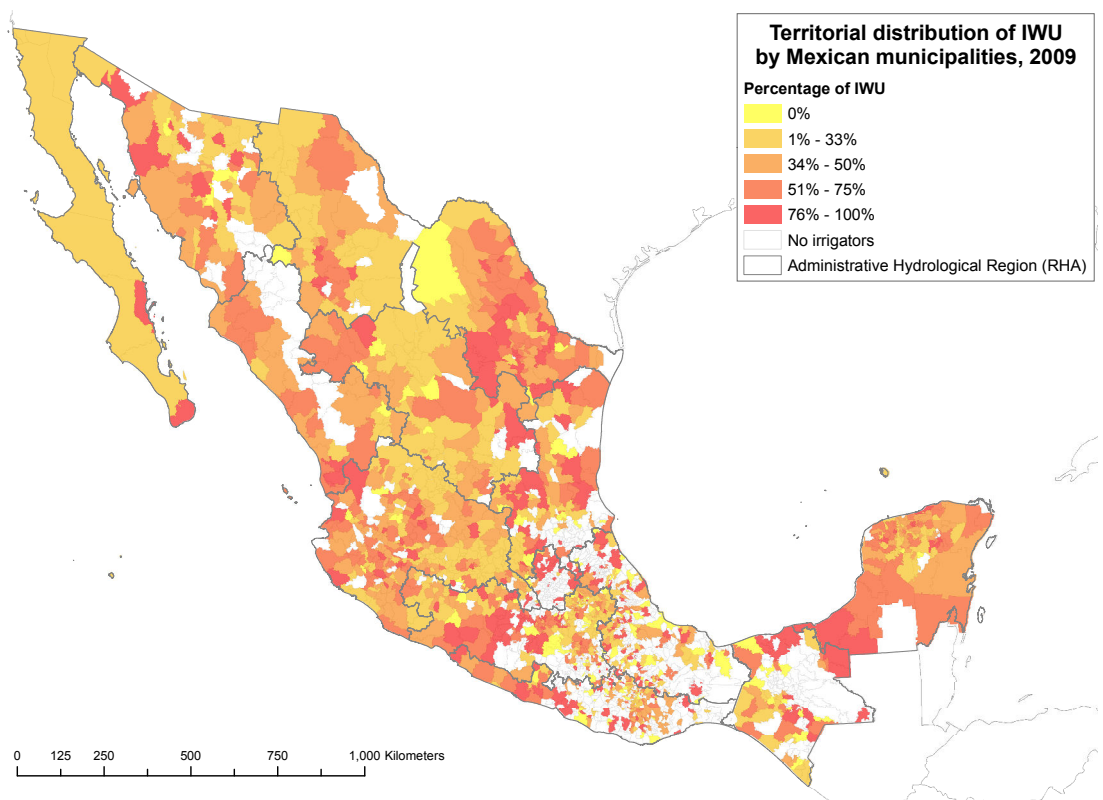
- Both high and low rates of IWU can be found in every state. This is also the case for states having some of the lowest IWU rates (i.e. IWU aggregated at the state level) such as Baja California Sur, which although having the lowest state rate of IWU has municipalities with IWU rates higher than 75%.
- Clusters of municipalities with high IWU rates are present in most states. Moreover, some of these clusters spread across states. This

is the case of a group of municipalities at the border of Oaxaca and Mexico, for which IWU rates are significantly high.

What can we learn from these maps? First, clusters with high IWU can be found in regions of the country having both high and low water availability. This implies that water scarcity is not the only factor driving IWU. This been said, it is possible that in municipalities where no additional concessions are available IWU rates are higher. Second, clusters of high IWU are not only found in remote areas for which the costs of monitoring tend to be higher, they can also be spotted *close* to big populated centres. Moreover, the share of IWU is on average the same between urban and rural municipalities (see Figure 2.13 in the Appendix). The latter may suggest that distance itself may not be capturing monitoring costs, instead it is possible that costs are associated to accessibility. Third, clusters having high IWU rates do not respect state boundaries, suggesting that drivers may not be state specific, but related to functional forms linked to hydrological characteristics or spatially-based socio-economic processes.



**Figure 2.4** – Percentage of illegal water users across Mexican municipalities, 2009



**Source:** Map produced by the author using the official map layers provided by INEGI. This map has been produced using a quantile distribution for creating the classes grouping the values of IWU rates.

## 2.3 Empirical analysis

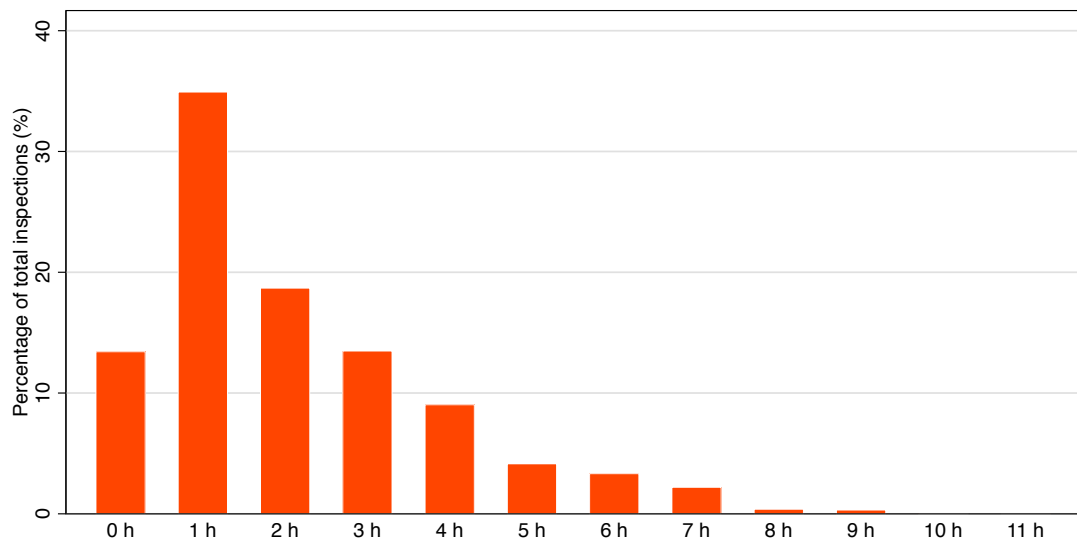
The main objective of the analysis is to examine the effects of enforcement actions on illegal water extraction in Mexico. In particular, my analysis focuses on the effects of environmental inspections - as a deterrence mechanism - on the number of illegal water users within the agriculture sector. My unit of analysis is the municipality, the third tier of government in Mexico.

I consider the number of illegal water users in each municipality as a count event. As can be expected, the total number of producers (i.e. both legal and illegal) significantly varies across municipalities. Probably the simplest way to account for these differences is by expressing IWU as a rate, i.e. the share of IWU over the total number of producers. However, for modelling purposes, this approach has a number of important caveats. The most important being that the differences in the total number of irrigators across municipalities can create spurious heterogeneity making it harder to compare IWU rates across the country. For some municipalities in Mexico the total number of irrigators can be as low as one, while in others it can be as high as five hundred. Thus, in municipalities with a small number of irrigators, a small number of illegal water users can be translated into high IWU rates. Rates based on a small number of irrigators are likely to be elevated artificially, reflecting a lack of data rather than capturing the process that prompts elevated illegal water extraction rates. For this reason I opted to model IWU through a count model in which the total number of irrigators enters into the model as an *exposure* term.

Environmental inspections are usually endogenous. In practice, inspections tend to focus on areas where the likelihood of infractions is higher, or in areas where non-compliance has important effects on the environment. In

the case of water resources in Mexico, inspections seem to focus on producers based in municipalities having high water stress levels, where the presence of illegal water users is more likely. In other words, inspections are not random. The latter may create a bias when estimating the effect of inspections on environmental compliance. Sometimes this bias is so important that the effect of inspections over illegal activity could even appear to be positive, suggesting that more inspections lead to more illegal actions.

**Figure 2.5** – Percentage of number of inspections by driving time between water agencies and municipalities, 2007-2009



My identification strategy relies on an instrumental variable approach that controls for the endogeneity of inspections. Due to geographic features and historical processes, certain municipalities are more accessible to environmental authorities than others. The latter is not necessarily captured through measures based on Euclidean distance, but through indicators reflecting accessibility. A simple example of the latter is driving time. For this reason, I opted to use the driving time between each municipality and the closest

regional office of CONAGUA within each hydrological administrative region. As can be seen from Figure 2.5, most inspections carried out by CONAGUA take place within 2 hrs driving time from CONAGUA's regional offices, having a small share of the inspections taking place over 3 hrs<sup>14</sup>. My identification further relies on the assumption that the driving time between each municipality and CONAGUA's closest regional office does not have a direct effect on the number of IWU in each municipality.

The frequency of inspections and driving time are related. To test for the latter, I run different specifications of both Probit and OLS models in order to analyse the strength of the linkage between accessibility and frequency of inspections. In the case of the Probit models, the dependent variable is defined as a dummy indicating whether a municipality has been visited by CONAGUA; with regard to the OLS models, the dependent variable is defined as the total number of inspections in each municipality. Results are presented in Table 2.16 in the Appendix. For both models, I tested for the instrument, driving time, expressed in terms of log and in terms of a set of dummy variables. In all cases, and after controlling for a number of covariates, both transformations of driving time are highly significant.

The following paragraphs describe the methodology used for the analysis of IWU. I start by introducing the analytical framework used for defining the specification of the econometric model, followed by a description of the statistical tools used for identifying the parameters of the model.

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<sup>14</sup> The long tale of the distribution is due to a really small number of municipalities in the north side of the country that may take up to 10 hours of driving time to reach them from CONAGUA's closest regional office.

### 2.3.1 Analytical framework and econometric specification

I relied on the analytical framework provided by [Becker \(1968\)](#) regarding public enforcement, and its adaptation to environmental regulation done by [Heyes \(2000\)](#), in order to model the number of illegal water users. Under this analytical framework, producers comply with environmental regulation only if the cost of compliance  $c_i$  is lower than the expected penalty from non-compliance. If random inspections are the main tool for enforcement, the expected penalty is defined by the product of  $\pi$ , the probability of being inspected, and  $D$  a lump-sum fine. Thus, producer  $i$  will comply only if  $c_i < \pi D$ . If  $c_i$  is distributed across the population with probability  $f(c_i)$ , and cumulative probability  $F(c_i)$ , then  $\Theta$  the rate of compliance across the population will be  $F(\pi D)$ . Changes in the probability of inspection or the amount of the fine can be expressed as follows:

$$\frac{\delta\Theta}{\delta\pi} = D \frac{\delta F}{\delta c} \geq 0 \quad (2.1)$$

$$\frac{\delta\Theta}{\delta D} = \pi \frac{\delta F}{\delta c} \geq 0 \quad (2.2)$$

These equations imply that increasing either the probability of inspection or the amount of the fines increases the level of compliance in the population. In addition to deterrence-related policies, [Becker \(1968\)](#) further considers that a series of socio-economic characteristics - most likely context-specific - also play a key role in the amount of offences.

The following equation represents the econometric specification for the baseline model. This specification not only considers deterrence-related variables, but also institutional, socio-economic, and geographic covariates in order to control for factors influencing illegal extraction that are not directly related

to policy actions. In this model I consider deterrence variables to be exogenous. An additional characteristic of this model is that, since IWU is treated as a count event, the total number of irrigators in each municipality enters the right side of the equation as an exposure term (i.e. its coefficient is constrained to one).

$$IWU_{i,t} = f(deterrence_{i,t}, policy_i, production_{i,t}, social_{i,t}, weather_{i,t}, N_{i,t}, C) \quad (2.3)$$

Where  $i$  represents a municipality in which irrigators used water for production in time  $t$ ;  $deterrence_{i,t}$  represents a set of deterrence-related variables;  $policy_i$  represents territorial policy tools that regulate water extractions by specifying limits to the number of concessions granted, and do not change in time;  $social_{i,t}$  represents socio-economic characteristics;  $production_{i,t}$  are production-related characteristics of irrigators;  $weather_{i,t}$  are weather-related variables;  $N_{i,t}$  is the total number of irrigators; and  $C$  is a group of controls including fixed-effects.

The set of deterrence variables is composed by the number of inspections and the number of legal procedures against water users implemented by CONAGUA. According to the theoretical background previously exposed, increasing the number of visits or the number of procedures is expected to reduce the number of IWU.

Two specific territorial policies controlling for groundwater extraction have a direct effect on the number of IWU in each municipality. The LAN stipulates that no additional concessions can be granted in closed aquifers and prohibition zones of type I. Thus, I consider the presence of prohibition zones and closed aquifers in the  $policy_i$  set of variables. The sign of these variables is not clear *a priori*. It is likely that municipalities overlapping with exploited

aquifers or prohibitions zones show a higher number of IWU. This said, it is possible that enforcement efforts concentrate in these places, or that water stress promotes local mechanisms that limit illegal extraction, thus reducing the number of IWU.

Since variables representing socio-economic characteristics tend to be highly correlated, I opt to only focus on two variables. These variables are a deprivation index and population density. High deprivation not only implies a low income level, but also low levels of human capital and limited access to basic services such as electricity, sanitation, and information technology. Small producers lacking education and access to information technologies may be illegal because they are not aware of the procedures needed to ask for a concession or the benefits granted by a concession. With regard to population density, I consider this variable to be important since it allows to differentiate between urban and rural areas, and because it can also capture - up to a certain extent - potential agglomeration effects. The effects of these two covariates on IWU can be either positive or negative.

With regard to the group of production-related variables, I also focus on a small number of variables. In this case, I consider the output per hectare and the mechanised area in each municipality. The sign of the coefficients of these variables are not clear in advance either.

The group of weather covariates is composed by precipitation and temperature. In addition to control for geographic differences, it is possible that these two variables have a direct influence on the number of IWU. Higher temperatures, less precipitation, or both, can trigger the demand for groundwater. Irrigators in closed aquifers or prohibitions zones - where no additional concessions are available - may opt to become illegal in order to access addi-

tional wells. Moreover, producers based outside these zones may also decide to become illegal in order to satisfy their water needs if authorities are not capable of providing concessions on time due to bureaucratic constraints.

The set of controls is composed by two types of fixed-effects and a variable accounting for the area of each municipality. Fixed-effects concern both time and hydrological administrative regions. As described in previous sections, the management of water resources in the country is done through the thirteen hydrological administrative regions. These regions are defined according to hydrologic characteristics, although they coincide with the administrative boundaries of municipalities. Accounting for HARs not only allows to further control for geographic differences directly related to hydrological systems, but also for differences in the capacity of regional authorities to monitor and prevent illegal water extraction. Finally, I opted to control for the size of municipalities since they tend to significantly vary across the country, particularly between rural and urban areas, usually being the later smaller. Table 2.5 describes all the covariates used for the analysis.

As previously discussed, a recurrent issue faced when analysing deterrence effects is the endogeneity characterising enforcement actions. In order to deal with this issue, I relax the assumption regarding the exogeneity of deterrence variables and identify the coefficient of environmental inspections through an instrument capturing the accessibility of environmental authorities. The intuition behind this instrument is simple: due to the limited number of inspectors and transportation costs (not just monetary costs, but also in terms of time), inspections are more frequent in areas closer to regional offices of CONAGUA. This relationship is expressed by Equation 2.4.



$$deterrence_{i,t} = f(access_i, policy_i, production_{i,t}, social_{i,t}, weather_{i,t}, N_{i,t}, C)$$
(2.4)

Where  $access_i$  represents the variables accounting for accessibility. I approach accessibility mainly through the driving time between each municipality and the closest CONAGUA regional office within the corresponding hydrological administrative region. In addition to this variable, I use the density of the road network as an additional instrument for robustness checks.

### 2.3.2 Estimation method

The parameters of Equation 2.3, the baseline specification, are estimated through a negative binomial regression model (NBRM). Poisson models assume that the conditional mean of the dependent variable is equal to the conditional variance. However, this is rarely the case in socio-economic phenomena, for which conditional variance is usually higher than the conditional mean. Under the presence of over-dispersion the estimates of the Poisson model are consistent but inefficient, with standard errors downward-biased (Cameron and Trivedi, 1998). The NBRM deals with this issue by allowing the conditional variance of the dependent variable to exceed the conditional mean.

I opt to use the NBRM after examining the distribution of IWU. As suggested by Cameron and Trivedi (1998), a first hint to identify over-dispersion is by comparing the unconditional variance of the distribution of the dependent variable. In the case of IWU, the mean has a yearly average of 14, while the variance is slightly above 900. For this reason, I chose the negative binomial as a baseline model rather than a Poisson regression. Moreover, the yearly

**Table 2.5** – Description of covariates and instruments

| Covariates Code | Group         | Units                          | Description   |
|-----------------|---------------|--------------------------------|---|
| INSP            | Deterrence    | Number                         | Yearly number of inspection done by CONAGUA in the municipality.  |
| INSP LAG        | Deterrence    | Number                         | Lagged yearly number of inspection done by CONAGUA in the municipality.   |
| LEG LAG         | Deterrence    | Number                         | Lagged yearly number of legal actions due to lack of concession or illegal discharges launched by CONAGUA in the state. |
| AQUIFER         | Policy        | km <sup>2</sup>                | Surface of the municipality comprising an overexploited aquifer.  |
| VEDA I          | Policy        | km <sup>2</sup>                | Surface of the municipality comprising a prohibition zone of type I.  |
| VEDA II         | Policy        | km <sup>2</sup>                | Surface of the municipality comprising a prohibition zone of type II.   |
| VEDA III        | Policy        | km <sup>2</sup>                | Surface of the municipality comprising a prohibition zone of type III.  |
| OUTPUT          | Production    | \$MEX (1000) per ha            | Value of agricultural production per hectare.   |
| MECH            | Production    | Ha                             | Mechanised surface.   |
| POP             | Social        | Population per km <sup>2</sup> | Population density.   |
| DEPRIV          | Social        | Index                          | Deprivation index.  |
| TEMP            | Weather       | Degrees Celsius                | Yearly average temperature.   |
| RAIN            | Weather       | Millimetres                    | Yearly average precipitation.   |
| Ln TIME         | Accessibility | Log of Hours                   | Log of driving time between the municipality and the closest water agency within the HAR.                               |
| TIME 2HR        | Accessibility | Dummy                          | Dummy =1, if the driving time between the municipality and the closest water agency within the HAR is: 1 hr < time ≤ 2. |
| TIME 3HR        | Accessibility | Dummy                          | Dummy =1, if the driving time between the municipality and the closest water agency within the HAR is: 2 hr < time ≤ 3. |
| TIME 3HR+       | Accessibility | Dummy                          | Dummy =1, if the driving time between the municipality and the closest water agency within the HAR is: time > 3.        |
| Ln NET          | Accessibility | Log of Km                      | Log of network density by municipality.   |

average amount of zeros in IWU only represents 15% of the total number of observations for each period. For this reason, based on the modelling strategies suggested by [Cameron and Trivedi \(1998\)](#), I did not consider as baseline model an estimation method that separately models the number of

zeros, such as zero-inflated or hurdle models. Nevertheless, I do consider the robustness checks of both types of models.

The negative binomial probability distribution, and its first and second conditional moments, are given by:

$$Pr(y_i|x_i) = \frac{\Gamma(y_i + \alpha^{-1})}{y_i! \Gamma(\alpha^{-1})} \left( \frac{\alpha^{-1}}{\alpha^{-1} + \mu_i} \right)^{\alpha^{-1}} \left( \frac{\mu_i}{\alpha^{-1} + \mu_i} \right)^{y_i} \quad (2.5)$$

$$E(y_i|x_i) = \mu_i = \exp(x_i' \beta + \ln(N_i)) \quad (2.6)$$

$$Var(y_i|\mathbf{x}) = \mu_i \left( 1 + \frac{\mu_i}{\alpha^{-1}} \right) = \mu_i + \alpha \mu_i^2 \quad (2.7)$$

Where  $y_i$  is a dependent count event variable,  $x_i$  is a vector of exogenous covariates,  $\mu_i$  is the conditional mean, and  $\alpha_i$  is known as the dispersion parameter. The conditional mean of the negative binomial is further described in Equation 2.6. This equation considers an offset term, which in the case of this analysis is the natural log of the total number of irrigators in each municipality. Equation 2.7 is the conditional variance of the negative binomial. Since both  $\mu_i$  and  $\alpha$  are positive, the value of the conditional variance is higher than the conditional mean, thus allowing to account for over-dispersion. Finally, the NBRM can be estimated by a maximum likelihood method, using Equation 2.5 as the input for the likelihood equation.

I rely on two different methods for counts that allow accounting for endogenous covariates. The first method is a count model based on a GMM estimator that allows to consider the error term to be either additive or multiplicative. Under the assumption of additive errors the dependent variable  $y_i$  is defined as follows:

$$y_i = \exp(x_i'\beta_1 + y_{2,i}'\beta_2 + \ln(N_i)) + \epsilon_i \quad (2.8)$$

Where  $x_i$  is a vector of covariates and  $y_{2,i}$  is the endogenous variables. The error function of this equation is thus given by:

$$u(y_i, x_i, y_{2,i}, \beta_1, \beta_2) = y_i - \exp(x_i'\beta_1 + y_{2,i}'\beta_2 + \ln(N_i)) \quad (2.9)$$

When assuming a multiplicative structure for the error term, the equations describing  $y_i$  and its corresponding error function are given by:

$$y_i = \exp(x_i'\beta_1 + y_{2,i}'\beta_2 + \ln(N_i))\epsilon_i \quad (2.10)$$

$$u(y_i, x_i, y_{2,i}, \beta_1, \beta_2) = \frac{y_i}{\exp(x_i'\beta_1 + y_{2,i}'\beta_2 + \ln(N_i))} - 1 \quad (2.11)$$

If  $w_i$  is a vector including both covariates and instruments ( $x_i', z_i'$ ), the population moment condition of the GMM estimator of both the additive and multiplicative models is given by:

$$E[w_i u(y_i, x_i, y_{2,i}, \beta_1, \beta_2)] = 0 \quad (2.12)$$

The GMM estimator solves the minimisation problem by bringing the sample-moment condition as close as possible to zero ([Cameron and Trivedi, 1998](#)).

The second method of counts allowing for endogenous covariates is based on a two-step estimation procedure. This estimator is known as a *control function*. During the first step, the endogenous regressor is regressed on the

exogenous regressors; the parameters from the first step are used to compute residuals that are then used in the second step to control for endogeneity. Among non-linear models the type of residual selected is not neutral across certain likelihood-based tests such as Wald and Lagrange Multiplier; standardised residuals perform better than raw residuals allowing not to reject the hypothesis of endogeneity when applying these tests (Geraci et al., 2014). In the same spirit as its linear counterpart, the matrix of variance and covariance has to be adjusted to account for the first step estimation (Cameron and Trivedi, 1998; Wooldridge, 2010). Software like Stata allows to estimate this model in one step following a GMM approach that does not require adjusting the variance and co-variance matrix. The control function estimator is given by:

$$y_{2,i} = \Omega w_i + v_i \quad (2.13)$$

$$y_i = \exp(x_i' \beta_1 + y_{2,i}' \beta_2 + v_i' \rho + \ln(N_i) + c_i) \quad (2.14)$$

Using the same notation as in the previous paragraph,  $w_i$  is a vector including covariates and instruments  $(x_i', z_i')$ . The term  $v_i' \rho$  is that controlling for the endogeneity;  $\rho$  captures the extent of the endogeneity, taking a value equal to zero when  $y_{i,2}$  is exogenous.

## 2.4 Data and descriptive statistics

The dataset for the analysis is composed of variables collected from official sources and space-related variables built through geographic information systems (GIS). The latter mainly concern covariates capturing the extent of territorial policies, weather, and accessibility.

### 2.4.1 Dependent variable

The main variable of interest for the analysis is the number of irrigators extracting water without a valid concession. As can be expected, information regarding illegal activities is scarce and of limited access to the general public. Nevertheless, as described in the background section, the institutional setting concerning water management in Mexico provides a particular framework for identifying those irrigators lacking a concession.

Illegal water users can be identified through their contracts with the electricity utility company. Having a concession is a necessary condition for accessing subsidised electricity tariffs (9CU and 9N); without a valid concession irrigators can only access electricity tariffs that are almost five times higher than those being subsidised. Hence, those irrigators using non-subsidised tariffs most certainly lack a valid concession. The dependent variable is thus built by counting the number of irrigators in each municipality that have electricity contracts based on non-subsidised tariffs: 9 or 9-M.

I obtained the information on the type of electricity tariffs from the Federal Electricity Commission (CFE)<sup>15</sup>. This dataset accounts for the universe of irrigators that have a contract with the electricity utility. The dataset includes the total number of irrigators in each municipality, as well as the type of tariff they have access to. The CFE does not provide services to the Distrito Federal, hence this dataset does not include this state. For practical reasons, I only consider those irrigators that were economically active each year, i.e. I only keep those observations with an electricity consumption different from zero. The resulting dataset is an unbalanced-panel that accounts

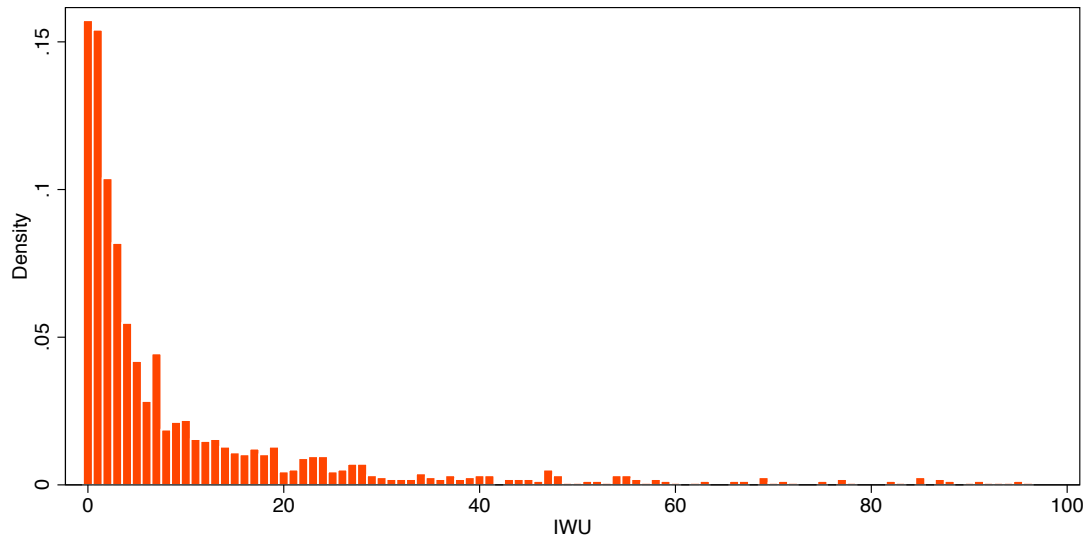
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<sup>15</sup> This agency is the main electricity utility in the country; it is attached to the Ministry of Energy.

for the period 2007 - 2009. The total number of observations (municipalities) is 4,545, while the average number of observations per year is 1,528 (between 2000 and 2010 there were 2,454 municipalities in Mexico).

The distribution of IWU across municipalities is highly skewed. Figure 2.6 shows the distribution of IWU in 2009. During that year the number of IWU in each municipality ranged from 0 to 272, with an average of 14.3 and a standard deviation of 30.1 IWU in each municipality. During 2008 and 2007, the number of IWU followed the same distribution and had almost the same statistics: in 2008 the maximum number of IWU was 262, the average number was 14.4, and the standard deviation was 30.4; in 2007, these statistics were 267, 13.19, and 30.2, respectively. Looking at the total number of IWU could be misleading since it does not account for the total number of irrigators in each municipality. To account for the extent of illegal irrigators in each municipality, Table 2.6 presents descriptive statistics of the share of IWU within and across states. With the exemption of a few states, the share of IWU by municipality ranges from 0 to 100%. The average value of IWU in each state does not vary considerably between 2007 and 2008. There seems to be however a slight increase in this trend between 2008 and 2009. This table also shows that IWU are present in all the municipalities of states like Aguascalientes, Baja California, and Baja California Sur. In contrast, in states like Oaxaca, not even half of the municipalities have IWU. The latter may be due to the fact that irrigation activities are not present in every municipality.

Although this is a very unique set of information, there are a number of caveats regarding this variable that should be highlighted. First, contracts with the electricity utility company do not only concern single producers.

**Figure 2.6** – Distribution of IWU, 2009

**Note:** The number of IWU in the histogram has been constrained to 100. The maximum number of IWU reaches up to 300 in some municipalities.

Indeed, some of these contracts concern *ejidos*<sup>16</sup>, or certain unions of farmers. This implies that for some municipalities the number of IWU and the total number of water users is underestimated. Unfortunately, I have no additional information that allows me to account for the extent of this issue. Second, although most irrigators rely on electricity as their main source of fuel (97% according to [CONUEE \(2011\)](#)), this variable does not account either for water users using a different fuel than electricity for irrigation. Finally, this variable does not account for irrigators that steal electricity. Information on electricity theft is not available, thus I cannot measure the extent of this potential issue.

<sup>16</sup> Ejidos are areas of communal land mainly used for agriculture.



Table 2.6 – Descriptive statistics of IWU across states, 2007-2009

| State                     | Mean | S.D. | 2007 |      |     | n   | Mean | S.D. | 2008 |     |     | n   | Mean | S.D. | 2009 |     |   | n |
|---------------------------|------|------|------|------|-----|-----|------|------|------|-----|-----|-----|------|------|------|-----|---|---|
|                           |      |      | Min  | Max  | n   |     |      |      | Min  | Max | n   |     |      |      | Min  | Max | n |   |
| Agascalientes (N=11)      | 6%   | 4%   | 0%   | 13%  | 11  | 6%  | 5%   | 0%   | 15%  | 11  | 10% | 9%  | 2%   | 33%  | 11   |     |   |   |
| Baja California (N=5)     | 9%   | 6%   | 3%   | 17%  | 5   | 9%  | 5%   | 2%   | 16%  | 5   | 10% | 5%  | 3%   | 16%  | 5    |     |   |   |
| Baja California Sur (N=5) | 26%  | 33%  | 5%   | 75%  | 4   | 26% | 32%  | 4%   | 73%  | 4   | 24% | 26% | 4%   | 75%  | 5    |     |   |   |
| Campeche (N=11)           | 43%  | 25%  | 18%  | 100% | 10  | 41% | 25%  | 18%  | 100% | 10  | 47% | 22% | 25%  | 100% | 10   |     |   |   |
| Cochula (N=38)            | 32%  | 21%  | 0%   | 100% | 37  | 32% | 20%  | 0%   | 100% | 37  | 30% | 14% | 0%   | 58%  | 37   |     |   |   |
| Colima (N=10)             | 10%  | 6%   | 0%   | 20%  | 10  | 13% | 7%   | 0%   | 23%  | 10  | 14% | 9%  | 0%   | 29%  | 10   |     |   |   |
| Chiapas (N=118)           | 28%  | 32%  | 0%   | 100% | 45  | 32% | 33%  | 0%   | 100% | 42  | 35% | 34% | 0%   | 100% | 43   |     |   |   |
| Chihuahua (N=67)          | 19%  | 22%  | 0%   | 100% | 52  | 20% | 22%  | 0%   | 100% | 51  | 18% | 18% | 0%   | 100% | 52   |     |   |   |
| Durango (N=39)            | 17%  | 18%  | 0%   | 53%  | 35  | 18% | 22%  | 0%   | 100% | 35  | 18% | 18% | 0%   | 54%  | 34   |     |   |   |
| Guajalajara (N=46)        | 25%  | 22%  | 0%   | 100% | 42  | 24% | 22%  | 0%   | 100% | 42  | 25% | 23% | 0%   | 100% | 42   |     |   |   |
| Guerrero (N=81)           | 63%  | 33%  | 0%   | 100% | 44  | 66% | 32%  | 0%   | 100% | 44  | 67% | 32% | 0%   | 100% | 44   |     |   |   |
| Hidalgo (N=84)            | 19%  | 30%  | 0%   | 100% | 14  | 30% | 33%  | 0%   | 100% | 14  | 64% | 39% | 0%   | 100% | 53   |     |   |   |
| Jalisco (N=124)           | 29%  | 20%  | 0%   | 100% | 109 | 32% | 21%  | 0%   | 100% | 109 | 32% | 20% | 0%   | 100% | 108  |     |   |   |
| Mexico (N=125)            | 52%  | 35%  | 0%   | 100% | 36  | 53% | 34%  | 0%   | 100% | 36  | 66% | 36% | 0%   | 100% | 47   |     |   |   |
| Michoacan (N=113)         | 20%  | 23%  | 0%   | 100% | 105 | 21% | 21%  | 0%   | 100% | 105 | 24% | 24% | 0%   | 100% | 105  |     |   |   |
| Morelos (N=33)            | 42%  | 27%  | 0%   | 100% | 26  | 43% | 27%  | 0%   | 100% | 26  | 47% | 32% | 0%   | 100% | 29   |     |   |   |
| Nayarit (N=20)            | 42%  | 34%  | 0%   | 100% | 18  | 40% | 32%  | 0%   | 100% | 17  | 47% | 34% | 0%   | 100% | 18   |     |   |   |
| Nuevo Leon (N=51)         | 41%  | 24%  | 0%   | 100% | 50  | 42% | 25%  | 0%   | 100% | 50  | 42% | 26% | 0%   | 100% | 49   |     |   |   |
| Oaxaca (N=570)            | 33%  | 31%  | 0%   | 100% | 240 | 35% | 30%  | 0%   | 100% | 235 | 41% | 33% | 0%   | 100% | 257  |     |   |   |
| Puebla (N=217)            | 25%  | 28%  | 0%   | 100% | 134 | 25% | 28%  | 0%   | 100% | 133 | 28% | 32% | 0%   | 100% | 143  |     |   |   |
| Queretaro (N=18)          | 20%  | 17%  | 6%   | 66%  | 15  | 21% | 18%  | 5%   | 68%  | 15  | 20% | 18% | 5%   | 68%  | 15   |     |   |   |
| Quintana Roo (N=8)        | 39%  | 14%  | 18%  | 63%  | 6   | 40% | 15%  | 24%  | 67%  | 6   | 46% | 13% | 36%  | 70%  | 6    |     |   |   |
| San Luis Potosi (N=58)    | 17%  | 17%  | 0%   | 83%  | 47  | 18% | 19%  | 0%   | 100% | 47  | 21% | 23% | 0%   | 100% | 49   |     |   |   |
| Sinaloa (N=18)            | 37%  | 16%  | 0%   | 69%  | 18  | 37% | 16%  | 0%   | 69%  | 18  | 38% | 17% | 0%   | 68%  | 18   |     |   |   |
| Sonora (N=72)             | 19%  | 23%  | 0%   | 100% | 58  | 17% | 18%  | 0%   | 100% | 57  | 17% | 19% | 0%   | 100% | 61   |     |   |   |
| Tabasco (N=17)            | 60%  | 38%  | 0%   | 100% | 11  | 70% | 40%  | 0%   | 100% | 11  | 61% | 44% | 0%   | 100% | 13   |     |   |   |
| Tamaulipas (N=43)         | 37%  | 27%  | 0%   | 100% | 33  | 37% | 26%  | 0%   | 100% | 33  | 36% | 26% | 0%   | 100% | 34   |     |   |   |
| Tlaxcala (N=60)           | 19%  | 26%  | 0%   | 100% | 51  | 19% | 26%  | 0%   | 100% | 51  | 23% | 29% | 0%   | 100% | 50   |     |   |   |
| Veracruz (N=212)          | 28%  | 36%  | 0%   | 100% | 86  | 28% | 35%  | 0%   | 100% | 83  | 30% | 37% | 0%   | 100% | 92   |     |   |   |
| Yucatan (N=106)           | 27%  | 16%  | 0%   | 75%  | 103 | 26% | 16%  | 0%   | 75%  | 103 | 28% | 16% | 0%   | 80%  | 102  |     |   |   |
| Zacatecas (N=58)          | 19%  | 21%  | 0%   | 100% | 53  | 21% | 22%  | 0%   | 100% | 52  | 21% | 22% | 0%   | 100% | 52   |     |   |   |

**Source:** Calculations made by the author using information from the Federal Electricity Commission. All statistics refer to the percentage of IWU in each municipality; Mean is the average percentage of IWU across municipalities in each state; S.D. is the standard deviation of IWU across municipalities in each state; Min and Max are the values of the municipalities with the lowest and highest percentages of IWU, respectively; n refers to the total number of municipalities in each state that had at least one user of electricity tariffs 9, 9-M, 9CU, or 9N; N refers to the total number of municipalities in each state according to the official territorial division of the 2010 census.

### 2.4.2 Deterrence variables

The two main variables accounting for environmental regulation are the number of inspections (at the municipal level) and the number of legal procedures against water users due to the lack of either a concession or a permit for waste water discharges (at the state level). CONAGUA classifies inspection visits according to the following types: national waters, waste water discharges, national goods, federal zones, and extraction of minerals. I consider all types of visits (even if these visits do not only concern irrigators) to account for the presence of CONAGUA's inspectors as a deterrence effect. Data on the number of inspections was obtained from CONAGUA's public registry of inspections<sup>17</sup>. The registry provides information on every visit during the last decade. Before 2007, the registry frequently lacks information on the municipality where the inspections took place. For this reason, it is not possible to use data on the number of inspections at the municipal level for the year 2006. With regard to legal procedures, I obtained the information from CONAGUA's Statistical Compendium of Water Management (CONAGUA, 2012a). This information only refers to procedures following infractions related to lack of concessions and waste water discharges. For confidentiality reasons, this information is not provided for municipalities but only for states.

**Table 2.7** – Descriptive statistics of the number of inspections and number of legal procedures by municipality

| Year | Mean | S.D. | Min | Max |
|------|------|------|-----|-----|
| 2007 | 2.36 | 8.44 | 0   | 191 |
| 2008 | 2.12 | 6.75 | 0   | 86  |
| 2009 | 2.48 | 10.4 | 0   | 300 |

**Source:** Computations made by the author.

<sup>17</sup> <http://www.conagua.gob.mx/>

**Table 2.8** – Number and share of inspections across states

| Region              | 2007 | 2008 | 2009 | 2007 (%) | 2008 (%) | 2009 (%) |
|---------------------|------|------|------|----------|----------|----------|
| Aguascalientes      | 59   | 53   | 58   | 1.34     | 1.34     | 1.27     |
| Baja California     | 160  | 190  | 364  | 3.64     | 4.8      | 7.99     |
| Baja California Sur | 128  | 88   | 88   | 2.91     | 2.22     | 1.93     |
| Campeche            | 119  | 99   | 91   | 2.7      | 2.5      | 2        |
| Coahuila            | 231  | 233  | 401  | 5.25     | 5.89     | 8.8      |
| Colima              | 92   | 91   | 80   | 2.09     | 2.3      | 1.76     |
| Chiapas             | 140  | 124  | 116  | 3.18     | 3.13     | 2.55     |
| Chihuahua           | 105  | 100  | 138  | 2.39     | 2.53     | 3.03     |
| Durango             | 87   | 83   | 76   | 1.98     | 2.1      | 1.67     |
| Guanajuato          | 193  | 174  | 218  | 4.39     | 4.4      | 4.78     |
| Herrero             | 184  | 172  | 168  | 4.18     | 4.35     | 3.69     |
| Hidalgo             | 66   | 71   | 69   | 1.5      | 1.79     | 1.51     |
| Jalisco             | 272  | 267  | 265  | 6.18     | 6.75     | 5.82     |
| Estado de Mexico    | 88   | 82   | 102  | 2        | 2.07     | 2.24     |
| Michoacán           | 253  | 221  | 234  | 5.75     | 5.59     | 5.13     |
| Morelos             | 135  | 92   | 87   | 3.07     | 2.32     | 1.91     |
| Nayarit             | 68   | 74   | 60   | 1.55     | 1.87     | 1.32     |
| Nuevo Leon          | 98   | 88   | 113  | 2.23     | 2.22     | 2.48     |
| Oaxaca              | 83   | 76   | 73   | 1.89     | 1.92     | 1.6      |
| Puebla              | 132  | 122  | 222  | 3        | 3.08     | 4.87     |
| Queretaro           | 59   | 70   | 58   | 1.34     | 1.77     | 1.27     |
| Quintana Roo        | 64   | 61   | 65   | 1.45     | 1.54     | 1.43     |
| San Luis Potosi     | 159  | 160  | 195  | 3.61     | 4.04     | 4.28     |
| Sinaloa             | 56   | 53   | 49   | 1.27     | 1.34     | 1.08     |
| Sonora              | 397  | 276  | 315  | 9.02     | 6.97     | 6.91     |
| Tabasco             | 55   | 52   | 77   | 1.25     | 1.31     | 1.69     |
| Tamaulipas          | 206  | 182  | 180  | 4.68     | 4.6      | 3.95     |
| Tlaxcala            | 35   | 40   | 45   | 0.8      | 1.01     | 0.99     |
| Veracruz            | 165  | 151  | 149  | 3.75     | 3.82     | 3.27     |
| Yucatán             | 154  | 121  | 117  | 3.5      | 3.06     | 2.57     |
| Zacatecas           | 168  | 143  | 143  | 3.82     | 3.61     | 3.14     |
| Total               | 4400 | 3957 | 4557 | 100      | 100      | 100      |

**Source:** Data obtained from [CONAGUA \(2012a\)](#); percentages computed by the author.

Table 2.7 presents descriptive statistics of the number of inspections across municipalities between 2007 and 2009. During this period, CONAGUA carried two inspections on average in each municipality. However, the distribution of inspections is highly skewed ranging from 0 to 191 in 2007 and from 0 to 300 in 2009.

Table 2.8 presents the number and share of inspections across states between 2007 and 2009. The number of inspections particularly increased in states like Coahuila, Puebla and Baja California. There it almost doubled between 2008 and 2009. The distribution of inspections across states has also evolved. In 2007, the states of Sonora and Jalisco accounted for the highest shares of inspections in the country, 9% and 6% respectively; while the state of Tlaxcala concentrated the lowest share (0.8%). However, by 2009 the states accounting for the highest shares of inspections were Baja California (8%) and Coahuila (9%); Tlaxcala remained the state with the lowest share.

Table 2.9 presents the number of legal procedures launched by CONAGUA in each state due to the lack of either a concession or a permit for waste water discharges. Overall, the number of procedures increased from 373 in 2008 to 1,070 in 2009. In states like Baja California, Puebla, Morelos, Durango and Coahuila the number of legal procedures increased by almost ten times between 2008 and 2009. In contrast, during the same period, in Yucatan the number of procedures decreased from 56 to 4; and in Chihuahua from 44 to 12. In 2007, the highest share of legal procedures was concentrated in Guanajuato (20%), but by 2009 this share had been divided by four (5%). The highest share of procedures in 2009 was found in Baja California (20%).

### 2.4.3 Policy variables

Policy variables refer to geographic areas where water extraction is limited by law. The two types of zones considered are a) closed aquifers; and b) prohibition zones. The spatial nature of these policy instruments imposes important challenges for building variables capturing their effects. In the first place, the limits of closed aquifers and prohibition zones do not always match the administrative boundaries of municipalities or states. In the second place, in some cases both policy tools overlap, Figure 2.7. The latter implies that certain areas within a municipality can cover a closed aquifer, a prohibition zone, or both of them. For this reason, I built these two variables using GIS. I have intersected the maps of closed aquifers and prohibition zones with the map of municipalities. This allows to account for the area in each municipality, expressed in square kilometres, where these two policy instruments are in place. In the case of prohibition zones, I create a variable for each type of prohibition zones (see the Background section for a description of prohibition zones).

The number and boundaries of both closed aquifers and prohibition zones have not been modified since the early 2000s. Thus, both variables are constant in time. Maps regarding aquifers and prohibition zones were obtained by CONAGUA, while administrative boundaries for municipalities and states were obtained from INEGI's cartographic repository.

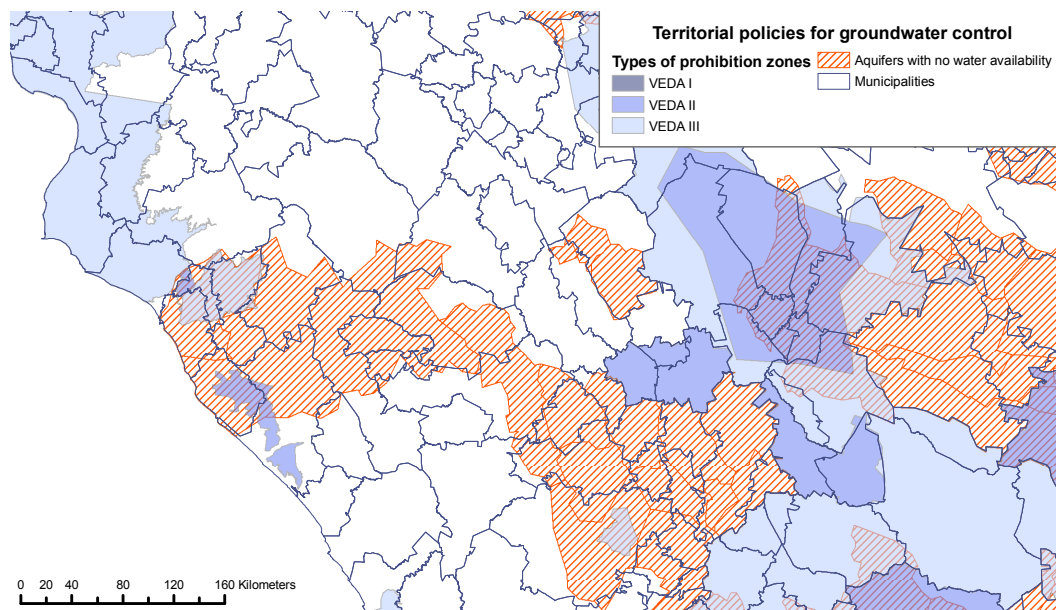
The area comprised by closed aquifers and prohibitions zones in each state is presented in Table 2.10. No municipality in the southern states of Campeche, Chiapas, Oaxaca or Quintana Roo comprises closed aquifers. By contrast, almost all of the surface of municipalities in Aguascalientes comprises closed aquifers. The largest extension of prohibition zones of type I - where no

**Table 2.9** – Number of administrative procedures, 2007 - 2009

| Region              | 2007 | 2008 | 2009 | 2007 (%) | 2008 (%) | 2009 (%) |
|---------------------|------|------|------|----------|----------|----------|
| Aguascalientes      | 2    | 28   | 19   | 0.55     | 7.51     | 1.78     |
| Baja California     | 57   | 24   | 222  | 15.62    | 6.43     | 20.75    |
| Baja California Sur | 0    | 13   | 9    | 0.00     | 3.49     | 0.84     |
| Campeche            | 19   | 9    | 13   | 5.21     | 2.41     | 1.21     |
| Chiapas             | 5    | 8    | 7    | 1.37     | 2.14     | 0.65     |
| Chihuahua           | 0    | 44   | 12   | 0.00     | 11.80    | 1.12     |
| Coahuila            | 1    | 15   | 158  | 0.27     | 4.02     | 14.77    |
| Colima              | 5    | 1    | 3    | 1.37     | 0.27     | 0.28     |
| Durango             | 1    | 16   | 158  | 0.27     | 4.29     | 14.77    |
| Guanajuato          | 74   | 38   | 59   | 20.27    | 10.19    | 5.51     |
| Guerrero            | 16   | 10   | 8    | 4.38     | 2.68     | 0.75     |
| Hidalgo             | 0    | 1    | 5    | 0.00     | 0.27     | 0.47     |
| Jalisco             | 7    | 0    | 18   | 1.92     | 0.00     | 1.68     |
| Mexico              | 9    | 6    | 5    | 2.47     | 1.61     | 0.47     |
| Michoacan           | 16   | 21   | 21   | 4.38     | 5.63     | 1.96     |
| Morelos             | 4    | 4    | 25   | 1.10     | 1.07     | 2.34     |
| Nayarit             | 2    | 0    | 3    | 0.55     | 0.00     | 0.28     |
| Nuevo Leon          | 26   | 24   | 99   | 7.12     | 6.43     | 9.25     |
| Oaxaca              | 8    | 1    | 19   | 2.19     | 0.27     | 1.78     |
| Puebla              | 0    | 6    | 91   | 0.00     | 1.61     | 8.50     |
| Queretaro           | 21   | 10   | 9    | 5.75     | 2.68     | 0.84     |
| Quintana Roo        | 4    | 7    | 4    | 1.10     | 1.88     | 0.37     |
| San Luis Potosi     | 1    | 0    | 57   | 0.27     | 0.00     | 5.33     |
| Sinaloa             | 2    | 0    | 4    | 0.55     | 0.00     | 0.37     |
| Sonora              | 21   | 0    | 6    | 5.75     | 0.00     | 0.56     |
| Tabasco             | 7    | 0    | 1    | 1.92     | 0.00     | 0.09     |
| Tamaulipas          | 0    | 1    | 1    | 0.00     | 0.27     | 0.09     |
| Tlaxcala            | 0    | 0    | 3    | 0.00     | 0.00     | 0.28     |
| Veracruz            | 1    | 24   | 23   | 0.27     | 6.43     | 2.15     |
| Yucatan             | 47   | 56   | 4    | 12.88    | 15.01    | 0.37     |
| Zacatecas           | 9    | 6    | 4    | 2.47     | 1.61     | 0.37     |
| Total               | 365  | 373  | 1070 | 100      | 100      | 100      |

**Source:** Data obtained from [CONAGUA \(2012a\)](#); percentages computed by the author. Number of administrative procedures due to the lack of either a valid concession for extracting groundwater or a valid licence for waste water discharges across Mexican states

**Figure 2.7** – Issues with territorial policies for groundwater control



Source: Maps provided by CONAGUA.

further extraction is allowed without damaging the ecosystem - takes place in Sonora and Guanajuato, 13,322 and 1,162 Km<sup>2</sup>, respectively. Except for Baja California and Baja California Sur, there are prohibition zones of type II in every state. Prohibition zones of type III are not present in the southern states of Chiapas, Guerrero, Tabasco, and Yucatan. As can be expected, closed aquifers and prohibition zones are correlated. The correlation of the area comprised in each municipality between closed aquifers and prohibitions zones ranges from 0.3 (closed aquifers vs prohibition zone type II) to 0.47 (closed aquifers vs prohibition zone type III).

#### 2.4.4 Social and production variables

Social variables were obtained from the National Committee for Social Development Policy Evaluation (CONEVAL) and the INEGI. The CONEVAL

**Table 2.10** – Descriptive statistics of closed aquifers and restriction zones

| State               | Area<br>(Km <sup>2</sup> ) | N   | CA<br>(Km <sup>2</sup> ) | CA<br>(n) | PZ-I<br>(Km <sup>2</sup> ) | PZ-I<br>(n) | PZ-II<br>(Km <sup>2</sup> ) | PZ-II<br>(n) | PZ-III<br>(Km <sup>2</sup> ) | PZ-III<br>(n) |
|---------------------|----------------------------|-----|--------------------------|-----------|----------------------------|-------------|-----------------------------|--------------|------------------------------|---------------|
| Aguascalientes      | 5492                       | 11  | 5374                     | 11        | 0                          | 0           | 49                          | 2            | 5443                         | 11            |
| Baja California     | 65084                      | 5   | 13958                    | 5         | 3                          | 1           | 0                           | 0            | 65081                        | 5             |
| Baja California Sur | 65490                      | 5   | 26286                    | 4         | 0                          | 0           | 0                           | 0            | 65490                        | 4             |
| Campeche            | 44035                      | 11  | 0                        | 0         | 0                          | 0           | 51                          | 4            | 3                            | 1             |
| Chiapas             | 34780                      | 118 | 0                        | 0         | 0                          | 0           | 23485                       | 32           | 0                            | 0             |
| Chihuahua           | 192453                     | 67  | 32672                    | 33        | 0                          | 0           | 28824                       | 15           | 44314                        | 35            |
| Coahuila            | 133941                     | 38  | 47404                    | 32        | 38                         | 3           | 11720                       | 11           | 9409                         | 8             |
| Colima              | 5684                       | 10  | 597                      | 3         | 0                          | 0           | 5675                        | 10           | 9                            | 5             |
| Durango             | 102139                     | 39  | 25379                    | 24        | 0                          | 0           | 18870                       | 17           | 4969                         | 15            |
| Guanajuato          | 29161                      | 46  | 17985                    | 41        | 1162                       | 6           | 19613                       | 39           | 8364                         | 36            |
| Guerrero            | 44790                      | 81  | 0                        | 0         | 0                          | 0           | 23694                       | 33           | 0                            | 0             |
| Hidalgo             | 4655                       | 84  | 1773                     | 9         | 168                        | 3           | 272                         | 7            | 864                          | 5             |
| Jalisco             | 67802                      | 124 | 5001                     | 29        | 0                          | 1           | 20004                       | 78           | 48323                        | 101           |
| Mexico              | 11804                      | 125 | 4837                     | 21        | 196                        | 5           | 10498                       | 32           | 1073                         | 13            |
| Michoacan           | 56875                      | 113 | 6009                     | 49        | 0                          | 0           | 52841                       | 104          | 4031                         | 38            |
| Morelos             | 4143                       | 33  | 678                      | 13        | 0                          | 1           | 1590                        | 18           | 2550                         | 26            |
| Nayarit             | 22686                      | 20  | 0                        | 0         | 0                          | 0           | 9867                        | 15           | 8                            | 7             |
| Nuevo Leon          | 59397                      | 51  | 24658                    | 42        | 0                          | 0           | 10585                       | 24           | 2601                         | 5             |
| Oaxaca              | 32672                      | 570 | 0                        | 0         | 0                          | 0           | 8944                        | 76           | 5182                         | 90            |
| Puebla              | 25488                      | 217 | 3011                     | 43        | 7                          | 3           | 2988                        | 30           | 11031                        | 97            |
| Queretaro           | 9892                       | 18  | 4040                     | 11        | 287                        | 3           | 4740                        | 14           | 392                          | 4             |
| Quintana Roo        | 42170                      | 8   | 0                        | 0         | 0                          | 0           | 6129                        | 5            | 14783                        | 3             |
| San Luis Potosi     | 49899                      | 58  | 12173                    | 19        | 0                          | 0           | 12084                       | 26           | 3921                         | 15            |
| Sinaloa             | 54490                      | 18  | 14029                    | 9         | 0                          | 0           | 2031                        | 7            | 12895                        | 13            |
| Sonora              | 132432                     | 72  | 43969                    | 36        | 13322                      | 5           | 60053                       | 42           | 31583                        | 21            |
| Tabasco             | 16859                      | 17  | 0                        | 0         | 0                          | 0           | 8879                        | 10           | 0                            | 0             |
| Tamaulipas          | 53220                      | 43  | 12272                    | 16        | 0                          | 0           | 1653                        | 3            | 22832                        | 23            |
| Tlaxcala            | 3787                       | 60  | 17                       | 3         | 353                        | 4           | 525                         | 10           | 1521                         | 39            |
| Veracruz            | 30846                      | 212 | 1                        | 2         | 0                          | 0           | 9409                        | 35           | 1309                         | 18            |
| Yucatan             | 37462                      | 106 | 0                        | 0         | 0                          | 0           | 36832                       | 103          | 0                            | 0             |
| Zacatecas           | 68909                      | 58  | 24692                    | 38        | 0                          | 0           | 14494                       | 26           | 54190                        | 51            |

**Source:** Calculations made by the author using Arcinfo. Area refers to the total state surface; N refers to the total number of municipalities in each state according to the official territorial division of the 2010 census; CA stands for closed aquifers; PZ stands for prohibition zone while the numerals I, II, and III refer to the different types of prohibition zones; n refers in every case to the number of municipalities within each state that comprise either a closed aquifer or a prohibition zone.

produces a series of poverty-related statistics, including a multidimensional deprivation index. This index takes into account different variables related to education, access to health services, livelihood, and wealth in every municipality in the country. Population density was computed using information on total population and area for each municipality. This data was obtained



from INEGI's SIMBAD database<sup>18</sup>. Table 2.11 presents descriptive statistics on both the deprivation index and population density. The deprivation index ranges between -1.91 and 3.59 across the entire sample of municipalities, i.e. from very low to very high levels of deprivation. However, its average value does not change across time (-0.23). The municipalities with the highest deprivation are in the states of Guerrero, Chiapas, and Oaxaca. Population density ranges from 0.14 to 8,278 inhabitants per Km<sup>2</sup>. The municipalities with the lowest population density are part of the state of Chihuahua, while those with the highest levels can be found in Nuevo Leon.

Production variables were also obtained from the SIMBAD database. Total output is expressed in MEX\$ per hectare and refers to the main crops produced in the country: green alfalfa, forage oats, green chile, beans, grain maize, grass, grain sorghum, red tomato, green tomato and wheat grain. Output ranges from 0.01 to 80.4 MEX\$ per hectare, Table 2.11. The lowest output can be found in municipalities in Puebla while the highest values are in the states of Sonora, Hidalgo, and Chihuahua. Mechanised area refers to the surface accounting for any machinery that requires a source energy different from men, which is used for agricultural production processes. Mechanised areas range across municipalities from 1 to 2,190 hectares. The municipalities with the largest extension of mechanised areas can be found in the states of Baja California, Zacatecas and Chihuahua.

#### **2.4.5 Weather variables**

Measures on precipitation and temperatures were computed for each municipality using GIS. The main source for computing these variables is [Willmott and Matsuura \(2001\)](#), which provide worldwide monthly and annual esti-

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<sup>18</sup><http://sc.inegi.org.mx/cobdem/>

**Table 2.11** – Descriptive statistics for socio-economic and weather variables, 2006-2008

| Variable      | Mean   | S.D.   | Min   | Max     | N    |
|---------------|--------|--------|-------|---------|------|
| Year = 2006   |        |        |       |         |      |
| OUTPUT HA     | 5.57   | 6.91   | 0.03  | 77.57   | 1497 |
| MECHANISED    | 58.02  | 159.03 | 1     | 2190.78 | 1497 |
| POP DENS      | 153.44 | 490    | 0.14  | 8278.71 | 1497 |
| DEPRIVATION   | -0.23  | 0.88   | -1.97 | 3.2     | 1497 |
| TEMPERATURE   | 20.49  | 4.22   | 9.80  | 28.98   | 1497 |
| PRECIPITATION | 72.52  | 44.49  | 3.02  | 355.62  | 1497 |
| Year = 2007   |        |        |       |         |      |
| OUTPUT HA     | 5.62   | 6.88   | 0.03  | 57.15   | 1483 |
| MECHANISED    | 59.61  | 157.66 | 1     | 2083.14 | 1483 |
| POP DENS      | 156.48 | 496.56 | 0.14  | 8160.77 | 1483 |
| DEPRIVATION   | -0.23  | 0.88   | -1.94 | 3.39    | 1483 |
| TEMPERATURE   | 20.41  | 4.14   | 9.88  | 28.92   | 1483 |
| PRECIPITATION | 72.23  | 41.4   | 1.56  | 346.61  | 1483 |
| Year = 2008   |        |        |       |         |      |
| OUTPUT HA     | 5.94   | 7.94   | 0.01  | 80.42   | 1588 |
| MECHANISED    | 57.78  | 159.32 | 1     | 2115.56 | 1588 |
| POP DENS      | 167.8  | 517.45 | 0.44  | 8042.8  | 1588 |
| DEPRIVATION   | -0.23  | 0.89   | -1.91 | 3.59    | 1588 |
| TEMPERATURE   | 20.22  | 4.17   | 9.82  | 28.54   | 1588 |
| PRECIPITATION | 73.14  | 43.55  | 7.88  | 342.88  | 1588 |

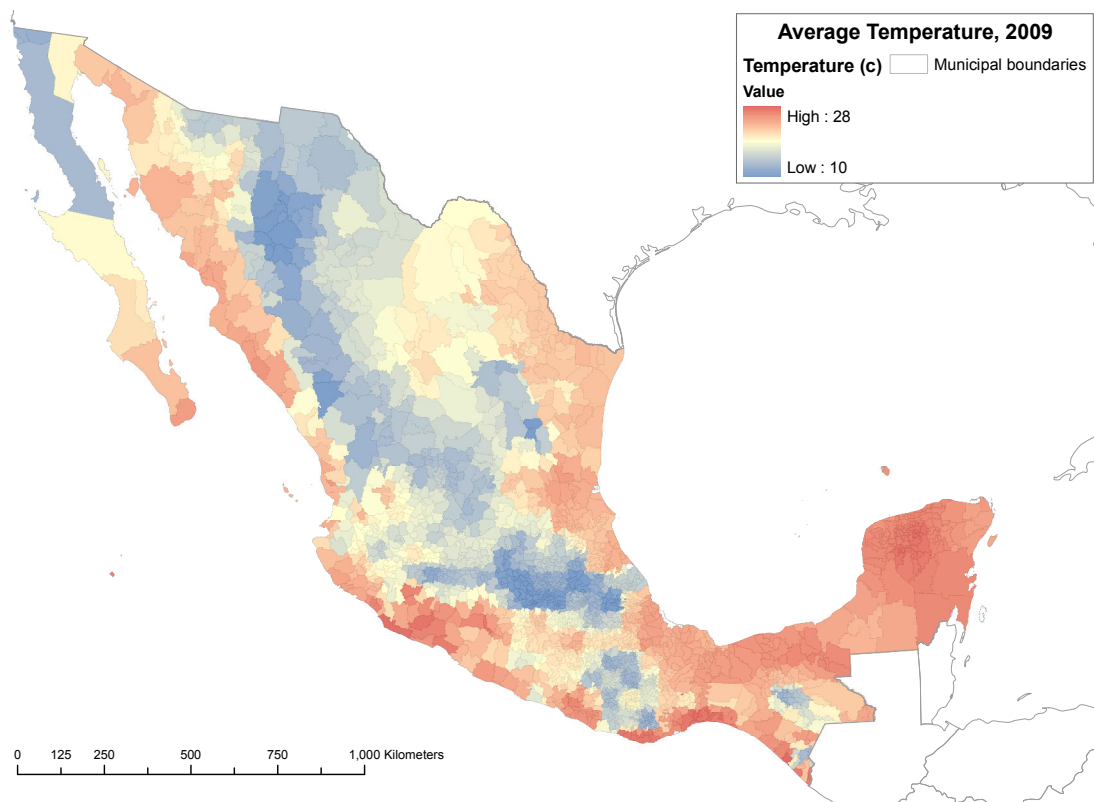
**Source:** Calculations made by the author.

mates for terrestrial air temperature and precipitation between 1900 and 2010. This dataset is based on station values of both monthly precipitation and air temperatures interpolated to a 0.5 degree by 0.5 degree latitude/longitude grid, where the grid nodes are centred on the 0.25 degree. Average values for precipitation and temperature are computed by overlapping municipal administrative boundaries and the grids of temperatures and precipitation (area-weighted). Basic statistics of both precipitation and temperatures across all municipalities are presented in Table 2.11. Average yearly temperatures range from 10 to 29 degrees Celsius in the three years considered for the analysis. Precipitation shows slightly higher variation across time. For instance, in 2007 precipitation ranged from 1.5 to 346.6 mm while in 2008 it ranged from 7.8 to 342.8 mm. As can be seen from Figure 2.8, yearly average temperatures tend to be higher in coastal areas, particularly in the south of the country. However, coastal areas in the northern states of Sonora, Sinaloa and Tamaulipas are also characterised by high temperatures. With regard to precipitation, there is a clearer spatial pattern. Precipitation tends to be higher in the southern part of Mexico and in particular around the Gulf of Mexico, Figure 2.9.

#### **2.4.6 Accessibility variables**

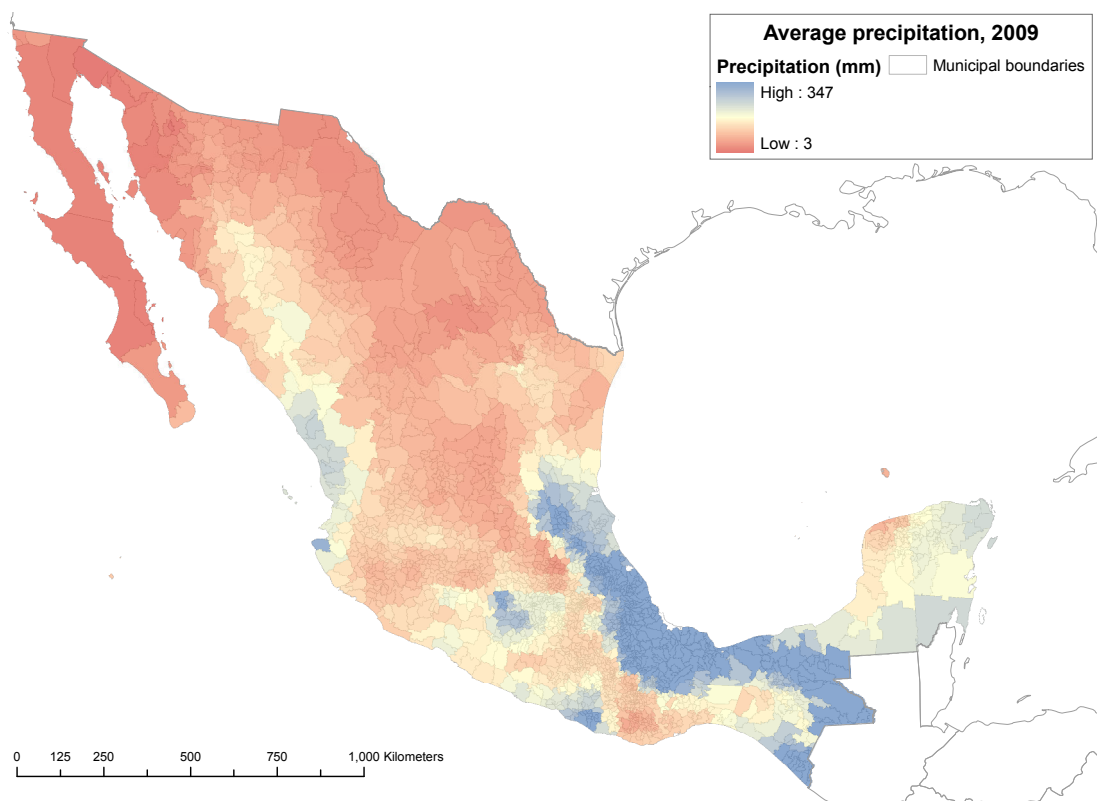
I use the accessibility of the regulator as my main instrument for identifying the effect of inspections over IWU. I measure accessibility by computing the driving time between the regional water agencies and municipalities. I build this variable through GIS using maps on the location of regional water agencies, the main population centres of every municipality, the road network, and the administrative boundaries of hydrological administrative regions. All these geographic datasets were obtained from INEGI.

**Figure 2.8** – Yearly average temperature at municipal level, 2009



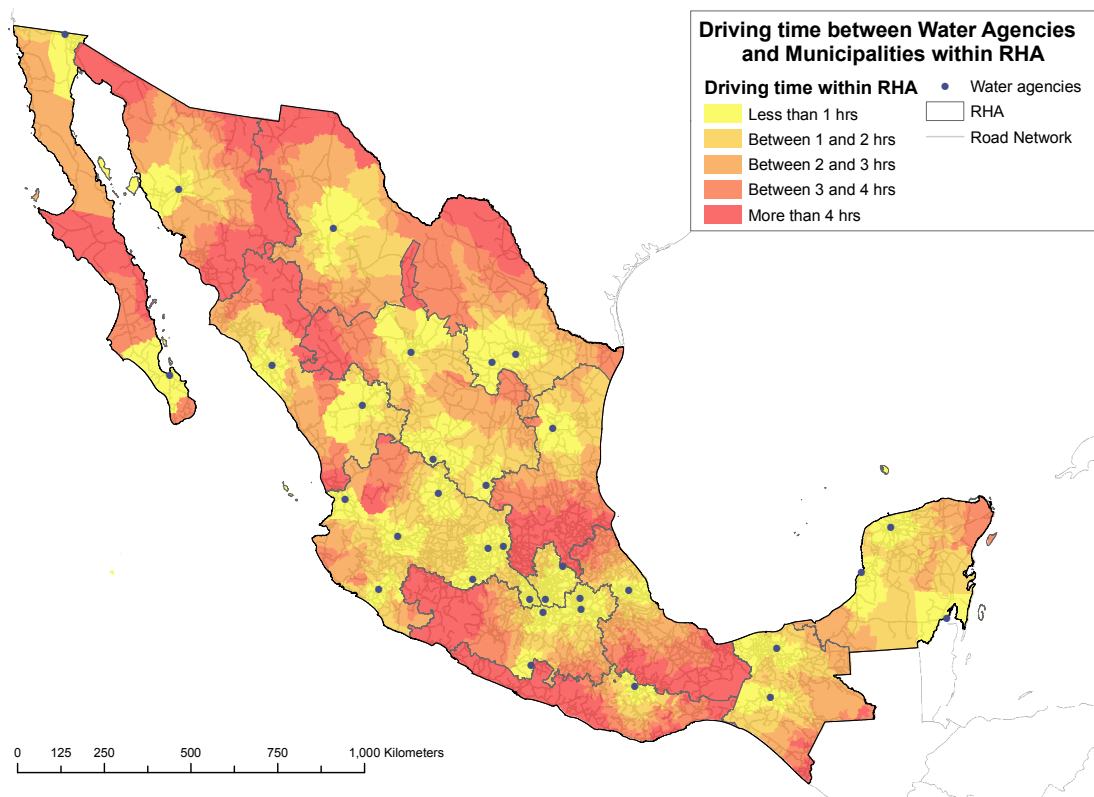
**Source:** Computations made by the author using data from [Willmott and Matsuura \(2001\)](#).

**Figure 2.9** – Yearly average precipitation at municipal level, 2009



**Source:** Computations made by the author using data from [Willmott and Matsuura \(2001\)](#).

**Figure 2.10** – Driving time between municipalities and water agencies within HAR

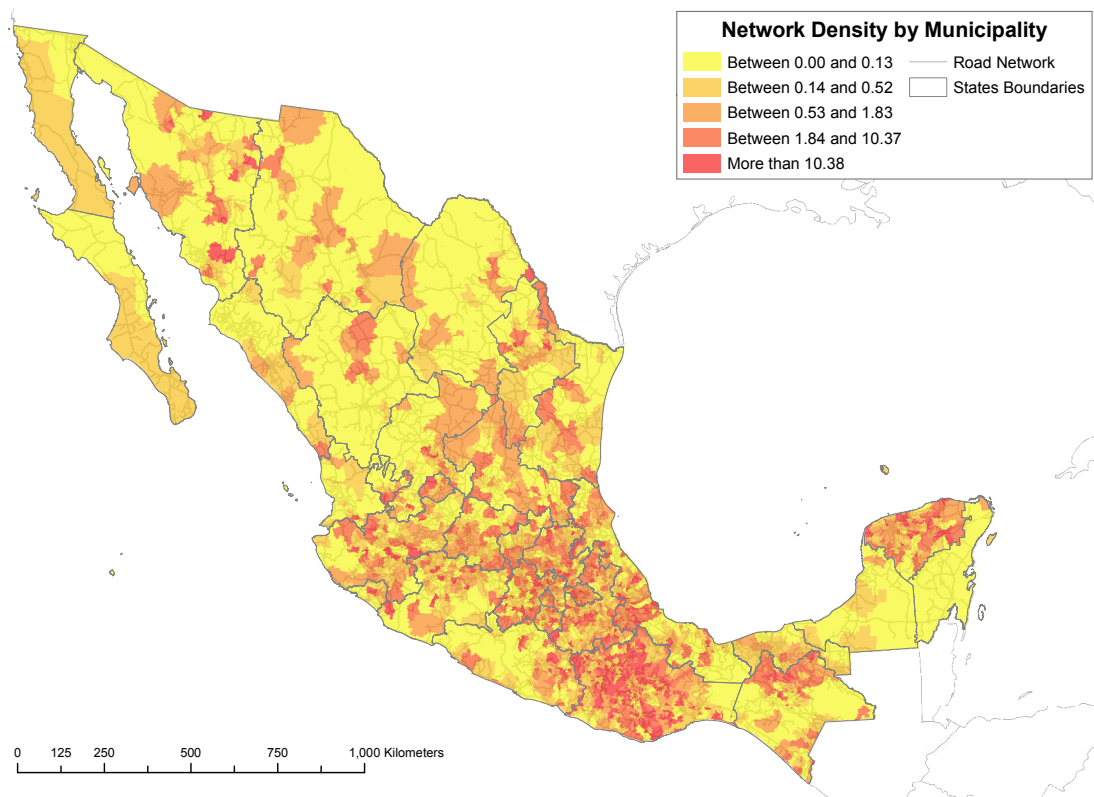


**Source:** Computations made by the author using data from INEGI.

Driving time is measured as the time it would take to go from a municipality to the closest water agency within each hydrological administrative region. The latter implies measuring the driving time between two points on the road network. I locate water agencies using their exact coordinates. Points representing municipalities refer to the location of the biggest population centre within each municipality (I consider this approach to be more accurate than using centroids). I use Arcinfo's Network Analyst to compute driving time. The algorithm used by Arcinfo provides the least costly route between two points over the network. The cost is expressed in terms of driving time. Driving time is computed for each segment of the network using the formula  $time = \frac{length}{speed}$ . Both the length and the driving speed (this refers to the estimated maximum speed for a vehicle) for each segment were computed by INEGI. Figure 2.10 shows the driving time between water agencies and municipalities. Average driving time across all municipalities is 2.1 hours, but it ranges from 0.1 to 10.8 hours. The least accessible municipalities are found in the states of Guerrero, Baja California Sur, and Chihuahua.

My second instrument, network density, is also built using GIS. I define network density as the ratio of the total amount of kilometres of roads (ranging from single roads to highways) over the area of each municipality. I use the same network dataset as in the case of driving time for computing the amount of kilometres of road. The average road density across municipalities is 10.9 Km of roads per Km<sup>2</sup>, this values goes from 0.0011 in a municipality in Chihuahua to 1366.69 in a municipality in Puebla.

**Figure 2.11** – Network density by municipality



**Source:** Computations made by the author using data from INEGI.



## 2.5 Results

I start the analysis considering deterrence variables to be exogenous. I begin by estimating different specifications of the baseline model described in Equation 2.3 using a negative binomial regression (NBRM). All these models exploit the variation across municipalities and include time and regional<sup>19</sup> dummies, while using robust standard errors clustered by municipality.

The estimates of the number of inspections and legal procedures are presented in Table 2.12. Since the main interest of my analysis relies on the models that consider inspections to be endogenous, I limit the results presented in this table to the estimates of inspections and legal procedures. The results including all covariates are presented in Table 2.17 in the Appendix. For specifications (1) and (2), I only consider the number of inspections as the main deterrence variable. In the first case, I use inspections for year  $t$  (*INSP*), while in the second case I use inspections for  $t - 1$ , i.e. inspections lagged one period (*INSP LAG*). Specification (3) considers both current and inspections lagged. Specification (4) only considers inspections lagged. Finally, specification (5) considers inspections lagged along with the lagged of the number of legal procedures launched against water users at the state level (*LEG LAG*).

The estimates of the number of inspections suggest a potential bias due to endogeneity. In all models, inspections are always positive and significant at 95%. The positive sign of these coefficients goes against the theoretical framework regarding deterrence described in the analytical framework. The latter points to a potential endogeneity problem. In this regard, specification

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<sup>19</sup> These regions refer to the 13 hydrological administrative regions on which water management is based on.

**Table 2.12** – Base-line model: negative binomial regression models (NBRM)

|                     | (1)                   | (2)                   | (3)                   | (4)                   | (5)                   |
|---------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| INSP                | 0.00339**<br>(1.98)   |                       | 0.000553<br>(0.38)    |                       |                       |
| INSP LAG            |                       | 0.00544***<br>(2.61)  | 0.00502**<br>(2.32)   |                       | 0.00538***<br>(2.66)  |
| LEG LAG             |                       |                       |                       | -0.00219*<br>(-1.67)  | -0.00215*<br>(-1.65)  |
| Constant            | -1.498***<br>(-8.52)  | -2.163***<br>(-7.45)  | -2.163***<br>(-7.45)  | -2.170***<br>(-7.35)  | -2.150***<br>(-7.38)  |
| Inalpha<br>Constant | -0.935***<br>(-17.42) | -0.935***<br>(-17.32) | -0.935***<br>(-17.32) | -0.934***<br>(-17.30) | -0.937***<br>(-17.36) |
| <i>AIC</i>          | 16703.6               | 16303.6               | 16305.6               | 16306.1               | 16302.1               |
| <i>BIC</i>          | 16866.4               | 16465.4               | 16473.3               | 16467.9               | 16469.9               |
| Log-likelihood      | -8324.8               | -8124.8               | -8124.8               | -8126.1               | -8123.0               |
| HAR Fixed effects:  | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   |
| Year Fixed effects: | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   |
| Observations        | 3069                  | 2958                  | 2958                  | 2958                  | 2958                  |

*t* statistics in parentheses

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

<sup>1</sup> The dependent variable is the number of IWU.

<sup>2</sup> Table 2.12 in the Appendix shows the results for all variables included in these models.

<sup>3</sup> Robust standard errors clustered by municipality.

(3) shows that even when controlling for both inspections and its lag the positive sign remains. Moreover, *INSP LAG* does not seem to be influenced by the presence of *LEG LAG*. An additional element to notice is that *LEG LAG* has a negative sign and is significant at 90%, with or without accounting for the lagged value of inspections.

Before moving onto models that explicitly account for endogeneity, I estimate the baseline model using zero-inflated and hurdle regression models. The latter follows from the fact that in the dependent variable approximatively to 15% of the observations are equal to zero. These results are presented in Table 2.18 in the Appendix. The results from both these models are similar to those of the NBRM. The zero-inflated model does not seem to be superior to the NBR based on the AIC and BIC criteria. However, under these criteria

the hurdle model does seem to be superior.

I relax the assumption of exogeneity and estimate the coefficient of the number of inspections through an instrumental variable approach. To this end, I use the driving time between the CONAGUA regional offices and each municipality as an instrumental variable. I instrument the number of inspections through three different types of count models that rely on GMM-based estimators. The first model considers the error term to be additive (GMM-S), the second considers it to be multiplicative (GMM-M) and the third one considers a two-step estimation commonly known as control function (GMM-CF). These three models are described in more detail in section 2.3.2.

The GMM-M and GMM-CF estimators seem to correct for the endogeneity bias. Table 2.13 shows the estimation results after controlling for endogeneity of inspections. For the latter, I focus on specifications (2) and (5) from Table 2.17. In both specifications, I only consider the lag of inspections (*INSP LAG*) to be endogenous. This follows from the fact that the sign of *LEG LAG* does not go against the theoretical framework. In (2) the number of legal actions against water users (*LEG LAG*) is not controlled for. In specification (5), I consider both *INSP LAG* and *LEG LAG*. I test these two specifications for the three count models that account for endogeneity. Results show that both GMM-M and GMM-CF estimators provide a negative and significant coefficient for inspections lagged. Moreover, the presence of *LEG LAG* does not have an influence on the coefficient of *INSP LAG*. Although the coefficients for *LEG LAG* given by GMM-M and GMM-CF are practically the same as that from the NBRM, none of them are statistically significant. Between these two models, GMM-CF provides a better adjustment with a Pseudo-R Square equal to 0.88.

The results from the GMM-M and GMM-CF estimators suggest that one additional inspection in the previous year can on average reduce the number of IWU in each municipality by 2% to 3%. However, since both estimators are non-linear, the effect of a covariate  $x_j$  over the dependent variable further depends on the level of  $x_j$  as well as on the rest of the covariates. For instance, Figure 2.12 shows the expected number of IWU according to the GMM-M count model when legal procedures are not controlled for. The estimate on the number of inspections provided by this model has a higher t-value and is more conservative than that from GMM-CF. According to this result, in order to halve the number of IWU, the number of inspection would have to go up on average from 2 to 36 per year. The marginal effect of the number of inspections is also non-linear. Figure 2.12 also depicts the marginal effect of increasing the number of inspections from 2 to 40 according to the estimates of the GMM-M model. This figure shows that the effect of inspections on the number of IWU decreases with the number of inspections.

The results from the models presented in Table 2.13 show that closed aquifers and prohibition zones are related in opposite ways to the number of IWU. Municipalities accounting for larger areas of closed aquifers have a lower number of IWU. Indeed, in all models *AQUIFER* is negative and significant. However, this is not the case for the variables accounting for prohibition zones (*VEDA I, II, III*). Prohibition zones of type I and II are only significant for GMM-M and GMM-CF models, having a positive sign in both cases.

With regard to the remaining covariates, only population density, mechanised area, and temperatures are significant. Table 2.13 shows that the coefficients of both population density and temperatures are positive. This suggests that, on average, IWU do not necessarily operate in remote areas, but tend to be close to populated centres. This may follow from the need to be close

to urban markets. IWU seem to be more present in areas with higher temperatures, even after controlling for regional differences through fixed effects. One possible reason for the latter is that higher temperatures may trigger the demand for water, but that due to institutional constraints limiting water extraction it may not be possible to legally access water. Hence, producers need to illegally extract water to satisfy their water needs. In contrast, IWU are less present in municipalities with larger extents of mechanised areas. The latter may be due to the fact that authorities tend to pay more attention to municipalities including irrigation districts, which also happen to be more visible for the authorities.

**Table 2.13** – Results from GMM-based count models controlling for the potential endogeneity of the number of inspections

|                     | GMM-S                  | GMM-S                  | GMM-M                   | GMM-M                   | GMM-CF                 | GMM-CF                 |
|---------------------|------------------------|------------------------|-------------------------|-------------------------|------------------------|------------------------|
| INSP LAG            | 0.00190<br>(0.24)      | 0.00191<br>(0.24)      | -0.0188**<br>(-2.34)    | -0.0184**<br>(-2.30)    | -0.0304*<br>(-1.95)    | -0.0301*<br>(-1.93)    |
| LEG LAG             | -0.000226<br>(-0.15)   |                        | -0.00204<br>(-1.30)     |                         | -0.00161<br>(-0.98)    |                        |
| AQUIFER             | -0.0000577*<br>(-1.66) | -0.0000578*<br>(-1.66) | -0.000116***<br>(-2.88) | -0.000119***<br>(-3.00) | -0.000109**<br>(-2.50) | -0.000110**<br>(-2.54) |
| VEDA I              | 0.000123<br>(1.25)     | 0.000122<br>(1.24)     | 0.000315***<br>(2.78)   | 0.000306***<br>(2.74)   | 0.000432**<br>(2.40)   | 0.000428**<br>(2.38)   |
| VEDA II             | 0.0000126<br>(0.48)    | 0.0000123<br>(0.47)    | 0.000119**<br>(2.34)    | 0.000112**<br>(2.24)    | 0.000110**<br>(2.08)   | 0.000105**<br>(2.00)   |
| VEDA III            | 0.00000127<br>(0.05)   | 0.00000108<br>(0.04)   | -0.0000338<br>(-1.33)   | -0.0000364<br>(-1.44)   | -0.0000191<br>(-0.62)  | -0.0000209<br>(-0.69)  |
| OUTPUT              | -0.000314<br>(-0.17)   | -0.000316<br>(-0.17)   | -0.000471<br>(-0.43)    | -0.000501<br>(-0.46)    | -0.000657<br>(-0.61)   | -0.000667<br>(-0.62)   |
| MECHA               | -4.107***<br>(-3.16)   | -4.127***<br>(-3.21)   | -3.030**<br>(-2.32)     | -3.169**<br>(-2.45)     | -2.626*<br>(-1.79)     | -2.736*<br>(-1.88)     |
| POP                 | 0.000161**<br>(2.01)   | 0.000161**<br>(2.02)   | 0.000207***<br>(3.22)   | 0.000203***<br>(3.19)   | 0.000207***<br>(3.08)  | 0.000205***<br>(3.06)  |
| DEPRIV              | 0.00180<br>(0.03)      | 0.00143<br>(0.02)      | -0.00558<br>(-0.13)     | -0.00870<br>(-0.20)     | -0.00788<br>(-0.18)    | -0.0106<br>(-0.24)     |
| TEMP                | 0.0558***<br>(4.72)    | 0.0559***<br>(4.74)    | 0.0308***<br>(4.31)     | 0.0308***<br>(4.30)     | 0.0318***<br>(4.40)    | 0.0318***<br>(4.39)    |
| RAIN                | 0.000883<br>(0.91)     | 0.000890<br>(0.91)     | 0.000417<br>(0.50)      | 0.000458<br>(0.55)      | 0.000629<br>(0.74)     | 0.000660<br>(0.77)     |
| Constant            | -2.412***<br>(-5.31)   | -2.415***<br>(-5.32)   | -1.784***<br>(-7.31)    | -1.792***<br>(-7.35)    | -1.799***<br>(-7.28)   | -1.806***<br>(-7.31)   |
| Pseudo-R Square     | 0.916                  | 0.916                  | 0.808                   | 0.816                   | 0.885                  | 0.886                  |
| HAR Fixed effects:  | Yes                    | Yes                    | Yes                     | Yes                     | Yes                    | Yes                    |
| Year Fixed effects: | Yes                    | Yes                    | Yes                     | Yes                     | Yes                    | Yes                    |
| Observations        | 2958                   | 2958                   | 2958                    | 2958                    | 2958                   | 2958                   |

*t* statistics in parentheses

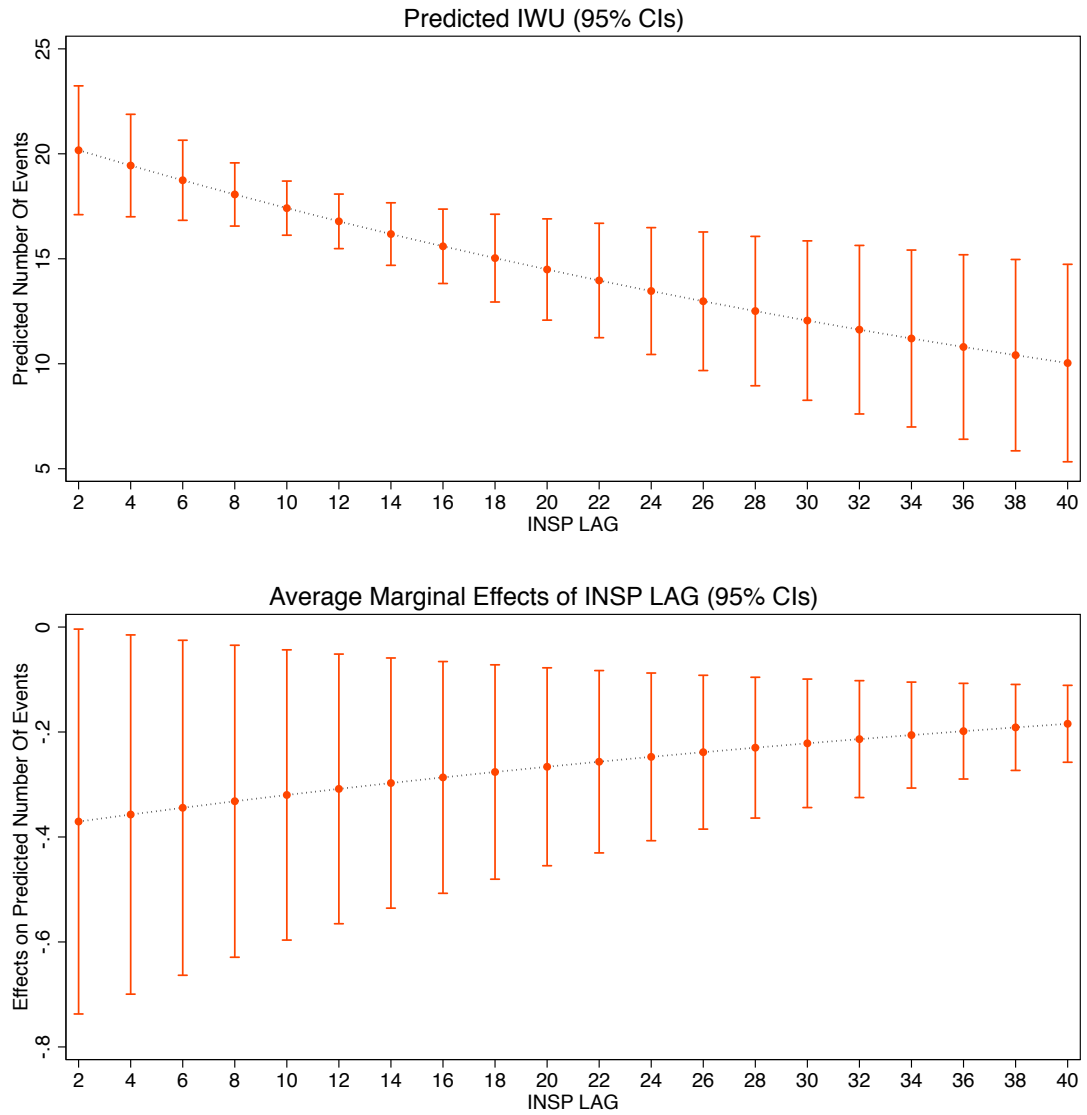
\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

<sup>1</sup> The dependent variable is the number of IWU; the endogenous variable is INSP LAG; and the instrument is the log of driving time.

<sup>2</sup> Robust standard errors clustered by municipality.

<sup>3</sup> Table 2.19 in the Appendix presents the estimation results of the first-step procedure of control function (CF) estimator.

**Figure 2.12** – Expected number of IWU and marginal effects due to different number of inspections implemented by CONAGUA during the previous year



**Note:** Expected number of counts at the top; marginal effects at the bottom. Marginal effects are computed as:  $\text{Marginal Effect of } x_j = \frac{\delta E[y|x]}{\delta x_j} = \frac{\delta \exp(x'\beta)}{\delta x_j} = \exp(x'\beta)\beta_j$

To test the validity of my results, I run the three count models accounting for endogeneity using driving time expressed as dummy variables. Indeed, instead of using the log of driving time I express this instrument as dummy variables that indicate 1, 2, 3 or more hours of driving time. Under this approach, in both GMM-M and GMM-CF models, the coefficient of the number of inspections is negative and significant, Table 2.14. However, in the case of the GMM-M model, this coefficient is bigger than that estimated through the log of driving time (-0.03 vs -0.01). Moreover, it is only significant at a 90% confidence level. The opposite happens to this coefficient in the case of the GMM-CF model, which goes from -0.03 to -0.01. The significance of this coefficient remains the same. With regard to other covariates, the coefficient of closed aquifers and that of mechanised area (for the GMM-CF model) are no longer significant. Another element to notice is that the Pseudo-R Square for the GMM-M model follows a significant reduction when using the instrument expressed as a dummy. This is not the case of the GMM-CF. Thus, in terms of goodness of fit, the GMM-CF appears to be more robust to the way in which the instrument is expressed.



**Table 2.14** – Results from GMM-based estimators controlling for endogeneity - alternative form of IV

|                     | GMM-S                 | GMM-S                 | GMM-M                 | GMM-M                 | GMM-CF                | GMM-CF                |
|---------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| INSP LAG            | -0.00559<br>(-0.18)   | -0.00484<br>(-0.16)   | -0.0350*<br>(-1.79)   | -0.0353*<br>(-1.85)   | -0.102*<br>(-1.84)    | -0.103*<br>(-1.84)    |
| LEG LAG             | -0.000282<br>(-0.17)  |                       | -0.00288<br>(-1.53)   |                       | -0.00187<br>(-0.80)   |                       |
| AQUIFER             | -0.0000599<br>(-1.20) | -0.0000608<br>(-1.21) | -0.0000827<br>(-1.22) | -0.0000868<br>(-1.31) | -0.0000914<br>(-0.96) | -0.0000919<br>(-0.97) |
| VEDA I              | 0.000191<br>(0.63)    | 0.000183<br>(0.60)    | 0.000491**<br>(2.10)  | 0.000489**<br>(2.17)  | 0.00118*<br>(1.92)    | 0.00118*<br>(1.92)    |
| VEDA II             | 0.0000105<br>(0.33)   | 0.00000976<br>(0.30)  | 0.000179*<br>(1.65)   | 0.000174<br>(1.63)    | 0.000208*<br>(1.79)   | 0.000203*<br>(1.76)   |
| VEDA III            | 0.00000674<br>(0.18)  | 0.00000586<br>(0.16)  | -0.0000531<br>(-1.29) | -0.0000578<br>(-1.39) | -0.0000140<br>(-0.23) | -0.0000159<br>(-0.27) |
| OUTPUT              | 0.0000652<br>(0.04)   | 0.0000717<br>(0.05)   | 0.000158<br>(0.09)    | 0.000155<br>(0.09)    | -0.000329<br>(-0.19)  | -0.000342<br>(-0.20)  |
| MECHA               | -3.323**<br>(-2.16)   | -3.377**<br>(-2.19)   | -2.631*<br>(-1.65)    | -2.788*<br>(-1.79)    | 0.0160<br>(0.01)      | -0.0926<br>(-0.03)    |
| POP                 | 0.000167<br>(1.56)    | 0.000165<br>(1.55)    | 0.000297*<br>(1.71)   | 0.000293*<br>(1.75)   | 0.000351**<br>(2.30)  | 0.000350**<br>(2.29)  |
| DEPRIV              | -0.0368<br>(-0.22)    | -0.0339<br>(-0.21)    | -0.0668<br>(-0.71)    | -0.0751<br>(-0.81)    | -0.129<br>(-1.25)     | -0.133<br>(-1.29)     |
| TEMP                | 0.0525***<br>(3.67)   | 0.0529***<br>(3.66)   | 0.0294***<br>(3.70)   | 0.0292***<br>(3.66)   | 0.0313***<br>(3.65)   | 0.0313***<br>(3.64)   |
| RAIN                | 0.00102<br>(0.68)     | 0.00100<br>(0.68)     | 0.000378<br>(0.44)    | 0.000434<br>(0.51)    | 0.000995<br>(0.98)    | 0.00103<br>(1.01)     |
| Constant            | -2.417***<br>(-4.51)  | -2.417***<br>(-4.56)  | -1.835***<br>(-7.07)  | -1.846***<br>(-7.12)  | -1.942***<br>(-6.67)  | -1.951***<br>(-6.71)  |
| Pseudo-R Square     | 0.910                 | 0.911                 | 0.656                 | 0.664                 | 0.888                 | 0.889                 |
| HAR Fixed effects:  | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   |
| Year Fixed effects: | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   |
| Observations        | 2958                  | 2958                  | 2958                  | 2958                  | 2958                  | 2958                  |

*t* statistics in parentheses

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

<sup>1</sup> The dependent variable is the number of IWU; the endogenous variable is INSP LAG; and the instruments are the dummy variables of driving time for 2, 3, or more than 3 hours.

<sup>2</sup> Robust standard errors clustered by municipality.

<sup>3</sup> Table 2.20 in the Appendix presents the estimation results of the first-step procedure of control function (CF) estimator.

I corroborate the validity of driving time as an instrumental variable through an over-identification test. For this test, I rely on a second instrument. My second instrument is the density of the road network in each municipality. In general terms, this instrument captures the connectivity of a municipality. Better connected municipalities could be easier to reach by environmental authorities, thus more likely to be visited. Although this instrument is related to accessibility, it is not strongly correlated with driving time, having a correlation coefficient of -0.05. From Table 2.21, it can be observed that both instruments are significant in what could be considered the first step of the GMM-CF estimator.

The results from the three count models using both instruments are presented in Table 2.15. The coefficients of both GMM-M and GMM-CF are significant and negative. Moreover, their values do not differ much from that using driving time as the only instrument. In the case of the GMM-M model, adding the second instrument translates into a higher goodness of fit. In the case of the GMM-CF model, the additional instrument does not affect the goodness of fit but does slightly lower the value of the inspection coefficient from -0.03 to -0.026. Table 2.15 also shows the values of the Hansen's J Chi-square statistic for models GMM-S and GMM-M. In the latter case, this statistic equals 1.416 (p-value of 0.234) when the number of legal procedures is not controlled for and 0.219 when it is. Based on these results, I do not reject the hypothesis of over-identification. Although this test does not evaluate the quality of the instrument, these results provide additional information to support the use of driving time as a valid instrument for the number of inspections. The results of the remaining covariates mimic those of the models estimated using the log of driving time as the only instrument.

**Table 2.15** – Results from GMM-based estimators controlling for endogeneity - log of driving time and network density used as instruments

|                     | GMM-S                 | GMM-S                 | GMM-M                   | GMM-M                   | GMM-CF                  | GMM-CF                  |
|---------------------|-----------------------|-----------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| INSP LAG            | 0.00390<br>(0.54)     | 0.00394<br>(0.54)     | -0.0183**<br>(-2.28)    | -0.0179**<br>(-2.23)    | -0.0263*<br>(-1.79)     | -0.0261*<br>(-1.78)     |
| LEG LAG             | -0.000297<br>(-0.20)  |                       | -0.00210<br>(-1.34)     |                         | -0.00158<br>(-0.97)     |                         |
| AQUIFER             | -0.0000579<br>(-1.64) | -0.0000580<br>(-1.64) | -0.000118***<br>(-2.97) | -0.000120***<br>(-3.08) | -0.000110***<br>(-2.67) | -0.000111***<br>(-2.70) |
| VEDA I              | 0.000100<br>(1.09)    | 0.0000990<br>(1.07)   | 0.000307***<br>(2.72)   | 0.000298***<br>(2.68)   | 0.000388**<br>(2.30)    | 0.000384**<br>(2.28)    |
| VEDA II             | 0.0000119<br>(0.46)   | 0.0000115<br>(0.45)   | 0.000118**<br>(2.35)    | 0.000111**<br>(2.24)    | 0.000105**<br>(2.06)    | 0.0000994**<br>(1.98)   |
| VEDA III            | 0.00000293<br>(0.11)  | 0.00000271<br>(0.10)  | -0.0000353<br>(-1.39)   | -0.0000381<br>(-1.50)   | -0.0000203<br>(-0.70)   | -0.0000220<br>(-0.76)   |
| OUTPUT              | -0.000194<br>(-0.11)  | -0.000197<br>(-0.11)  | -0.000522<br>(-0.48)    | -0.000550<br>(-0.51)    | -0.000714<br>(-0.67)    | -0.000723<br>(-0.68)    |
| MECHA               | -4.077***<br>(-3.18)  | -4.105***<br>(-3.23)  | -3.006**<br>(-2.31)     | -3.142**<br>(-2.44)     | -2.818**<br>(-1.99)     | -2.923**<br>(-2.07)     |
| POP                 | 0.000155**<br>(2.00)  | 0.000155**<br>(2.01)  | 0.000204***<br>(3.21)   | 0.000200***<br>(3.18)   | 0.000199***<br>(3.06)   | 0.000197***<br>(3.04)   |
| DEPRIV              | 0.0106<br>(0.16)      | 0.0103<br>(0.16)      | -0.00606<br>(-0.14)     | -0.00935<br>(-0.21)     | -0.000920<br>(-0.02)    | -0.00374<br>(-0.08)     |
| TEMP                | 0.0557***<br>(4.70)   | 0.0559***<br>(4.72)   | 0.0307***<br>(4.30)     | 0.0307***<br>(4.29)     | 0.0317***<br>(4.42)     | 0.0317***<br>(4.41)     |
| RAIN                | 0.000900<br>(0.93)    | 0.000906<br>(0.93)    | 0.000469<br>(0.56)      | 0.000509<br>(0.61)      | 0.000617<br>(0.72)      | 0.000648<br>(0.76)      |
| Constant            | -2.387***<br>(-5.31)  | -2.390***<br>(-5.32)  | -1.785***<br>(-7.32)    | -1.793***<br>(-7.36)    | -1.792***<br>(-7.28)    | -1.799***<br>(-7.31)    |
| Pseudo-R Square     | 0.917                 | 0.917                 | 0.807                   | 0.815                   | 0.883                   | 0.884                   |
| Hansen's J          | 0.743                 | 0.754                 | 1.508                   | 1.416                   |                         |                         |
| Hansen's J p-value  | 0.389                 | 0.385                 | 0.219                   | 0.234                   |                         |                         |
| HAR Fixed effects:  | Yes                   | Yes                   | Yes                     | Yes                     | Yes                     | Yes                     |
| Year Fixed effects: | Yes                   | Yes                   | Yes                     | Yes                     | Yes                     | Yes                     |
| Observations        | 2958                  | 2958                  | 2958                    | 2958                    | 2958                    | 2958                    |

*t* statistics in parentheses

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

<sup>1</sup> The dependent variable is the number of IWU; the endogenous variable is INSP LAG; and the instruments are the log of driving and the density of the road network.

<sup>2</sup> Robust standard errors clustered by municipality.

<sup>3</sup> Table 2.21 in the Appendix presents the results for these estimators including all covariates.

## Conclusions

The objective of this paper is to analyse the drivers of illegal groundwater extraction in Mexico. To this end, I use a unique dataset that includes information on the number of illegal water users at municipal level. Illegal water users (IWU) are those irrigators lacking a valid concession for extracting groundwater. Based on Becker's analysis of public enforcement, I focus my analysis on the effects of inspection visits as one of the main policy tools limiting the number of IWU in each municipality.

The endogeneity characterising enforcement efforts, and in particular the number of inspections, has been a key challenge within the framework of this analysis. Indeed, inspections are not random; instead they tend to focus on specific geographic areas considered to be a priority for basin councils and regional offices. Moreover, due to transaction costs, inspections tend to be more frequent in municipalities closer to CONAGUA's offices. Based on the latter, I use the driving time between each municipality and the closest CONAGUA office within a water administrative region as an instrument for the number of inspections.

After controlling for the endogeneity of the number of inspections, my results show that one additional inspection can on average reduce the number of IWU by 1% to 3% percent. Moreover, this effect seems to decrease as long as inspections increase. Although this effect appears to be strong, and bearing in mind the low frequency of inspections alone may not be an effective tool for granting water sustainability. Indeed, during the period of analysis (2007-2009), the average number of inspections per municipality was only as high as two. In other words, if the enforcement capacity of regional authorities does not increase - and if the number of inspections remains low - the inspections

programme risks having a limited impact for curbing groundwater overdraft.

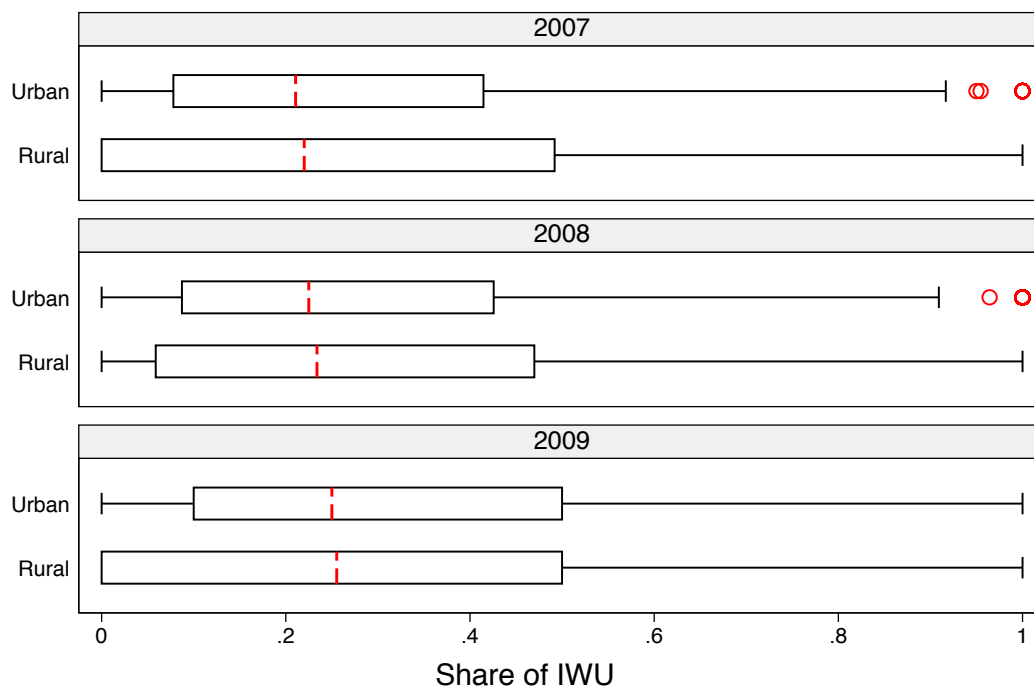
Price mechanisms remain a key instrument for promoting the sustainability of groundwater resources, but their reform may promote illegality. Electricity subsidies, provided to concession holders, are considered to be a key factor promoting inadequate levels of water pumping. However, at the same time, they are one of the main reasons for adopting a concession. Decoupling electricity subsidies, while maintaining the current level of enforcement, will remove the incentives for water users to have a concession, and most likely increase the number of IWU. Thus, how much decoupling should take place in order to maintain the incentives for legal water users, whilst better reflecting the scarcity of groundwater resources? This question is out of the scope of this paper, but it is certainly an area for future research.

My results further highlight some structural characteristics between municipalities with high numbers of IWU and those without. For instance, municipalities accounting for a larger extent of aquifers suffering from groundwater overdraft host a smaller number of IWU. This holds even when controlling for the number of inspections. One reason for low counts of IWU in overexploited aquifers could be that, in areas suffering from high levels of water stress local, actors find ways to coordinate and limit the negative effects of overdraft. Moreover, these areas tend to be more frequently inspected by authorities. Another interesting result concerns the differences in terms of temperature across areas with high and low numbers of IWU. In every model, even when controlling for regional differences, municipalities with higher temperatures are characterised by higher IWU. The effect of temperature on the number of IWU is not negligible, around 5% following an increase of one degree Celsius. This points to new directions in which changes in weather patterns could further affect environmental compliance.

There are certain caveats regarding this analysis that should be mentioned. In the first place, my analysis exploits the spatial variation across municipalities. Although I control for regional and time effects, it is possible that unobservable heterogeneity at the municipal level affects the results of the analysis. In the second place, my analysis does not control for the level of fines across municipalities. It is thus possible that inspections capture part of the effect of fines. Finally, my analysis considers the effect of inspections across the country. However, a spatial heterogeneity in the effectiveness of the inspections programme may exist. In other words, in some regions of the country producers may be more responsive to deterrence mechanisms. A possible way to improve the analysis could be by accounting for potential spatial heterogeneity.

## 2.A Appendix: Chapter 2

**Figure 2.13** – Distribution of the share of IWU between rural and urban areas, 2007 - 2009.



Graphs by Year

**Source:** Computations made by the author using data provided by the CFE. Red dash line represents the median of the distribution.

**Table 2.16** – Does driving time influence the number of inspections?

|                     | Probit                | Probit                | Probit                | OLS                  | OLS                  | OLS                  |
|---------------------|-----------------------|-----------------------|-----------------------|----------------------|----------------------|----------------------|
| AQUIFER             | 0.000180**<br>(2.46)  | 0.000162**<br>(2.24)  | 0.000171**<br>(2.30)  | 0.00268*<br>(1.67)   | 0.00238<br>(1.57)    | 0.00260<br>(1.64)    |
| OUTPUT              | 0.00784**<br>(2.07)   | 0.00807**<br>(2.06)   | 0.00801**<br>(2.18)   | 0.00909<br>(0.47)    | 0.0123<br>(0.66)     | 0.00951<br>(0.49)    |
| MECHA               | 12.11***<br>(3.25)    | 12.09***<br>(3.26)    | 12.13***<br>(3.41)    | 18.14<br>(0.84)      | 12.43<br>(0.57)      | 17.11<br>(0.79)      |
| POP                 | 0.000399***<br>(3.71) | 0.000278***<br>(3.09) | 0.000311***<br>(3.28) | 0.00206***<br>(3.24) | 0.000922*<br>(1.79)  | 0.00173***<br>(2.80) |
| DEPRIV              | -0.481***<br>(-9.60)  | -0.417***<br>(-8.14)  | -0.440***<br>(-8.85)  | -1.655***<br>(-6.15) | -0.909***<br>(-3.67) | -1.423***<br>(-5.45) |
| Ln TIME             |                       | -0.163***<br>(-4.77)  |                       |                      | -1.820***<br>(-4.20) |                      |
| TIME 2HR            |                       |                       | -0.362***<br>(-5.30)  |                      |                      | -1.601***<br>(-4.18) |
| TIME 3HR            |                       |                       | -0.430***<br>(-4.97)  |                      |                      | -1.446***<br>(-3.05) |
| TIME 3HR+           |                       |                       | -0.182**<br>(-2.16)   |                      |                      | -1.320*<br>(-1.87)   |
| Constant            | -0.858***<br>(-4.38)  | -0.794***<br>(-4.08)  | -0.608***<br>(-2.95)  | -1.667**<br>(-2.57)  | -0.818<br>(-1.34)    | -0.491<br>(-0.72)    |
| <i>AIC</i>          | 5032.6                | 4994.7                | 4979.5                | 31257.2              | 31052.1              | 31230.9              |
| <i>BIC</i>          | 5167.6                | 5136.1                | 5133.7                | 31392.2              | 31193.5              | 31385.2              |
| HAR Fixed effects:  | Yes                   | Yes                   | Yes                   | Yes                  | Yes                  | Yes                  |
| Year Fixed effects: | Yes                   | Yes                   | Yes                   | Yes                  | Yes                  | Yes                  |
| Observations        | 4568                  | 4568                  | 4568                  | 4568                 | 4568                 | 4568                 |

*t* statistics in parentheses

Note: Cluster-robust standard errors by municipality.

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$



**Table 2.17** – Base-line model: negative binomial regression models (NBRM)

|                     | (1)                      | (2)                     | (3)                     | (4)                     | (5)                      |
|---------------------|--------------------------|-------------------------|-------------------------|-------------------------|--------------------------|
| AQUIFER             | -0.0000981***<br>(-3.34) | -0.000101***<br>(-3.40) | -0.000101***<br>(-3.38) | -0.000101***<br>(-3.39) | -0.0000996***<br>(-3.35) |
| VEDA I              | 0.0000791**<br>(2.30)    | 0.0000523<br>(1.38)     | 0.0000522<br>(1.38)     | 0.000108***<br>(3.44)   | 0.0000544<br>(1.46)      |
| VEDA II             | 0.0000300<br>(0.95)      | 0.0000389<br>(1.22)     | 0.0000379<br>(1.17)     | 0.0000546*<br>(1.66)    | 0.0000454<br>(1.39)      |
| VEDA III            | -0.0000228<br>(-1.30)    | -0.0000173<br>(-1.02)   | -0.0000182<br>(-1.04)   | -0.0000153<br>(-0.88)   | -0.0000151<br>(-0.89)    |
| OUTPUT              | -0.000724<br>(-0.70)     | -0.000718<br>(-0.69)    | -0.000710<br>(-0.69)    | -0.000701<br>(-0.68)    | -0.000700<br>(-0.68)     |
| MECHA               | -4.196***<br>(-3.68)     | -4.339***<br>(-3.79)    | -4.333***<br>(-3.79)    | -3.952***<br>(-3.48)    | -4.182***<br>(-3.67)     |
| POP                 | 0.000153***<br>(2.97)    | 0.000172***<br>(3.51)   | 0.000171***<br>(3.51)   | 0.000189***<br>(3.87)   | 0.000174***<br>(3.56)    |
| DEPRIV              | 0.0264<br>(0.81)         | 0.0387<br>(1.17)        | 0.0390<br>(1.18)        | 0.0296<br>(0.91)        | 0.0430<br>(1.29)         |
| TEMP                | 0.0429***<br>(6.30)      | 0.0430***<br>(6.27)     | 0.0431***<br>(6.26)     | 0.0424***<br>(6.20)     | 0.0427***<br>(6.24)      |
| RAIN                | 0.000793<br>(1.09)       | 0.000642<br>(0.89)      | 0.000636<br>(0.88)      | 0.000641<br>(0.89)      | 0.000592<br>(0.82)       |
| INSP                | 0.00339**<br>(1.98)      |                         | 0.000553<br>(0.38)      |                         |                          |
| INSP LAG            |                          | 0.00544***<br>(2.61)    | 0.00502**<br>(2.32)     |                         | 0.00538***<br>(2.66)     |
| LEG LAG             |                          |                         |                         | -0.00219*<br>(-1.67)    | -0.00215*<br>(-1.65)     |
| Constant            | -1.498***<br>(-8.52)     | -2.163***<br>(-7.45)    | -2.163***<br>(-7.45)    | -2.170***<br>(-7.35)    | -2.150***<br>(-7.38)     |
| lnalpha<br>Constant | -0.935***<br>(-17.42)    | -0.935***<br>(-17.32)   | -0.935***<br>(-17.32)   | -0.934***<br>(-17.30)   | -0.937***<br>(-17.36)    |
| <i>AIC</i>          | 16703.6                  | 16303.6                 | 16305.6                 | 16306.1                 | 16302.1                  |
| <i>BIC</i>          | 16866.4                  | 16465.4                 | 16473.3                 | 16467.9                 | 16469.9                  |
| HAR Fixed effects:  | Yes                      | Yes                     | Yes                     | Yes                     | Yes                      |
| Year Fixed effects: | Yes                      | Yes                     | Yes                     | Yes                     | Yes                      |
| Observations        | 3069                     | 2958                    | 2958                    | 2958                    | 2958                     |

*t* statistics in parentheses

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

<sup>1</sup> The dependent variable is the number of IWU.

<sup>2</sup> Additional controls include the area of municipalities.

<sup>3</sup> Robust standard errors clustered by municipality.

Table 2.18 – Comparison with zero-inflated and hurdle models

|                     | Negative Binomial        | Zero Inflated            |                       | Hurdle                   |                      |
|---------------------|--------------------------|--------------------------|-----------------------|--------------------------|----------------------|
|                     | NBR                      | NBR                      | Logit                 | NBR                      | Logit                |
| AQUIFER             | -0.0000996***<br>(-3.35) | -0.0000944***<br>(-3.21) | 0.000750*<br>(1.65)   | -0.0000951***<br>(-3.24) | -0.000336<br>(-1.14) |
| VEDA I              | 0.0000544<br>(1.46)      | 0.0000551<br>(1.49)      | -0.179*<br>(-1.76)    | 0.0000626*<br>(1.71)     | 0.00347<br>(0.50)    |
| VEDA II             | 0.0000454<br>(1.39)      | 0.0000549*<br>(1.65)     | 0.00274**<br>(2.41)   | 0.0000415<br>(1.30)      | 0.000313<br>(1.19)   |
| VEDA III            | -0.0000151<br>(-0.89)    | -0.0000150<br>(-0.89)    | -0.00654**<br>(-1.98) | -0.0000177<br>(-1.05)    | 0.0000533<br>(0.23)  |
| OUTPUT              | -0.000700<br>(-0.68)     | -0.000848<br>(-0.79)     | -0.258**<br>(-2.08)   | -0.000535<br>(-0.51)     | 0.00164<br>(0.33)    |
| MECHA               | -4.182***<br>(-3.67)     | -3.945***<br>(-3.53)     | 52.10**<br>(2.39)     | -3.667***<br>(-3.29)     | -4.382<br>(-0.35)    |
| POP                 | 0.000174***<br>(3.56)    | 0.000195***<br>(3.79)    | 0.00103**<br>(2.02)   | 0.000226***<br>(4.00)    | -0.000231<br>(-1.43) |
| DEPRIV              | 0.0430<br>(1.29)         | 0.0364<br>(1.09)         | -1.432**<br>(-2.34)   | 0.0143<br>(0.40)         | 0.135<br>(1.05)      |
| TEMP                | 0.0427***<br>(6.24)      | 0.0413***<br>(5.99)      | -0.0545<br>(-0.31)    | 0.0458***<br>(6.27)      | 0.00923<br>(0.39)    |
| RAIN                | 0.000592<br>(0.82)       | 0.000597<br>(0.83)       | -0.00802<br>(-0.50)   | 0.000142<br>(0.20)       | 0.00180<br>(0.68)    |
| INSP LAG            | 0.00538***<br>(2.66)     | 0.00478**<br>(2.36)      | -0.0989<br>(-0.39)    | 0.00432**<br>(2.17)      | 0.0618**<br>(2.41)   |
| LEG LAG             | -0.00215*<br>(-1.65)     | -0.00247*<br>(-1.89)     | -0.359***<br>(-3.87)  | -0.00252*<br>(-1.86)     | 0.0119*<br>(1.92)    |
| Constant            | -2.150***<br>(-7.38)     | -2.162***<br>(-7.25)     | -0.337<br>(-0.12)     | -2.544***<br>(-6.45)     | -0.529<br>(-0.60)    |
| <i>AIC</i>          | 16302.1                  | 16310.3                  |                       | 16197.1                  |                      |
| <i>BIC</i>          | 16469.9                  | 16567.9                  |                       | 16526.6                  |                      |
| HAR Fixed effects:  | Yes                      | Yes                      |                       | Yes                      |                      |
| Year Fixed effects: | Yes                      | Yes                      |                       | Yes                      |                      |
| Observations        | 2958                     | 2958                     |                       | 2958                     |                      |

*t* statistics in parentheses

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

<sup>1</sup> The dependent variable is the number of IWU.

<sup>2</sup> Additional controls include the area of municipalities.

<sup>3</sup> Robust standard errors clustered by municipality.

**Table 2.19** – First step of control function; dependent variable: number of inspections; instrument: log of driving time

|                     | Control Function     | Control Function     |
|---------------------|----------------------|----------------------|
| LEG LAG             | 0.0000682<br>(0.00)  |                      |
| AQUIFER             | 0.0000175<br>(0.02)  | 0.0000175<br>(0.02)  |
| VEDA I              | 0.0101***<br>(11.34) | 0.0101***<br>(11.32) |
| VEDA II             | 0.00148**<br>(2.49)  | 0.00148**<br>(2.51)  |
| VEDA III            | 0.0000447<br>(0.10)  | 0.0000448<br>(0.10)  |
| OUTPUT              | 0.00770<br>(0.62)    | 0.00770<br>(0.62)    |
| MECHA               | 32.41**<br>(2.07)    | 32.41**<br>(2.08)    |
| POP                 | 0.000891*<br>(1.68)  | 0.000891*<br>(1.67)  |
| DEPRIV              | -0.882***<br>(-3.43) | -0.882***<br>(-3.44) |
| TEMP                | 0.0736*<br>(1.88)    | 0.0736*<br>(1.88)    |
| RAIN                | 0.00947**<br>(2.40)  | 0.00947**<br>(2.38)  |
| Ln TIME             | -1.924***<br>(-4.26) | -1.924***<br>(-4.25) |
| Constant            | -2.656***<br>(-3.07) | -2.655***<br>(-3.09) |
| $\rho$              | 0.0407**<br>(2.52)   | 0.0405**<br>(2.51)   |
| HAR Fixed effects:  | Yes                  | Yes                  |
| Year Fixed effects: | Yes                  | Yes                  |
| Observations        | 2958                 | 2958                 |

*t* statistics in parentheses

Note: Robust SE clustered by municipality.

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

**Table 2.20** – First step of control function; dependent variable: number of inspections; instrument: dummies for driving time

|                     | Control Function     | Control Function     |
|---------------------|----------------------|----------------------|
| LEG LAG             | -0.00404<br>(-0.25)  |                      |
| AQUIFER             | 0.000208<br>(0.25)   | 0.000208<br>(0.25)   |
| VEDA I              | 0.0104***<br>(10.72) | 0.0104***<br>(10.73) |
| VEDA II             | 0.00138**<br>(2.10)  | 0.00137**<br>(2.11)  |
| VEDA III            | 0.0000693<br>(0.15)  | 0.0000667<br>(0.14)  |
| OUTPUT              | 0.00600<br>(0.45)    | 0.00593<br>(0.45)    |
| MECHA               | 37.67**<br>(2.37)    | 37.32**<br>(2.37)    |
| POP                 | 0.00181***<br>(2.70) | 0.00180***<br>(2.70) |
| DEPRIV              | -1.485***<br>(-5.13) | -1.492***<br>(-5.14) |
| TEMP                | 0.0132<br>(0.31)     | 0.0136<br>(0.32)     |
| RAIN                | 0.00670*<br>(1.70)   | 0.00676*<br>(1.70)   |
| TIME 2HR            | -1.269***<br>(-3.40) | -1.271***<br>(-3.39) |
| TIME 3HR            | -1.229***<br>(-2.75) | -1.223***<br>(-2.77) |
| TIME 3HR+           | -0.994*<br>(-1.78)   | -0.997*<br>(-1.78)   |
| Constant            | -1.583<br>(-1.50)    | -1.602<br>(-1.53)    |
| $\rho$              | 0.110**<br>(1.98)    | 0.111**<br>(1.98)    |
| HAR Fixed effects:  | Yes                  | Yes                  |
| Year Fixed effects: | Yes                  | Yes                  |
| Observations        | 2958                 | 2958                 |

*t* statistics in parentheses

Note: Robust SE clustered by municipality.

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

**Table 2.21** – First step of control function; dependent variable: number of inspections; instrument: log of driving time and network density

|                     | CF                   | CF                   |
|---------------------|----------------------|----------------------|
| LEG LAG             | -0.000517<br>(-0.03) |                      |
| AQUIFER             | 0.0000309<br>(0.04)  | 0.0000308<br>(0.04)  |
| VEDA I              | 0.0102***<br>(11.52) | 0.0102***<br>(11.50) |
| VEDA II             | 0.00146**<br>(2.48)  | 0.00146**<br>(2.51)  |
| VEDA III            | 0.0000985<br>(0.21)  | 0.0000982<br>(0.21)  |
| OUTPUT              | 0.00732<br>(0.59)    | 0.00731<br>(0.59)    |
| MECHA               | 30.77**<br>(1.99)    | 30.72**<br>(1.99)    |
| POP                 | 0.000912*<br>(1.73)  | 0.000912*<br>(1.72)  |
| DEPRIV              | -0.823***<br>(-3.27) | -0.824***<br>(-3.28) |
| TEMP                | 0.0640*<br>(1.67)    | 0.0641*<br>(1.67)    |
| RAIN                | 0.00893**<br>(2.26)  | 0.00894**<br>(2.25)  |
| Ln TIME             | -1.950***<br>(-4.33) | -1.950***<br>(-4.32) |
| Ln NET              | -0.166***<br>(-2.60) | -0.166***<br>(-2.60) |
| Constant            | -2.398***<br>(-2.87) | -2.400***<br>(-2.88) |
| $\rho$              | 0.0363**<br>(2.38)   | 0.0362**<br>(2.37)   |
| HAR Fixed effects:  | Yes                  | Yes                  |
| Year Fixed effects: | Yes                  | Yes                  |
| Observations        | 2958                 | 2958                 |

*t* statistics in parentheses

Note: Robust SE clustered by municipality.

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

**Figure 2.14** – Mexico's political division: states





## Chapter 3

Do climatic events influence internal migration? Evidence from Mexico



### 3.1 Introduction

A growing body of evidence suggests that changes in both the quality of the environment and climatic patterns influence human migrations. Emerging economies like Mexico, characterised by a large territory, a wide range of climates, and large migration flows are particularly concerned by this issue. Internal migration has played a key role in the development process of Mexico, but until today there is little evidence on how this process has been influenced by natural phenomena like the excess or lack of precipitation. Although academics and international organisations have mostly focused on international migration, Mexico being one of the most important migration corridors in the world, internal migration accounts today for a much larger flow of population. Demographic changes, human capital accumulation, and higher costs for crossing the border have contributed to reducing the migration flow to the United States during the last couple of decades (Ríos, 2012). During the period 2005-2010, the migration flow across Mexican states represented 3.3% of the total population in the country, compared to 1.1% for the population moving to another country (INEGI, 2010b). There are many *pull* factors promoting internal migration. These include, for instance, better job opportunities, higher expected income, and overall a better quality of life in other regions (Lucas, 1994); in parallel, internal migration is further influenced by *push* factors, such as armed conflicts and lower wages in dominant sectors like agriculture in the place of origin (Raleigh, 2011). Moreover, a growing number of studies has recognised the influence of a decrease in environmental quality, natural disasters, and climate change as push factors for migration (Laczko and Aghazarm, 2009; Lilleør and Van den Broeck, 2011; Hugo, 2011). However, in spite of the environmental challenges that Mexico

is to face in the next decades, there is little we know about the effects of environmental changes on internal migration. This paper contributes to the literature by analysing the effects of earthquakes, hurricanes, droughts, and floods on internal migration flows in Mexico.

Climate change is expected to have significant and negative impacts on Mexico, but the extent of these impacts could be different across regions. Recent projections suggest that by the end of the century temperatures may increase between 1 and 4 degrees Celsius, while rainfall could decrease by 11%. Moreover, these projections further suggest that effects will be stronger in northern and northwestern areas of Mexico, which are characterised by arid climates (Estrada et al., 2013). Higher temperatures and rainfall shortages will impose additional pressure on hydric resources, further reducing environmental quality and increasing the economic and social costs associated to adaptation. For instance, Skoufias et al. (2011) find that weather shocks associated to changes in rainfall and temperatures have both negative and positive impacts on consumption per capita and child height-for-age across Mexican households.

Groundwater will be particularly sensitive to these changes. Some Mexican regions are already experiencing high levels of water stress. The number of Mexican aquifers classified as overexploited or suffering from salinisation problems has significantly increased in the past decades<sup>1</sup>, which has further increased the pressure on hydric systems in central and northern regions where population and economic activities are concentrated. According to the Mexican National Water Commission (CONAGUA), in 2013 there were

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<sup>1</sup> Mexican authorities consider an aquifer to be overexploited when the amount of water extracted is higher than the amount of water filtering in and recharging the aquifer within a given period of time.

101 (out of 653) aquifers in the country classified as overexploited, compared to 32 overexploited aquifers in 1975. Moreover, during the same year, 76 additional aquifers were considered to be at risk of overdraft, 16 aquifers suffering from seawater intrusion, and 32 suffering from salinisation problems (CONAGUA, 2014). Overexploited aquifers in Mexico supply up to 50% of all the groundwater consumed in the country (CONAGUA, 2014). Moreover, in 2010, 70% of the water consumed in Mexican cities came from groundwater reservoirs, making aquifers the main source of freshwater for 75 million people (CONAGUA, 2010). This suggests that, even under a conservative scenario, climatic changes are expected to have important effects on the well-being of the population.

There is no clear answer on how the Mexican population will react to future climatic and environmental changes. Moreover, it is not clear either whether these changes will impact migration. As noted by Millock (2015), migration is one of many possible strategies that individuals can adopt following environmental changes. For instance, economic activities in rural areas tend to rely on the environment as an input for production, which makes the population in these areas particularly exposed to environmental changes. For these populations, migration may not necessarily be an optimal choice, instead their adaptation strategies may rely on off-farm activities, a diversification of crops produced, adoption of new technologies, etc. Adaptation strategies depend on the vulnerability of the individuals exposed to environmental changes, which in turn depends on household characteristics (e.g. composition, human capital, types and amount of assets), as well as on the type and magnitude of the environmental change. Indeed, some drastic and unexpected environmental changes such as earthquakes and hurricanes may trigger the decision to migrate in the short-term. Changes in the climate pat-

tern such as the gradual decrease in rainfall or the increase in temperatures may influence migration in the long-term. In these cases, environmental and climatic changes are considered to act as push factors for migration. In other cases, environmental changes can also act as pull factors when the decision to migrate is based on valuable environmental amenities or public goods in the place of destination<sup>2</sup>. A better understanding of environmental-induced migration, as well as of the channels through which it takes place, will be key for evidence-based policy making in Mexico.

What do previous empirical studies tell us about environmental-driven migration? Although results are mixed, the bulk of the literature suggests that environmental changes influence migration through direct and indirect channels. However, due to the differences in migration costs, internal and international migration should be considered as different adaptation strategies that, under certain circumstances, are interlinked. I invite the interested reader to see [Piguet et al. \(2011\)](#) for an overview of the nexus between migration and climate change, and [Millock \(2015\)](#) for an extensive review of the economic literature on this topic.

Environmental changes influence migration through indirect channels when the decision to migrate follows a change in the relative price of production inputs or productivity, which leads to a wage differential between origin and destination. For instance, environmental changes can affect productivity in agriculture, which in turn creates an income differential between rural and ur-

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<sup>2</sup> For instance, [Rappaport and Sachs \(2003\)](#) analyse the concentration of population in coastal areas in the United States and found that both productivity gains associated to coastal areas and amenities that reflect a better quality of life are key explanatory factors for the increase in population in these regions; [Rappaport \(2007\)](#) analyses the presence of this channel in the case of internal county migration also in the United States and finds empirical evidence suggesting that the increasing valuation of weather amenities has been a key driver for population growth in U.S. counties.

ban areas and eventually leads to rural-to-urban migration ([Marchiori et al., 2012](#)). One of the first studies focusing on environmental-induced international migration is [Barrios et al. \(2006\)](#). This study analyses the effects of climatic changes in Sub-Saharan Africa with respect to the rest of the world. Their results show that the reduction in rainfall has decreased the productivity of the agriculture sector contributing to rural-to-urban migration and in turn to an increase in urbanisation. However, these results only seem to hold for Sub-Saharan Africa.

Climatic factors have influenced international migration between Mexico and the U.S. [Munshi \(2003\)](#) analyses the impact of networks among Mexican migrants in the United States, using rainfall in the community of origin as an instrument to control for the size of the network at the destination. Results show that employment in the United States is negatively correlated with distant-past rainfall in the Mexican community of origin, but recent-past rainfall has little effect on employment. [Kniveton et al. \(2008\)](#) analyse the effects of climate variability and international migration for the states of Zacatecas and Durango. In contrast to [Munshi \(2003\)](#), their results show a positive correlation between rainfall and migration to the United States. [Feng et al. \(2010\)](#) analyse the effects of climate (annual precipitation, annual mean temperature, and summer mean temperature) on the percentage of Mexican population migrating to the U.S. This is done by analysing the effects of climate on crop yields (climate is used as an instrument), which in turn affect the share of the population migrating to the U.S. Their results show a semi-elasticity of emigration with respect to crop yields of -0.2. This suggests that changes in climatic factors that have a negative influence on agricultural productivity will increase the flow of migrants to the United States.

Studies on internal migration also suggest that environmental and climatic changes act as push factors through indirect channels. [Feng et al. \(2013\)](#) analyse the indirect effects of climate variations on migration within the Corn Belt in the United States between 1970 and 2009. In this study, the effects of climatic changes are captured through their impact on crop yields, which in turn influence net migration across counties. Results show that one percent change in yields leads to an opposite 0.3-0.4 percentage point change in the net migration rate. [Hornbeck \(2012\)](#) studies the effects of the American Dustbowl on a series of outcomes including county population. The American Dustbowl was a series of dust storms that swept topsoil from land causing permanent soil erosion during the 1930s. Results show that erosion had a long-term impact on agricultural costs; the main channel of economic adjustment following increasing costs took place through changes in the labour supply, i.e. labour equilibrium was reached through population decline rather than capital inflows or an increase in local industry. [Viswanathan and Kavi Kumar \(2015\)](#) use the same methodological approach as [Feng et al. \(2013\)](#) to analyse the effects of changes in temperature and rainfall on key economic factors such as wheat yield, rice yield, and per capita net state domestic product from agriculture. Results show that changes in these factors influenced outmigration rates across Indian states: a decline of 1% in crop yields leads on average to an increase of 1% or 2% in outmigration.

Environmental changes influence migration through direct channels when the decision to migrate is based on a significant decrease in environmental quality. Moreover, environmental changes further affect the capacity or the expectations of individual to maintain their livelihoods or basic well-being standards. Evidence shows that changes in climatic factors have directly influenced international migration. [Beine and Parsons \(2015\)](#) analyse the effect of both

temperature and rainfall on bilateral flows for more than 150 countries over the period 1960-2000 using a gravity-based specification. Their results show no evidence of the effects of climatic variations on international migration. However, their results do show a positive effect of natural disasters on rural-to-urban migration in the case of developing countries. [Coniglio and Pesce \(2015\)](#) also analyse environmental-induced international migration using a similar approach to [Beine and Parsons \(2015\)](#), but relying on more frequent observations and different measures to capture climatic variations. In contrast to [Beine and Parsons \(2015\)](#), this study finds that past climatic shocks have contributed to migration flows from developing to OECD countries: changes in the intra-annual variability of rainfall have a significant effect on migration towards OECD countries; rainfall shortages are also significant for explaining international migration, but excessive rainfall seems to have a stronger impact on bilateral migration. In the case of Mexico, [Nawrotzki et al. \(2013\)](#) analyse the influence of climatic factors on emigration from Mexican rural communities to the U.S. This study uses a multi-level approach to analyse the decision to migrate at the household level. The results show that a decrease in precipitation is associated with migration to the U.S., but only for dry Mexican states. [Hunter et al. \(2013\)](#) also analyse the effect of precipitation on migration from rural Mexican communities to the U.S. Based on a discrete-event survival analysis, results suggest that very recent droughts have a stronger effect on migration flows to the U.S. However, this only holds for communities with a long migration history. Moreover, these results also show that in communities characterised by low social capital a decrease in precipitation can actually limit migration to the U.S.

Internal migration is also influenced by climatic factors through direct channels. [Dallmann and Millock \(2013\)](#) study the effects of droughts and floods over bilateral migration flows for across Indian states for both the 1991 and 2001 censuses. The frequency and length of droughts and floods are captured through measures based on a standardised precipitation index (SPI). Following the same methodological approach as [Beine and Parsons \(2015\)](#), environmental-induced migration is analysed through a gravity-based specification. This study shows that drought frequency has a positive effect on internal migration: an additional month of drought increases the internal migration rate by 1.6%. [Saldaña-Zorrilla and Sandberg \(2009\)](#) investigate the vulnerability of Mexican population to natural disasters - including droughts, floods, earthquakes, etc. - and how this affects emigration rates in Mexican municipalities, showing that municipalities exposed to higher numbers of disasters are characterised by higher outmigration rates.

A small number of studies has simultaneously addressed internal and international environmental-driven migration. For instance, [Gray \(2009\)](#) analyses the effects of land ownership and climatic effects over different migration streams in the Ecuadorian Andes. Results show that rainfall negatively affects both internal and international migration, while land ownership has a positive effect on international migration. [Marchiori et al. \(2012\)](#) analyse the effects of weather anomalies on internal and international migration in Africa, as well as through both direct and indirect channels. Under the assumption of a two-sector model, mainly accounting for rural and urban areas, their results show that the negative effects of weather over agricultural productivity will reduce wages in the sector and trigger rural-to-urban migration. The latter will in turn reduce urban wages, which results in increased wage-differentials across countries prompting international migration. However, rural-to-urban



migration can enhance agglomeration effects that can deter international migration. In addition to the latter, this study also identifies direct effects of weather anomalies on migration. In the case of Sub-Saharan Africa the direct channel could be due to health-related or risk-reducing migration.

In this paper I seek to provide evidence-based analysis regarding the effects of environmental changes on internal migration in Mexico. In particular, I focus on the roles of droughts and floods. To this end, I exploit a dataset including information on migration flows across Mexican states for the periods 2000 - 2005 and 2005 - 2010. To account for the effects of weather variability on migration, I build a series of indicators based on a Standardised Precipitation Index (SPI). Moreover, I control for natural disasters that could have further influenced internal migration. Regarding my empirical strategy, I exploit the information of bilateral migration flows across Mexican states through a gravity-based model. Due to the panel structure of my dataset, I can control for origin and destination-time fixed effects, thus limiting potential omitted variables bias. Overall, my analysis is closely related to the work of [Dallmann and Millock \(2013\)](#). My results show that both droughts and floods act as push factors for internal migration in Mexico. In addition, my results show that income differential, murders, and educational attainments are key drivers for internal migration in the country.

The contribution of this paper is twofold. In the first place, and to my knowledge, this is the first study to explicitly analyse the role of both droughts and floods along with natural disasters on internal migration in Mexico. In the second place, this paper contributes to the migration literature by being the first study analysing bilateral migration flows in Mexico through a gravity-based model using a panel structure that allows to better control for unobservables.

This paper is structured as follows. The first section provides background information on geographic and demographic characteristics of Mexico, including an overview of general migration patterns across states. The second section presents the empirical analysis, including the analytical framework that leads to defining the specification of the econometric model. The third section describes the data used for the analysis. This section is followed by a description of the main results. The paper concludes discussing possible areas of improvement as well as policy recommendations.

## 3.2 Background: geography, climate, and internal migration in Mexico

### 3.2.1 Geography and climate

A large extent of Mexico's territory is dominated by arid regions. Mexico's territory extends over an area of 1,964,375 km<sup>2</sup>, which is characterised by dry and arid regions in the north, and warm and humid climates in the south<sup>3</sup>, Figure 3.1. Indeed, 51% of Mexico's climate can be classified as dry, 26% as warm, 23% as mild, and only 0.01% as cold (INEGI, 2010a). Climatic differences are further portrayed through the distribution of precipitation across the country. Rainfall is more prominent in the southern part of the country, in particular in states<sup>4</sup> bordering the Gulf of Mexico like Veracruz and Tabasco, as well as further south in states like Chiapas, and on the coastal area of Oaxaca, Figure 3.2.

Figure 3.1 and Figure 3.2 also show the distribution of the population across the country<sup>5</sup>. With the exception of Monterrey, in the northern state of Nuevo Leon, most population centres are placed in mild climates. However, they also tend to be placed in regions with precipitation levels lower than 1,500 mm per year.

Mexico's geographic characteristics make some regions more prone to droughts. Although droughts may happen at any place and at any time, the high pres-

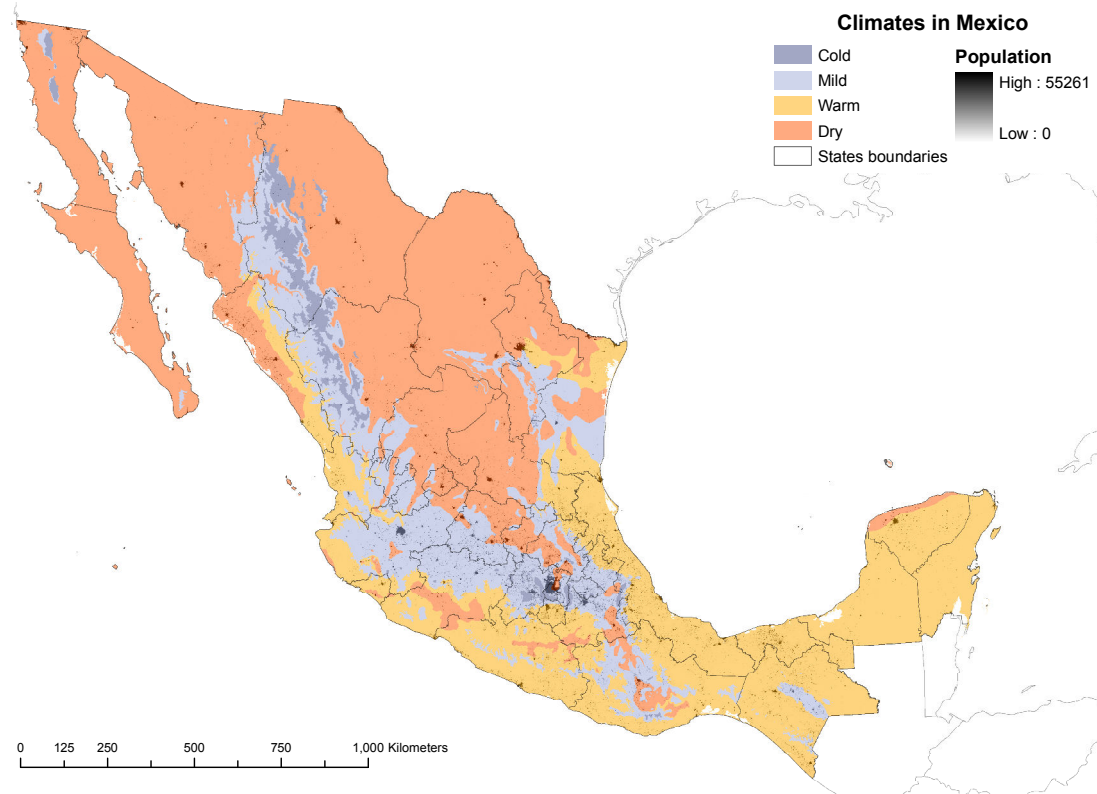
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<sup>3</sup>Mexico is the third largest country in Latin America. With respect to European countries, Mexico is 3.5 times bigger than Metropolitan France (547,030 km<sup>2</sup>), 8 times bigger than the United Kingdom (243,610 km<sup>2</sup>), and 47 times bigger than the Netherlands (41,543 km<sup>2</sup>).

<sup>4</sup>See Figure 3.7 for a map including Mexican states.

<sup>5</sup> Population is expressed in the maps as the total number of people in a cell of approximately 1 km<sup>2</sup>.

**Figure 3.1** – Type of climates in Mexico



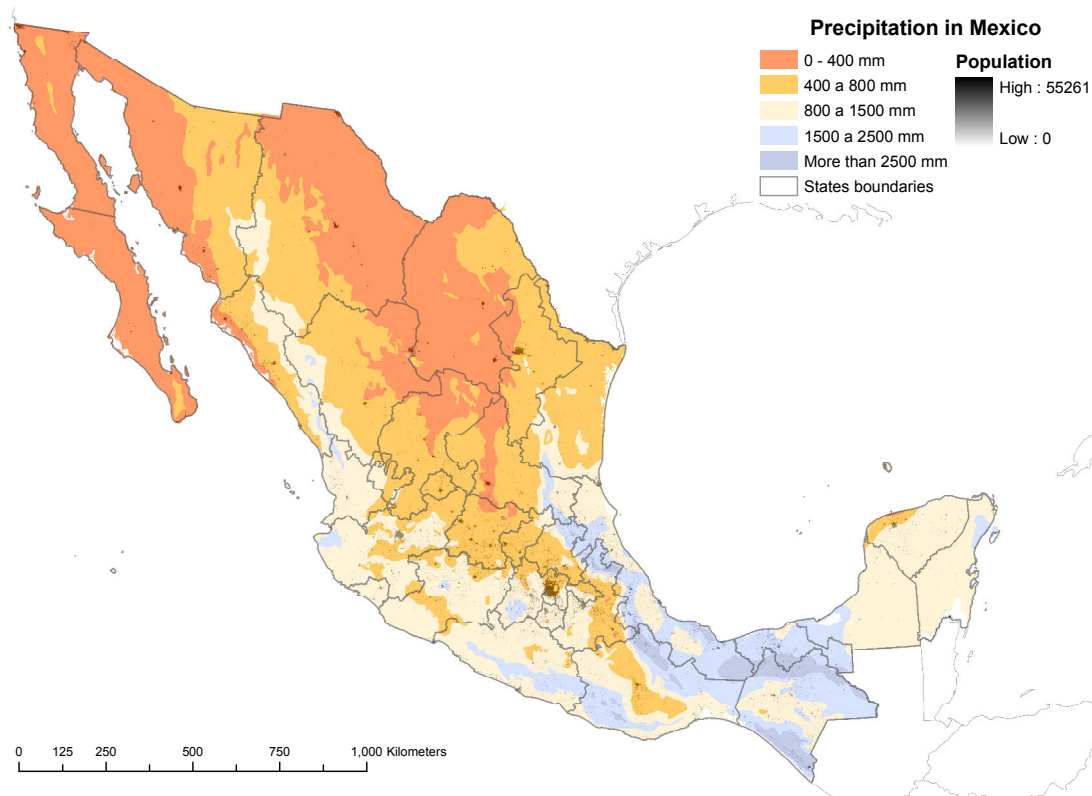
**Sources:** Climate data: National Geo-statistical Framework, INEGI; spatial distribution of the population: LandScan. Computations and maps elaborated by the author.

sure strip in the northern side of country makes some states more likely to be affected<sup>6</sup>. These states include Chihuahua, Coahuila, Durango, Nuevo Leon, Baja California, Sonora, Sinaloa, Zacatecas, San Luis Potosi, Aguascalientes, Guanajuato, Queretaro, Hidalgo, and Tlaxcala.

Geography is not the only factor defining the impact of droughts. Socio-economic processes that exert pressure on hydric resources can accentuate the vulnerability of populations to droughts. CONAGUA (2012b) identifies a number of regions in the country that will be particularly sensitive to different

<sup>6</sup> *Comision Nacional del Agua, (CONAGUA), <http://www.conagua.gob.mx>*

**Figure 3.2** – Precipitation in Mexico



**Sources:** Precipitation data: National Geo-statistical Framework, INEGI; spatial distribution of the population: LandScan. Computations and maps elaborated by the author.

scenarios of climate change in the following decades. In addition to northern states, this study identifies the Metropolitan Area of Mexico City as one of the most vulnerable places to droughts in the country. The latter follows from the high population density characterising the city, as well as the high demand of water that will have to be covered during the next decades.

During the last decades, Mexico has experienced a number of important droughts. [Ortega-Gaucin and Velasco \(2013\)](#) revise the latest droughts that have affected Mexico since the 1990s pointing out the high frequency and magnitude that have characterised recent episodes of droughts. For instance,

the basin of the Bravo river experienced one of the longest drought episodes in Mexico's modern history, lasting between 1993 and 2005 and having important hydrological side effects in Nuevo Leon, Chihuahua, Coahuila, and Tamaulipas. Moreover, between 2009 and 2011, Mexico experienced some of the strongest droughts of the last 70 years. According to [Ortega-Gaucin and Velasco \(2013\)](#), in 2011 droughts affected more than 70% of the territory causing an economic loss estimated at 10% of Mexico's GDP.

Floods are common in some states of the country, causing important material losses. Floods result from an excessive amount of precipitation within a short period of time. Floods manifest by an increase in the level of rivers and other types of water bodies having a negative and direct effect on agriculture, livestock, and infrastructure. The state of Yucatan, states in the North-East region, and those bordering the Gulf of Mexico are prone to floods ([Salas and Jiménez, 2007](#)). In 2010, extreme precipitation and floods in the states of Michoacan, Distrito Federal, Mexico, Oaxaca and Chiapas caused losses for more than MEX\$15,000 million, or approximately US\$1,200 million ([García Arróliga et al., 2011](#)). Floods are directly associated to the presence of hurricanes. Despite the fact that hurricanes are present in both the Pacific and Atlantic coasts of Mexico, they tend to be more frequent in the former. States such as Guerrero, Michoacan, Colima, Jalisco and Baja California Sur (on the Pacific coast) and Quintana Roo (on the Atlantic coast) have been affected by at least 10 hurricanes in the last 60 years; every state bordering the Gulf of Mexico and the Caribbean Sea has been affected by at least 5 hurricanes during this period ([Martín, 2007](#)).

In addition to droughts and floods, certain parts of Mexico are also exposed to earthquakes. Southeastern parts of the country, including the coasts of states like Nayarit, Guerrero, Oaxaca, and Chiapas face higher risks of earth-

quakes. This is also the case of Mexico City, which is particularly vulnerable to earthquakes due to the characteristics of the soil it has been built on. According to [Gutiérrez et al. \(2008\)](#), approximately 33% of the population in the country is exposed to high intensity earthquakes.

### 3.2.2 Population and internal migration

The Mexican population is highly concentrated. In 2010, Mexico's total population reached 112 million people, most living in a small number of states<sup>7</sup>. Distrito Federal and the states of Mexico, Veracruz, Jalisco, Puebla, Guanajuato and Chiapas accounted for more than 50% of the total population in the country, Table 3.14. The uneven distribution of the population is further reflected by marked differences of population density across states, ranging from 7.55 Inhab/km<sup>2</sup> in Baja California Sur to 5,956 Inhab/km<sup>2</sup> in Distrito Federal, Table 3.14. Distrito Federal and the state of Mexico are not only the regions with the highest population densities, but they also account for more than 20% of the total population in the country.

A large share of the Mexican population lives in urban areas. During the last 60 years, the share of rural population has been divided by half, going from 57% in 1950 to 22% in 2010 (INEGI's Databank). In other words, by 2010, 78% of the Mexican population lived in urban areas.

Internal migration is an important socio-economic phenomenon in Mexico, the patterns of which have changed in the last decades. According to the last census, 3.2 million people changed residence across Mexican states dur-

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<sup>7</sup> Mexico is a Federal Republic composed by autonomous states. There are 31 states and a federal district (Distrito Federal). States have their own congress and constitution; they differ in size and in terms of the concentration of their population, which tends to be higher in central parts of the country. The location and name of each state is presented in Figure 3.7 in the Appendix.

ing the period 2005-2010. The socio-economic factors that motivate these populations flows have changed over time. They include structural changes in the Mexican economy, the consolidation of the urban system, and a recent increase in drug-related crimes. [Ordorica and Prud'homme \(2010\)](#) suggest that the opening process of the Mexican economy that started in the 1980s contributed to moving industrial activities away from mayor populated centres and into intermediary cities. This has been further influenced by the increasing role of manufacturing and services in the economy. As a result, internal migration patterns have become more complex and are not longer limited to rural-urban flows; instead they tend to account for bigger population flows across urban areas. In 2010, 68.8 million people lived in the 59 metropolitan areas of Mexico, representing 56.8% of total population and 78.6% of urban population; during the period 2005-2010, close to 2.3 million people moved across the municipalities composing these metropolitan areas ([Romo et al., 2013](#)).

In addition to the structural transformation of the economy, a recent increase in violence related to drug cartels has prompted outmigration in a number of Mexican states. Starting in 2006, Mexican authorities began a war against drug cartels, which affected the interactions within and across cartels and eventually translated into violence and an unprecedented number of homicides. This is particularly the case of states bordering the United States. An increasing number of studies suggest that violence has triggered internal and international migration flows. For instance, according to [Ríos \(2012\)](#) around 115,000 Mexicans have arrived to the U.S. border cities since 2006, while another large number of migrants - hard to estimate - has moved to the central and southern states of Mexico.

The flow of internal migrants in Mexico is dominated by short-distance



streams in economically active and populated parts of Mexico. Figure 3.3 presents the bilateral migration flows across all Mexican states during the period 2005-2010. As can be seen from this figure, the biggest flow takes place from Distrito Federal to Mexico, its neighbouring state. This flow accounted for almost 800,000 people during 2005-2010, and represented 65% of all the people moving into the state of Mexico. In relative terms, this flow represented a migration rate<sup>8</sup> of 50 people per 1,000 population, and is thus the highest rate in the country. It is important to note that in spite of being the region with the highest GDP per capita in the country (see Figure 3.9 in the Appendix) the Distrito Federal has experienced the highest net population loss. Moreover, this phenomenon has been taking place for the last two decades (see Figure 3.8 in the Appendix)<sup>9</sup>. According to [Sobrinho \(2010\)](#), this short-distance migration flow has followed the development of an important industrial sector in the state of Mexico and the integration of a number of its municipalities into the metropolitan network led by the Distrito Federal. Since both the Distrito Federal and the state of Mexico compose Mexico City Metropolitan Area, this migration trend can be actually considered as an intra-metropolitan flow. Other high migration rates can be found across neighbouring states such as the corridors Quintana Roo - Yucatan, and Nayarit - Jalisco characterised by migration rates of 17 and 14 people per 1,000 population, respectively. In both cases, these flows are taking place in two of the most important touristic areas of the country. With the exception of some outmigration flows in northern states, overall migration patterns across Mexican states have not significantly changed with respect to the period 2000-2005, Figure 3.4.

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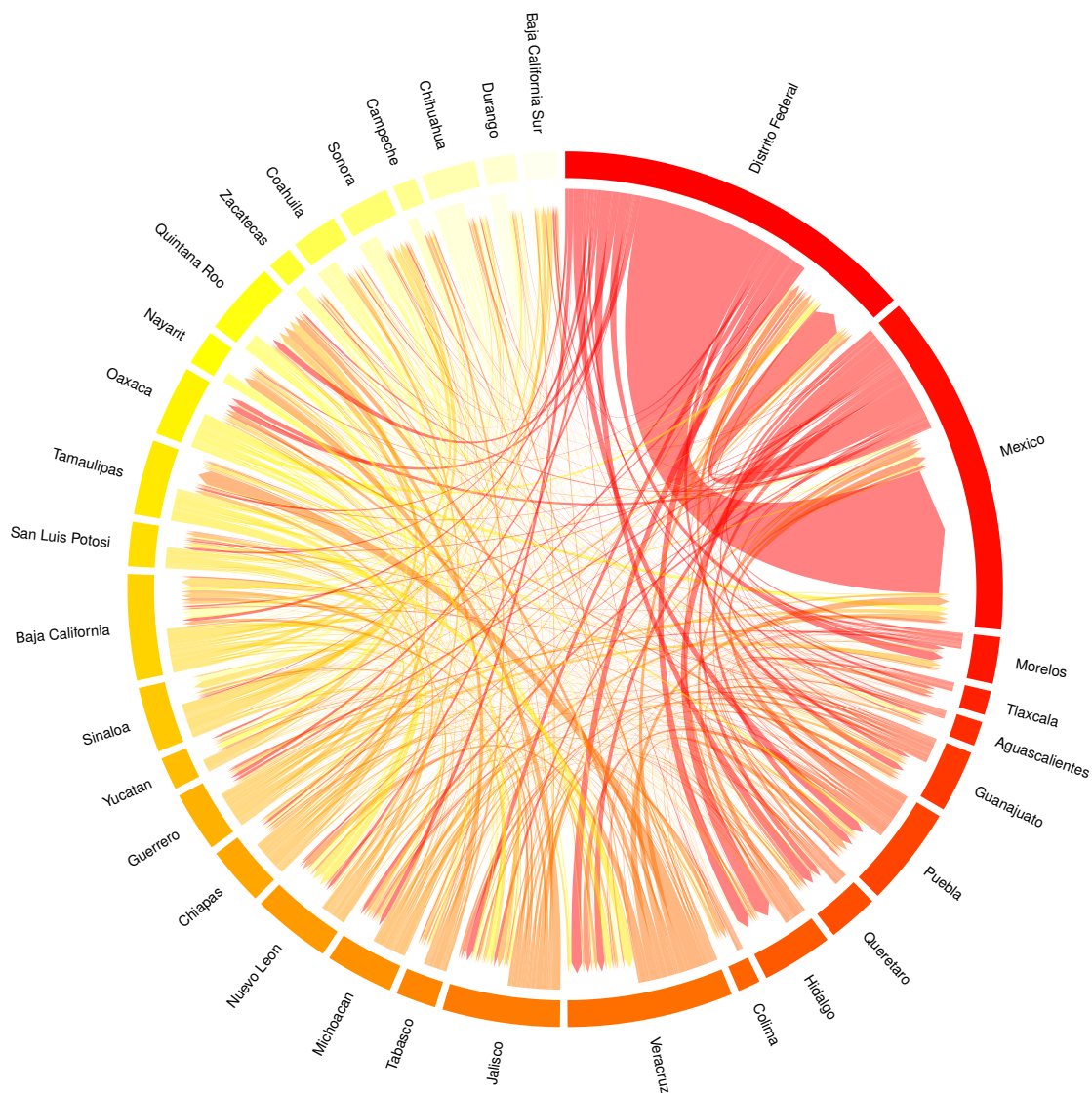
<sup>8</sup> This rate is computed as the number of population that moved from state *i* to state *j*, divided by the number of population that stayed in *i* during the migration period.

<sup>9</sup> Between 2005-2010, the net migration rate of Distrito Federal was -6.3.

Coastal states characterised by a strong touristic sector are becoming important attracting poles for migrants. Baja California Sur, in the north of the country, and Quintana Roo in the south are the states with the highest positive net migration rates over the past two decades, Figure 3.3 and Figure 3.8 in the Appendix. This pattern is the result of important public investments started in the 1970s that contributed to consolidating these states as two of the most important touristic poles in Mexico (Sobrinho, 2010).

In contrast, states like Chihuahua that have faced high levels of extreme violence seem to have lost population during the migration period 2005-2010. Between 2005 and 2010, the murder rate of Chihuahua was multiplied by ten, while in other northern states like Durango and Nuevo Leon murder rates were multiplied by five (INEGI's Databank). During this period Chihuahua's outmigration rates increased (compared to the migration period 2000-2005), Figure 3.3. The latter translated into a net migration rate equal to -0.9% between 2005-2010, which contrasts with the positive trend of net migration rates from previous migration periods (see Figure 3.8 in the Appendix).

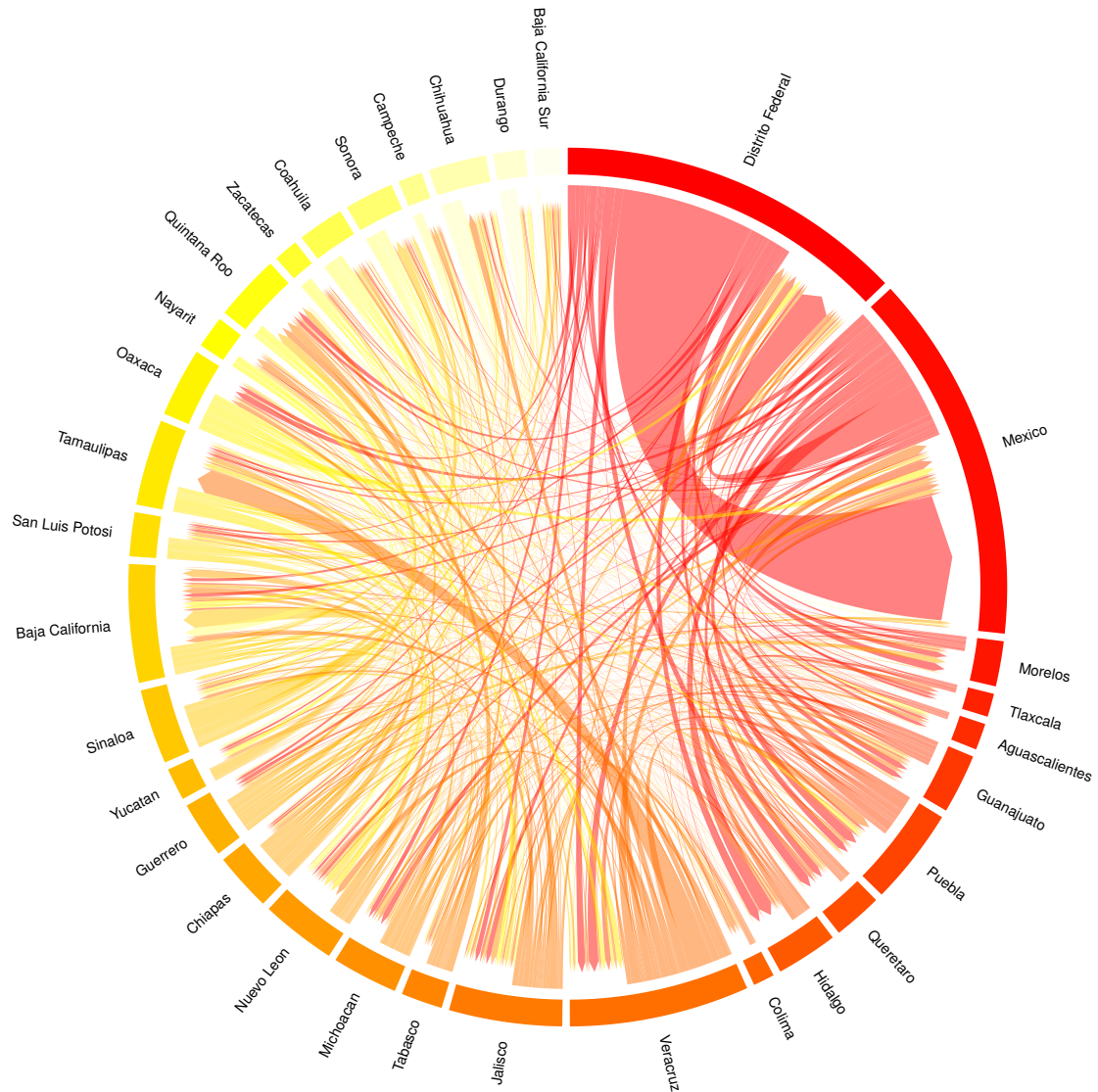
**Figure 3.3** – Bilateral population flows, total population, 2005-2010



**Source:** INEGI's Databank.

**Note:** The variable presented in this figure is the total population that migrated from one Mexican state to another during the period 2005-2010. Arrows represent migration flows. The width of each arrow represents the magnitude of the flow. The colour of each arrow accounts for the population density in the state of origin: dark red represents high population density, while light yellow represents low population density. The order of the states around the circle is also based on population density. Starting at 90 degrees, Distrito Federal is the state with the highest population density. Population density decreases clockwise around the circle until it reaches Baja California Sur, the state with the lowest population density in the country.

**Figure 3.4** – Bilateral population flows, total population, 2000-2005



**Source:** INEGI's Databank.

**Note:** The variable presented in this figure is the total population that migrated from one Mexican state to another during the period 2000-2005. Arrows represent migration flows. The width of each arrow represents the magnitude of the flow. The colour of each arrow accounts for the population density in the state of origin: dark red represents high population density, while light yellow represents low population density. The order of the states around the circle is also based on population density. Starting at 90 degrees, Distrito Federal is the state with the highest population density. Population density decreases clockwise around the circle until it reaches Baja California Sur, the state with the lowest population density in the country.

### 3.3 Empirical analysis

The main objective of this paper is to empirically test for the influence of weather-related events on internal migration in Mexico. To this end, I apply an econometric model to analyse bilateral migration flows across Mexican states for the periods 2000-2005 and 2005-2010. To exploit the information provided by bilateral migration flows, the empirical analysis relies on a gravity-based model. This section describes the analytical framework used for the specification of the econometric model, as well as the corresponding estimation method. The set of covariates considered in the empirical model discussed in this section are described in Table 3.1.

#### 3.3.1 Analytical framework

The empirical specification of my model relies on the analytical framework provided by the random utility model (RUM). Within the literature, the random utility model has been adapted and further developed to analyse international migration patterns by [Grogger and Hanson \(2011\)](#) and [Beine et al. \(2016\)](#). [Beine and Parsons \(2015\)](#) have further extended this model to account for the effects of long-term weather phenomena as part of the factors influencing international migration flows in countries of origin, while [Dallmann and Millock \(2013\)](#) have applied this model to analyse the effects of droughts and floods on internal migration. In the next paragraphs, I describe the micro-foundations of the RUM for analysing bilateral migration flows based on the theoretical background and notation provided by [Beine and Parsons \(2015\)](#).

Under the RUM framework, people decide to migrate or not in order to maximise their utility. This model assumes that individuals are homogenous

and capable of choosing across the whole set of potential destinations (in the present case all Mexican states) including their own place of residence. After comparing the utility provided by each destination, an individual chooses the optimal destination that maximises her utility. This decision process considers the characteristics in the place of origin, those of a potential destination, as well as the costs associated to migration. The utility of an individual staying in her place of residence can thus be represented by:

$$u_{ii,t} = \ln(w_{i,t}) + A_{i,t} + \epsilon_{i,t} \quad (3.1)$$

where  $w_{i,t}$  stands for the wage of place  $i$  at time  $t$ , and  $A_{i,t}$  represents the main characteristics of place  $i$ . The stochastic term  $\epsilon_{i,t}$  comes from an extreme-value distribution and is considered to be independent and identically distributed. The utility of an individual that opts to migrate to destination  $j$  is represented by:

$$u_{ij,t} = \ln(w_{j,t}) + A_{j,t} - C_{ij,t}(\cdot) + \epsilon_{j,t} \quad (3.2)$$

Where,  $A_{j,t}$  represents the main characteristics of place  $j$  and  $C_{ij,t}(\cdot)$  represents the costs of migrating from  $i$  to  $j$  at time  $t$ . When the stochastic term follows an extreme-distribution, the probability from individual  $i$  moving to place  $j$  can be expressed as:

$$Pr[u_{ij,t}] = \frac{N_{ijt}}{N_{i,t}} = \frac{\exp[\ln(w_{j,t}) + A_{j,t} - C_{ij,t}(\cdot)]}{\sum_k \exp[\ln(w_{k,t}) + A_{k,t} - C_{ik,t}(\cdot)]} \quad (3.3)$$

Where  $N_{i,t}$  is the size of the population in place  $i$  at time  $t$ , and  $N_{ijt}$  is the number of people moving from place  $i$  to  $j$  at time  $t$ . The migration rate

between  $i$  and  $j$  can thus be re-written as:

$$\frac{N_{ijt}}{N_{ii,t}} = \frac{\exp[\ln(w_{j,t}) + A_{j,t} - C_{ij,t}(\cdot)]}{\exp[\ln(w_{i,t}) + A_{i,t}]} \quad (3.4)$$

Following [Beine and Parsons \(2015\)](#), and after taking logs and rearranging some terms, the bilateral migration rate can be expressed as follows:

$$\ln\left(\frac{N_{ijt}}{N_{ii,t}}\right) = \ln\left(\frac{w_{j,t}}{w_{i,t}}\right) + A_{j,t} - A_{i,t} - C_{ij,t}(\cdot) \quad (3.5)$$

Equation 3.5 establishes the main elements influencing the migration rate. The intuition behind this equation is straight forward. Wage differentials between states of destination and those of origin expressed in logs,  $\ln\left(\frac{w_{j,t}}{w_{i,t}}\right)$ , aim to account for a pecuniary driver for migration from  $i$  to  $j$ . Differences in wages could be an incentive to move from  $i$  to  $j$ . Non-pecuniary factors that change in time in the state of destination are captured by  $A_{j,t}$ , while those in the state of origin are captured by  $A_{i,t}$ . For instance, natural and social amenities in the state of destination can act as pull factors for migration, while insecurity, limited job opportunities, and negative effects associated with weather can act as push factors in the state of origin. Finally, higher costs of migration,  $C_{ij,t}$ , will tend to limit migration across states. Migration costs are not limited to travelling expenses associated to moving from  $i$  to  $j$ , but they also include time and distance, and the costs of leaving family and friends behind ([Bodvarsson and Berg, 2009](#)). Moreover, some of these costs change in time, but those like distance tend to be fixed.

### 3.3.2 Econometric specification and estimation method

The specification of the econometric model is based on Equation 3.5. This specification models the migration flow as a function of wage differentials and different sets of covariates accounting for time-varying characteristics in the state of origin, as well as migration costs. Indeed, this analysis focuses on the effects of weather-related events in the state of origin, while accounting for the characteristics of destinations through time-destination fixed effects. The latter also allows accounting for changes at the national level that may have influenced all Mexican states across time. Time-invariant characteristics in the state of origin are further controlled through origin fixed effects. The main specification of the econometric model is given by:

$$\begin{aligned}
 \ln N_{ij,t} = & \alpha \ln \text{GDP DIFF}_{ji,t} & (3.6) \\
 & + \omega_1 \ln \text{KM}_{i,j} + \omega_2 \text{CONTIGUITY}_{i,j} \\
 & + \beta_1 \ln \text{EDUCATION}_{i,t} \\
 & + \beta_3 \ln \text{MURDER}_{i,t} + \beta_4 \ln \text{MURDER CHNG}_{i,t} \\
 & + \gamma_1 \text{EARTHQUAKE}_{i,t} + \gamma_k \text{HURRICANE}_{k,i,t} \\
 & + \mu_k \text{CLIMATE}_{k,i,t} \\
 & + \delta_i + \delta_{j,t} + \ln M_{ii,t} + \epsilon_{ij,t}
 \end{aligned}$$

Where  $N_{ij,t}$  is the migration flow between origin  $i$  and destination  $j$ . In this specification, wage differentials between destination and origin are represented by  $\ln \text{GDP DIFF}_{ji,t}$ ;  $\ln \text{KM}_{i,j}$  and  $\text{CONTIGUITY}_{i,j}$  account for migration costs; the share of population that has achieved a certain degree of educa-



tion (primary, secondary, or tertiary) is represented by  $\ln\text{EDUCATION}_{i,t}$ ; the extent of homicides in region  $i$  is captured by  $\ln\text{MURDER}_{i,t}$  and  $\ln\text{MURDER CHNG}_{i,t}$ ;  $\text{EARTHQUAKE}_{i,t}$  accounts for the number of earthquakes in  $i$ ;  $\text{HURRICANE}_{k,i,t}$  refers to the  $k$ -th variable considered to account for the different categories of hurricanes in  $i$ ; similarly,  $\text{CLIMATE}_{k,i,t}$  accounts for the  $k$ -th variables capturing the frequency, magnitude, or length of either droughts or floods in the state of origin. In addition to the set of covariates previously described, this specification includes the term  $\ln M_{ii,t}$ , which is the log of the total population that stayed in the region of origin; while  $\delta_i$  and  $\delta_{j,t}$  are origin fixed effects and destination-time fixed effects, respectively.

The dependent variable accounts for all migration flows across Mexican states. Indeed,  $M_{ij,t}$  measures the total number of people that changed residence during each migration period. Since this is an analysis on internal migration, it considers the 32 states in the country. Nevertheless, it is important to highlight that due to the substantial flow of international migrants, the U.S. could for modelling purposes be considered as an additional destination. Moreover, emigration rates tend to vary across states, which may not be fully captured through fixed effects. However, due to limited information on migration flows to the U.S. across Mexican states, I do not consider the U.S. as an additional destination in the present analysis<sup>10</sup>.

Wage differentials are proxied through the ratio of GDP per capita in the state of destination over that of the state of origin. No information on net income is available for the period under study, thus I follow previous literature and use GDP per capita as a proxy for wages. I express GDP per capita differentials in logarithmic terms. Using a logarithmic transformation

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<sup>10</sup> Information on the number of migrants to the U.S. across states is only available for the period 2005-2010.

assumes that migration flows react to relative changes in wages between the origin and destination. This assumption has further implications regarding credit constraints. Indeed, an increase in the same proportion of GDP per capita at both states of origin and destination will not result in any change in the migration flow. However, this may not hold if credit constraints at the origin are present, since the increase in revenue at the origin may in turn translate into a larger migration flow (Beine et al., 2016). In addition, using a logarithmic transformation implicitly assumes that individuals' utility function is characterised by a Constant Relative Risk Aversion (Anderson, 2011).

The first set of covariates accounting for characteristics in the state of origin regards social factors influencing migration. I focus on human capital and violence. I proxy human capital through educational attainments. I consider that better educational attainments provide a set of skills that is valuable for labour markets, which in turn makes skilled population more likely to migrate in order to look for better job opportunities and the possibility of increasing their human capital. The role of education as a push factor for internal migration has been previously discussed by Lucas (1994) and Todaro (1980), and used for empirically analysing internal migration in the case of Mexico by Saldaña-Zorrilla and Sandberg (2009) and Sobrino (2010). Regarding violence, I proxy this factor for internal migration through the murder rate. Violence has been one of the most challenging issues to tackle in Mexico during the last couple of decades. Both the media and an increasing number of empirical literature (Dell, 2015; Robles et al., 2013; Concepcion et al., 2015) have pointed out the strong linkage between organised crime and the steep trend in the number of homicides in Mexico since the mid-2000s, as well as the important side effects on both the economy and society. Moreover,

as previously discussed, extreme violence manifested through murder rates seems to be associated with internal and international outmigration.

The second group of covariates influencing migration in the state of origin considers natural disasters. Due to Mexico's climatic and geographic characteristics, populations across the country face different risks regarding natural disasters such as earthquakes and hurricanes. Indeed, the population of certain states is more likely to suffer from an earthquake than others. This is particularly the case of states in the Pacific coasts and in the centre of the country, including the Distrito Federal. To account for earthquakes that actually influence migration, I focus on the frequency of earthquakes with a magnitude of at least seven degrees in the scale of Richter. Although earthquakes could trigger outmigration, they can also limit population movements by destroying household assets and imposing financial constraints; population can also opt to stay in order to help with reconstruction actions. For instance, previous empirical work such as [Halliday \(2008\)](#) has analysed the linkage between earthquakes and migration in El Salvador, showing that the 2001 earthquake deterred female migration but had no impact on male migration. Regarding hurricanes, I consider different categories. Hurricanes are classified according to wind speed, ranging from category 1 to category 4 (the latter being the most destructive). The effect of natural disasters has been studied by [Naudé \(2009\)](#) in the case of Sub-Saharan Africa; this study identifies a positive effect between this type of disasters on net international migration. A general review of the linkage between hurricanes and migration can be found in [Kniveton et al. \(2008\)](#), while recent empirical work on internal migration that accounts for hurricanes as a push factor includes [Drabo and Mbaye \(2011\)](#), [Saldaña-Zorrilla and Sandberg \(2009\)](#) in the case of Mexico, and [McIntosh \(2008\)](#) who analyses the effects of hurricane Katrina in the

United States. These studies suggest that hurricanes tend to be associated with positive migration rates.

The third group of variables represents the centre of interest of the analysis and accounts for those covariates associated with droughts and floods. Mexico is exposed to both droughts and floods, making these natural phenomena potential drivers for internal migration. Floods manifest through an increase of precipitation that eventually raises the levels of rivers and other water bodies. Floods can take place without too much warning, leaving a short period of time for the population to react. They can translate into damages to infrastructure and agriculture. The nature of droughts makes them different from other natural phenomena such as earthquakes, floods, and hurricanes: the beginning and end of droughts is usually hard to anticipate, they can prevail for long periods of time (even years), and the extent of their effects can reach large geographic areas. Droughts manifest through the lack of precipitation. If the deficit of rainfall lasts for a long period of time, the effects of droughts eventually have an impact on soil moisture, percolation, and recharge of aquifers, which eventually affects the water supply to lakes, dams, and water-based ecosystems<sup>11</sup>. For this reason, droughts directly affect the agricultural sector, and are particularly damaging for ecosystems already experiencing water stress.

By looking at droughts and floods (as well as natural disasters) I aim to account for short and medium term environmental phenomena. This approach differs from that followed by studies like [Beine and Parsons \(2015\)](#) where long-term climatic changes are analysed and deviations from long-term precipitation and temperature means considered. Although long-term climatic

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<sup>11</sup> National Drought Mitigation Centre, 2015, <http://drought.unl.edu>.

effects are most likely to take place in Mexico<sup>12</sup>, I opt to focus the analysis on droughts and floods, and natural disasters, because I consider that these phenomena are more suitable to explain population movements during the short period of time in which the analysis takes place. Indeed, the analysis only accounts for ten years (2000-2010), i.e. two consecutive migration periods of five years.

I account for the frequency of both droughts and floods through the Standardised Precipitation Index (SPI) designed by [McKee et al. \(1993\)](#) and computed by CONAGUA. The SPI has previously been used to analyse the effects of weather on migration. Notably, [Strobl and Valfort \(2015\)](#) and [Dallmann and Millock \(2013\)](#) have previously used the SPI index to analyse internal migration in Uganda and India, respectively. Using the same approach as [Dallmann and Millock \(2013\)](#), I compute a set of variables capturing the frequency, length and magnitude of both droughts and floods. Since the information on migration flows across Mexican states refers to five-year migration periods, all variables in this set are computed between the first and the fourth year of each migration period. [Feng et al. \(2010\)](#) and [Beine and Parsons \(2015\)](#) also consider climatic changes within migration periods.

Finally, migration costs are captured through two distance-related covariates. The first covariate is the Euclidean distance between states of origin and states of destination. The second covariate is a dummy variable that identifies whether states are contiguous or not. Migration costs are dyadic and assumed to be separable.

The parameters of Equation 3.6, are estimated through a Poisson Pseudo Maximum Likelihood estimator (PPML). As shown by [Silva and Tenreyro](#)

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<sup>12</sup> As discussed in the introduction, [Estrada et al. \(2013\)](#) anticipate that climate change will affect different regions in Mexico in the next decades.

(2006), this approach provides consistent estimations for models specified in logarithmic terms, as most gravity models, and for which the dependent variable includes observations with zero values. Despite the fact that, in my sample all flows across states are non-zero, I opt to use this estimation method since it has been extensively used in the migration literature and has become the method of reference for estimating gravity-based models. See [Beine et al. \(2016\)](#) for a description of previous analysis using this method.

### 3.4 Data and descriptive statistics

The purpose of this section is to describe the dataset used for the empirical analysis. The main units of observation are Mexican states<sup>13</sup>, which are analysed across two migration periods. By migration period I refer to the number of years in which migration flows take place across Mexican states. These periods are 2000-2005 and 2005-2010. The total number of observations for each migration period is 992, which makes a total of 1,984 observations over the two periods under study. It is important to keep in mind that each observation in the dataset represents the migration flow from state  $i$  to state  $j$ , in other words this is a dyadic dataset that can account for variables regarding either  $i$  or  $j$ , as well as for variables related to both  $i$  and  $j$ .

This dataset was compiled through information from official public sources, most of them provided by the National Institute of Statistics and Geography (INEGI) and the National Water Commission (CONAGUA). The following paragraphs describe in detail the dependent variable and the different groups of covariates used for the analysis.

#### 3.4.1 Dependent variable: inter-state migration

The main variable of interest is the migration flow across Mexican states during the periods 2000-2005 and 2005-2010. Information for the period 2005-2010 refers to the 2010 census; and information for the period 2000-2005 refers to the population count carried out in 2005. Inter-state migrants

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<sup>13</sup> Mexico is a Federal State composed by 31 states and a federal district (Distrito Federal) that accounts for a large extent of what is commonly referred to as Mexico City. States significantly differ in terms of size and population. In spite of the size of the country (almost two million square kilometres), the 112 million people composing its population are concentrated in a small number of states and in particular in Mexico City, which accounts for almost 20% of the total population.

Table 3.1 – Description of covariates and summary statistics

| Variable                     | Unit             | Definition  | Mean   | Min. | Max.    |
|------------------------------|------------------|---|--------|------|---------|
| Migration Flow               | Population       | Number of people moving from state $i$ to state $j$ within the migration period                       | 2872   | 10   | 382202  |
| Migration Rate               | Rate per 10K pop | Migration flow divided by the total population that remained in state $i$ during the migration period | 0.95   | 0.01 | 49.67   |
| GDP DIFF $_{j,i,t}$          | Ratio            | GDP differential  | 1.20   | 0.17 | 5.69    |
| DISTANCE $_{i,j}$            | Kilometres       | Euclidean distance between state $i$ and state $j$  | 898.50 | 8.9  | 3132.92 |
| MURDER $_{i,t}$              | Rate per 10K pop | Number of murders divided by total population in state $i$ (murder rate)                              | 10.83  | 2.02 | 33.17   |
| MURDER CHNG $_{i,t}$         | Ratio            | Increase in murder rate in state $i$ during the migration period                                      | 1.66   | 0.47 | 10.71   |
| PRIMARY EDU $_{i,t}$         | Percentage       | Population with primary edu attainments, year before migration  | 65.74  | 44.4 | 82.5    |
| SECONDARY EDU $_{i,t}$       | Percentage       | Population with secondary edu attainments, year before migration                                      | 17.24  | 8.5  | 25.6    |
| TERTIARY EDU $_{i,t}$        | Percentage       | Population with tertiary edu attainments, year before migration                                       | 16.94  | 8.9  | 30.9    |
| EARTHQUAKES $_{i,t}$         | Number           | Earthquakes   | 0.14   | 0    | 2       |
| HURRICANE 1-4 $_{i,t}$       | Number           | Hurricanes type 1 to 4  | 0.76   | 0    | 6       |
| HURRICANE 3-4 $_{i,t}$       | Number           | Hurricanes type 3 to 4  | 0.17   | 0    | 2       |
| DROUGHT FREQ LONG $_{i,t}$   | Number           | Months with mild and severe droughts  | 2.14   | 0    | 14      |
| DROUGHT LENGTH LONG $_{i,t}$ | Months           | Length of longest drought episode   | 8      | 0    | 34      |
| DROUGHT MAG LONG $_{i,t}$    | SPI              | Magnitude of longest drought episode  | 4.92   | 0    | 20.39   |
| DROUGHT LENGTH ALL $_{i,t}$  | Months           | Length of all drought episode   | 9.71   | 0    | 34      |
| DROUGHT MAG ALL $_{i,t}$     | SPI              | Magnitude of all drought episodes   | 6.11   | 0    | 25.98   |
| FLOOD FREQ LONG $_{i,t}$     | No.              | Months with mild and severe floods  | 3.07   | 0    | 17      |
| FLOOD LENGTH LONG $_{i,t}$   | Months           | Length of longest flood episode   | 10.09  | 0    | 41      |
| FLOOD MAG LONG $_{i,t}$      | SPI              | Magnitude of longest flood episode  | 7.33   | 0    | 35.96   |
| FLOOD LENGTH ALL $_{i,t}$    | Months           | Length of all flood episodes  | 10.56  | 0    | 41      |
| FLOOD MAG ALL $_{i,t}$       | SPI              | Magnitude of all flood episodes   | 7.77   | 0    | 35.96   |



are identified through the question: *In which state did you reside in 5 years ago?* Both sources use the same question to quantify internal migration. For each period, the migration flows are presented as a 32 by 32 matrix that accounts for all population movements across Mexican states within the period. Additional information on the total population that remained in each state during the migration period is also provided by each dataset. The migration matrix for the 2010 census was obtained from the Population National Commission (CONAPO), while the information on the 2005 population count was obtained from INEGI.

Migration flows are very diverse in terms of size. They can range from 10 people moving from Campeche to Aguascalientes (2000-2005), to 382,202 people moving from the Distrito Federal to the state of Mexico (2005-2010). Indeed, the largest flow takes place between the neighbouring states of the Distrito Federal and Mexico. This holds for both migration periods. There is no clear pattern regarding the lowest migration flows since they take place across states from the south to the centre (Campeche - Aguascalientes) or from the centre to the south (Baja California Sur - Tabasco). See the background section for a description and discussion on the bilateral migration flows.

### **3.4.2 GDP per capita**

GDP per capita is used as a proxy to account for the pecuniary drivers of internal migration. Based on the analytical model described in the previous section, pecuniary incentives for migration are captured through the wage differential between states of destination and origin. I proxy wage differentials through the ratio of GDP per capita in the state of destination over that of the state of origin.

States' GDP per capita is expressed in Mexican pesos in real terms (base = 1993), and refers to the year previous to each migration period, i.e 1999, and 2004. This information was obtained from INEGI's Economic Information Bank (BIE). Figure 3.9 in the Appendix presents the GDP per capita for each state for the year prior to the migration period. Overall, the ranking of states has remained fairly stable across time. The Distrito Federal and Nuevo Leon have remained the states with the highest revenue during both migration periods; while Oaxaca, Chiapas and Guerrero are still the poorest states in the country.

Mexico is characterised by important regional disparities. In 2010, the Distrito Federal, which accounts for a significant share of Mexico City's metropolitan area, had a real GDP per capita of approximately MEX\$ 37,000. In contrast, during the same year, Oaxaca had a real GDP per capita of approximately MEX\$ 6,5000. In other words, the average income of people living in Mexico City is almost 5.6 times higher than someone living in Oaxaca. Table 3.1 shows basic statistics regarding the distribution of the ratio of GDP per capita in the state of destination over that of the origin state. The average value of this ratio is 1.2, but it ranges from 0.17 to 5.6 representing respectively the ratio of Oaxaca over the Distrito Federal and the Distrito Federal over Oaxaca.

### **3.4.3 Human capital and violence**

Internal migrants do not represent a random sample of the population, instead they tend to self select according to certain personal characteristics or by being exposed to certain socio-economic contexts. The latter includes the level of human capital and the extent of violence in the state of residence. I proxy human capital through primary, secondary, and tertiary educational

attainments; as for violence, I use the murder rate and the increase of murder rates during the migration period as proxies. The source of all these variables is the SIMBAD database from INEGI.

Educational attainments are computed as the ratio of the population that has completed the corresponding educational degree divided by the total population and multiplied by one hundred. Between the two migration periods, on average, 65% of the population across Mexican states only counted with elementary education, while 17% of the population had attained a secondary education degree. However, these shares significantly vary across states. Primary educational attainments range from 44% in Oaxaca to 83% in the Distrito Federal, while secondary education ranges from 9% to 26%, and tertiary education between 16.9% and 30.9% also among these two states, Table 3.1. Overall, these values remain low compared to other OECD countries. For instance, in OECD countries the share of population with secondary educational attainments accounts for more than 40% of the total population (OECD.Stats).

The murder rate is computed as the total number of murders (i.e intentional homicides) over the total population in each state, during the year previous to the migration period. To follow a common international practice, I express the ratio by 100,000 population. The murder rate for each state is presented in Figure 3.10 in the Appendix. During 2004, the states of Guerrero and Oaxaca in the south-west, and Chihuahua and Baja California bordering the U.S. in the north of the country, had the highest murder rates. In contrast, Yucatan in the southeast and Aguascalientes in the centre had the lowest murder rates. The state of Guerrero had the highest murder rate in each of the years previous to the migration periods. Since 2006, there has been a notorious increase in drug-related crimes and homicides in the country. To

account for this factor, I proxy the increase in violence by considering the increase in murder rates in the states of origin. I compute the latter as the ratio of the murder rate in the last year of the migration period over the murder rate in the first year of the period. During the migration period 2000-2005, the highest increase in murder rates was experienced by the state of Durango where the murder rate increased by a factor of 1.3. During the migration period 2005-2010, the number of murders reveal an unprecedented increase, in particular along U.S. bordering states. During this period the state that experienced the biggest increase was Chihuahua where the murder rate increased by a factor of 10.6. In contrast, in the central states of San Luis Potosi and Morelos, as well as in the southern state of Chiapas, murder rates were reduced by half.

#### **3.4.4 Natural disasters**

The Mexican population is exposed to a number of natural disasters that can trigger or increase certain internal migration flows. Based on Mexico's climate and geography, I consider earthquakes and hurricanes to be two of the most important.

Information on earthquakes was obtained from the database of the National Centre for Prevention of Disasters (CENAPRED). This database includes the number of earthquakes in each state, including their magnitude. To actually account for those earthquakes that could have triggered migration, I only consider earthquakes with a magnitude of seven degrees in the scale of Richter or higher. Moreover, the CENAPRED considers these earthquakes as having affected the Mexican population the most in the last decades. I consider the total number of such earthquakes during the migration period. High-magnitude earthquakes are not common; on average, across the two

migration periods there have been 0.14 earthquakes per state, Table 3.1. Moreover, only a small group of states has been affected by high-magnitude earthquakes. This group includes Chiapas, Colima, the Distrito Federal, Guerrero, Jalisco, and Oaxaca.

**Table 3.2** – Classification of tropical storms

| Type of storm       | Wind's speed (kmh) |
|---------------------|--------------------|
| Tropical depression | < 62               |
| Tropical storms     | 62 - 118           |
| Hurricane class 1   | 118 - 154          |
| Hurricane class 2   | 154 - 178          |
| Hurricane class 3   | 178 - 210          |
| Hurricane class 4   | 210 - 250          |

**Source:** CONAGUA

Regarding hurricanes, I obtained the information from the National Water Commission (CONAGUA). CONAGUA has been collecting this information on tropical storms since the 1970s. It classifies them according to wind speed. The different types of storms are presented in Table 3.2. According to CONAGUA, storms reaching a wind speed higher than 118 kmh are considered as hurricanes. After reaching this threshold, hurricanes are classified in four categories (from Type 1 to Type 4). Based on this classification, I create two variables; one that accounts for the number of hurricanes in all categories and other that focuses on types 3 and 4. Although hurricanes of types 3 and 4 are the most destructive, I consider all types of hurricanes in order to be able to test for the possibility of accumulative effects. Quintana Roo, Guerrero, Sinaloa, Sonora, and Baja California Sur are the states with the highest frequencies of hurricanes within the two migration periods. However, the states

with the highest frequency are not always the same across migration periods. For instance, during the migration period 2005-2010, there were 6 hurricanes in Baja California of types 1 to 4; but during the period 2000-2005, there was only 1 hurricane of types 1 to 4.

### 3.4.5 Droughts and floods

To account for the effects of both droughts and floods, I use the Standardised Precipitation Index (SPI) designed by [McKee et al. \(1993\)](#) and computed by CONAGUA. Based on [McKee et al. \(1993\)](#), the methodology to compute the SPI can be summarised as follows.

The SPI is based on the probability of precipitation for any time scale, which is then transformed into an index. The SPI is calculated using a monthly precipitation dataset for a given period of months. However, it is recommended to use a dataset that accounts for at least 30 years. The SPI can account for different time scales. Although arbitrary, these time scales represent typical precipitation deficits affecting different types of water sources. These time scales are 3, 6, 12, 24, or 48 months. Based on these time scales, a moving average is applied to the whole dataset, which is then fitted to the Gamma function to define the relationship of probability to precipitation. This allows to calculate the probability of a given precipitation data point. This information is then used along with an estimate of the inverse normal to calculate the precipitation deviation for a normally distributed probability density with a mean of zero and standard deviation of unity. The result is the SPI value for a given precipitation data point.

[McKee et al. \(1993\)](#) proposed the classification system described in Table 3.3. Under this classification, a drought occurs when the SPI is continuously

negative and reaches an intensity of -1.0 or less. The event ends when the SPI becomes positive. Each drought event has a specific duration (the time between when it begins and when it ends). Each month can be considered to have a specific intensity; the positive sum of the SPI for all the months within a drought event can be considered as the magnitude of the event. A similar approach can be applied to floods, but by considering positive values instead.

**Table 3.3** – Classification of droughts

| SPI            | Type of drought  |
|----------------|------------------|
| 0 to -0.99     | Mild dryness     |
| -1.00 to -1.49 | Moderate dryness |
| -1.5 to -1.99  | Severe dryness   |
| < -2.0         | Extreme dryness  |

**Source:** [McKee et al. \(1993\)](#)

CONAGUA computes the SPI index for more than 700 hundred stations across the country. CONAGUA only considers those stations with more than 30 years of activity in order to have information for SPIs referring to 12 and 24 months. Based on the information of each station, I compute average values of the SPI across stations in every Mexican state. Following [Dallmann and Millock \(2013\)](#), I compute a number of variables within the migration period: the number of months with moderate and severe droughts/floods; the number of severe droughts/floods; the length of the longest drought/flood; the magnitude of the longest drought/flood; the length of all droughts/floods; and the magnitude of all droughts/floods. The number of moderate or severe droughts is computed as the number of months in which the SPI is lower than -1 or -1.99, respectively; in the case of floods, the same applies but considering

positive values. Regarding the length and magnitude of droughts/floods, I use the definition provided by [McKee et al. \(1993\)](#) that was described in the previous paragraph. In total, I compute 10 variables accounting for the effects of limited or excessive precipitation.

Descriptive statistics on the variables capturing the frequency and extent of both droughts and floods are presented in Table 3.1. The first thing to notice from these variables is that not every state is affected by droughts or floods. According to my calculations for the SPI at state level, in the states of Guerrero, Nayarit, Nuevo Leon and Oaxaca no month was classified as affected by neither moderate nor severe droughts during the migration periods. In contrast, the states of Aguascalientes, Baja California, Campeche, Hidalgo, Quintana Roo, Tabasco, Tlaxcala, Yucatan, and Zacatecas have experienced at least a month considered by the SPI as a severe drought. With regard to the length of droughts, the average length is of approximately 8 months across the two migration periods. However, there is high dispersion across states, ranging from 0 months in most central and southern states to 26 and 34 months in the northern states of Sinaloa and Baja California (2010-2005), respectively. These two states show an interesting difference between SPI-based measures focused on frequency and those focused on length or magnitude. Despite the fact that these are the two states with the longest episodes of drought, they both have low values in terms of the frequency of moderate or severe drought (3 for Baja California and 1 for Sinaloa). Another important thing to notice is that there is no clear pattern in terms of the frequency and extent of droughts across the two migration periods considered for the analysis. Figure 3.11 in the Appendix presents both the frequency and length of droughts for the two migration periods. From here it can be observed that states that experienced droughts/floods in the first



migration period do not necessarily experienced droughts in the following one, and vice versa. The same applies for the length of droughts. Finally, with regard to floods, their pattern is similar to that of droughts in the sense that they are not present in every state, and are not necessarily consistent across migration periods. The states of Oaxaca, Hidalgo, Chihuahua, Chiapas, Guerrero, Nuevo Leon, Puebla, and Jalisco have never experienced a flood. The state with the highest frequency of months experiencing moderate or severe floods is Guanajuato, with 41 months of moderate and severe floods over the migration period.

Table 3.15 shows the correlation across climatic variables and those capturing natural disasters. The correlation between both earthquakes and hurricanes with respect to climatic variables tends to be low. As can be expected, the correlation across variables capturing droughts (floods) is high.

### 3.5 Results

Results show that changes in the length and magnitude of both drought and flood episodes influence internal migration in Mexico. Both the lack or excess of precipitation act as push factors for migration. Nevertheless, socio-economic factors such as wage differentials, educational attainments, and violence are the main factors shaping internal migration patterns.

The section starts by presenting the results of a baseline model. The baseline model is a reduced version of the full model described in Equation 3.6; it accounts for income differential between origin and destination, migration costs, and socio-economic characteristics in the state of origin. The baseline model does not account for covariates representing weather-related events or natural phenomena. The section continues presenting the results of an extended model including earthquakes and hurricanes, as well as the results of the full model that considers the different measures of droughts and floods. This is followed by a number of robustness checks, and a short analysis on the indirect channels of internal migration. Finally, this section concludes with an exercise that considers the role of climatic factors in both origin and destination states.

The results of the baseline model are presented in Table 3.4. The wage differential between origin and destination states is positive and statistically significant. An increase of 10% in this variable translates into an increase ranging from 12% to 23% in the average migration flow (when controlling for educational attainments). The share of the population with primary education attainment is significant and has a very strong effect on migration flows, an increase of 1% in this variable translates into an increase on the average migration flow of 1.7%. The shares of the population with either

secondary or tertiary education have a significant and negative effect on migration flows: an increase of 1% in these variables translates in a reduction of 0.5% in the average migration flow. The latter could be due to the fact that a high share of the population with high educational achievements acts as a proxy of certain positive amenities that attract well-educated people and act as a pull factor for migration. The three education variables are highly correlated, which can be observed when accounting simultaneously for any two of them. I thus opt to only keep the share of tertiary education (which happens to be the most significant of the three) for capturing the stock of human capital in the remaining specifications of the model. Finally, the murder rate in the year previous to the migration period acts as a push factor, but its effect is small compared to other covariates. The increase in murder rates within the migration period is also positive and significant; a 10% increase in murder rates within the migration period contributes to increasing the average migration flow by 8%. It is worth noting that the values of the Pseudo R-Square<sup>14</sup> do not seem to change after I control for GDP per capita differentials and the variables related to both migration costs and murders. However, they do change albeit by a very small extent that is not captured by the number of decimal places presented in the table. This can be seen when looking at the values of the log-likelihood of each model. Adding educational variables rises the log-likelihoods, although this increase is very small; the highest log-likelihood is provided by the model accounting for tertiary education.

The results of the extended model including earthquakes and hurricanes are presented in Table 3.5. Under this specification, the number of earthquakes

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<sup>14</sup> This statistic is computed by comparing the values of the log-likelihood between the model including the intercept and the model including the selected covariates.

**Table 3.4** – Results from PPML regression - baseline model

|  | (1)                   | (2)                   | (3)                   | (4)                   | (5)                   | (6)                   |
|--|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| LN GDP DIFF <sub><i>ij,t</i></sub>     | 1.330***<br>(5.98)    | 1.124***<br>(5.17)    | 1.231***<br>(5.78)    | 1.132***<br>(4.93)    | 1.128***<br>(5.18)    | 1.117***<br>(5.01)    |
| LN DISTANCE <sub><i>ij</i></sub>       | -0.735***<br>(-10.98) | -0.735***<br>(-10.99) | -0.735***<br>(-10.99) | -0.735***<br>(-10.99) | -0.735***<br>(-10.99) | -0.735***<br>(-10.99) |
| CONTIGUITY <sub><i>ij</i></sub>        | 0.789***<br>(5.87)    | 0.790***<br>(5.89)    | 0.790***<br>(5.88)    | 0.790***<br>(5.89)    | 0.790***<br>(5.89)    | 0.790***<br>(5.89)    |
| LN MURDER <sub><i>i,t</i></sub>        | 0.168***<br>(3.07)    | 0.155***<br>(2.89)    | 0.166***<br>(3.02)    | 0.133**<br>(2.44)     | 0.157***<br>(2.89)    | 0.141***<br>(2.58)    |
| LN MURDER CHNG <sub><i>i,t</i></sub>   | 0.0998***<br>(3.56)   | 0.0887***<br>(3.11)   | 0.0963***<br>(3.34)   | 0.0780***<br>(2.82)   | 0.0895***<br>(3.14)   | 0.0817***<br>(2.95)   |
| LN PRIMARY EDU <sub><i>i,t</i></sub>   |                       | 1.709***<br>(3.02)    |                       |                       | 1.393**<br>(2.03)     | 0.786<br>(0.77)       |
| LN SECONDARY EDU <sub><i>i,t</i></sub> |                       |                       | -0.494***<br>(-2.65)  |                       | -0.170<br>(-0.78)     |                       |
| LN TERTIARY EDU <sub><i>i,t</i></sub>  |                       |                       |                       | -0.461***<br>(-3.12)  |                       | -0.274<br>(-1.04)     |
| Constant                               | 10.35***<br>(23.01)   | 3.311<br>(1.36)       | 11.79***<br>(18.20)   | 11.69***<br>(20.53)   | 5.109<br>(1.56)       | 7.909<br>(1.62)       |
| Pseudo $R^2$                           | 0.875                 | 0.876                 | 0.876                 | 0.876                 | 0.876                 | 0.876                 |
| Log-likelihood                         | -945616.5             | -944387.0             | -944797.1             | -944350.1             | -944331.2             | -944299.0             |
| Origen FE:                             | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   |
| Time-Destination FE:                   | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   |
| Observations                           | 1984                  | 1984                  | 1984                  | 1984                  | 1984                  | 1984                  |

<sup>1</sup>  $t$  statistics in parentheses

<sup>2</sup> \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.001$

<sup>3</sup> The dependent variable is the migration flow across Mexican states

<sup>4</sup> Robust standard errors clustered by origin-destination

during the migration period has a significant effect on migration flows, but only when the number of hurricanes of type 1 to 4 is not accounted for. The number of hurricanes of types 1 to 4 during the migration period limits internal migration: an additional hurricane decreases the average migration flow by 0.04%. The latter may be due to the loss of assets, or to liquidity constraints, that make migration an inadequate adaptation strategy.

Both the length and the magnitude of droughts and floods act as push factors for migration. The results from the models accounting for both droughts

**Table 3.5** – Results from PPML regression - earthquakes and hurricanes

|                          | (1)                   | (2)                   | (3)                   | (4)                   |
|--------------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| LN GDP DIFF $_{ij,t}$    | 1.132***<br>(4.93)    | 1.161***<br>(4.99)    | 1.503***<br>(5.32)    | 1.180***<br>(5.01)    |
| LN DISTANCE $_{ij}$      | -0.735***<br>(-10.99) | -0.735***<br>(-10.99) | -0.735***<br>(-11.00) | -0.735***<br>(-10.99) |
| CONTIGUITY $_{ij}$       | 0.790***<br>(5.89)    | 0.790***<br>(5.89)    | 0.790***<br>(5.90)    | 0.790***<br>(5.89)    |
| LN MURDER $_{i,t}$       | 0.133**<br>(2.44)     | 0.106*<br>(1.90)      | 0.130**<br>(2.25)     | 0.123*<br>(1.92)      |
| LN MURDER CHNG $_{i,t}$  | 0.0780***<br>(2.82)   | 0.0740***<br>(2.70)   | 0.0648**<br>(2.29)    | 0.0831***<br>(3.31)   |
| LN TERTIARY EDU $_{i,t}$ | -0.461***<br>(-3.12)  | -0.531***<br>(-3.56)  | -0.463***<br>(-3.24)  | -0.550***<br>(-3.83)  |
| EARTHQUAKES $_{i,t}$     |                       | -0.0370*<br>(-1.72)   | -0.0185<br>(-0.83)    | -0.0375*<br>(-1.75)   |
| HURRICANE 1-4 $_{i,t}$   |                       |                       | -0.0444***<br>(-3.09) |                       |
| HURRICANE 3-4 $_{i,t}$   |                       |                       |                       | -0.0562<br>(-0.90)    |
| Constant                 | 11.69***<br>(20.53)   | 11.88***<br>(21.19)   | 11.74***<br>(21.04)   | 11.95***<br>(20.90)   |
| Pseudo $R^2$             | 0.876                 | 0.876                 | 0.876                 | 0.876                 |
| Log-likelihood           | -944350.1             | -944113.1             | -943259.3             | -943916.3             |
| Origin FE:               | Yes                   | Yes                   | Yes                   | Yes                   |
| Time-Destination FE:     | Yes                   | Yes                   | Yes                   | Yes                   |
| Observations             | 1984                  | 1984                  | 1984                  | 1984                  |

<sup>1</sup>  $t$  statistics in parentheses

<sup>2</sup> \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.001$

<sup>3</sup> The dependent variable is the migration flow across Mexican states

<sup>4</sup> Robust standard errors clustered by origin-destination

and floods are presented in Table 3.6. For practical reasons, this table only shows the coefficients of hurricanes, earthquakes, and the different measures of droughts and floods. Table 3.16 and Table 3.17 in the Appendix present these results including all covariates in the models. The length of droughts has a positive and significant effect on migration flows. One additional month in the longest drought episode during the migration period is associated to an increase in the average migration flow by 0.46%, while an additional month of all drought episodes is associated to an increase of 0.2%. In the case of

floods, both their length and magnitude have a positive effect on the average migration flow. An additional month within the longest flood episode during the migration period increases the average migration flow by 0.52%, while an increase of one unit in the magnitude of the longest flood episode during the migration period increases the average migration flow by 0.3%. These results are consistent with the findings of [Coniglio and Pesce \(2015\)](#) in the case of international migration, but contrast with the results of [Dallmann and Millock \(2013\)](#) who find that floods are not significant for explaining migration flows across Indian states. The latter could be due to the fact that these studies consider different countries.

Predicted values of the average migration flow show the predominant role of income differentials as a push factor. Figure 3.5 presents the predicted value of the average migration flow for different levels of GDP DIFF, MURDER CHNG, DROUGHT LENGTH LONG, and FLOOD LENGTH ALL. The three former predictions are based on the model presented in Table 3.6 that considers DROUGHT LENGTH LONG as the covariate accounting for changes in precipitation, while the latter prediction is based on the model that accounts for FLOOD LENGTH ALL. The predicted average migration flow would be of 1,154 in a state where the GDP differential is close to zero (and the remaining covariates are evaluated at mean values). However, as can be seen in this figure, the predicted migration flow for states with higher GDP per capita differentials tends to grow more than proportionally. When the GDP per capita differential doubles, the predicted average migration flow is 3,278, and when it triples its value reaches 5,125. The latter is 4.5 times higher than the predicted value for an average state in which the logarithm of GDP per capita differential is close zero. This non-linearity is less marked in the rest of the covariates presented in this figure. An average state for which the

Table 3.6 – Results from PPML regression - droughts and floods during the migration period

|                           | (1)                   | (2)                  | (3)                   | (4)                   | (5)                   | (6)                 | (7)                  | (8)                  | (9)                  | (10)                 |
|---------------------------|-----------------------|----------------------|-----------------------|-----------------------|-----------------------|---------------------|----------------------|----------------------|----------------------|----------------------|
| HURRICANE $1-4_{i,t}$     | -0.0508***<br>(-3.51) | -0.0232*<br>(-1.81)  | -0.0376***<br>(-2.97) | -0.0379***<br>(-2.92) | -0.0455***<br>(-3.43) | -0.160*<br>(-1.92)  | -0.0327**<br>(-2.28) | -0.0361**<br>(-2.39) | -0.0297**<br>(-2.06) | -0.0343**<br>(-2.26) |
| EARTHQUAKES $i,t$         | -0.0305<br>(-1.34)    | -0.0123<br>(-0.54)   | -0.0143<br>(-0.62)    | -0.0106<br>(-0.45)    | -0.0207<br>(-0.88)    | -0.0221<br>(-0.23)  | -0.0235<br>(-1.10)   | -0.0240<br>(-1.09)   | -0.0253<br>(-1.17)   | -0.0252<br>(-1.15)   |
| DROUGHT FREQ LONG $i,t$   | -0.00595<br>(-1.32)   |                      |                       |                       |                       |                     |                      |                      |                      |                      |
| DROUGHT LENGTH LONG $i,t$ |                       | 0.00461***<br>(3.33) |                       |                       |                       |                     |                      |                      |                      |                      |
| DROUGHT MAG LONG $i,t$    |                       |                      | 0.00226<br>(0.98)     |                       |                       |                     |                      |                      |                      |                      |
| DROUGHT LENGTH ALL $i,t$  |                       |                      |                       | 0.00209*<br>(1.85)    |                       |                     |                      |                      |                      |                      |
| DROUGHT MAG ALL $i,t$     |                       |                      |                       |                       | -0.000654<br>(-0.34)  |                     |                      |                      |                      |                      |
| FLOOD FREQ LONG $i,t$     |                       |                      |                       |                       |                       | 0.0212<br>(0.94)    |                      |                      |                      |                      |
| FLOOD LENGTH LONG $i,t$   |                       |                      |                       |                       |                       |                     | 0.00526***<br>(5.24) |                      |                      |                      |
| FLOOD MAG LONG $i,t$      |                       |                      |                       |                       |                       |                     |                      | 0.00311***<br>(2.73) |                      |                      |
| FLOOD LENGTH ALL $i,t$    |                       |                      |                       |                       |                       |                     |                      |                      | 0.00526***<br>(5.38) |                      |
| FLOOD MAG ALL $i,t$       |                       |                      |                       |                       |                       |                     |                      |                      |                      | 0.00361***<br>(3.01) |
| Constant                  | 11.84***<br>(20.75)   | 11.36***<br>(20.31)  | 11.65***<br>(20.45)   | 11.51***<br>(19.86)   | 11.78***<br>(20.05)   | 8.002***<br>(68.00) | 11.09***<br>(20.73)  | 11.28***<br>(20.90)  | 10.86***<br>(20.35)  | 11.16***<br>(20.56)  |
| Pseudo $R^2$              | 0.876                 | 0.876                | 0.876                 | 0.876                 | 0.876                 | 0.015               | 0.876                | 0.876                | 0.876                | 0.876                |
| Log-likelihood            | -942981.0             | -942228.3            | -943186.2             | -942961.3             | -943248.2             | -7476090.3          | -941346.2            | -942658.7            | -941100.3            | -942469.2            |
| Origin FE:                | Yes                   | Yes                  | Yes                   | Yes                   | Yes                   | Yes                 | Yes                  | Yes                  | Yes                  | Yes                  |
| Time-Destination FE:      | Yes                   | Yes                  | Yes                   | Yes                   | Yes                   | Yes                 | Yes                  | Yes                  | Yes                  | Yes                  |
| Observations              | 1984                  | 1984                 | 1984                  | 1984                  | 1984                  | 1984                | 1984                 | 1984                 | 1984                 | 1984                 |

- 1  $t$  statistics in parentheses  
2 \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.001$   
3 The dependent variable is the migration flow across Mexican states  
4 Robust standard errors clustered by origin-destination

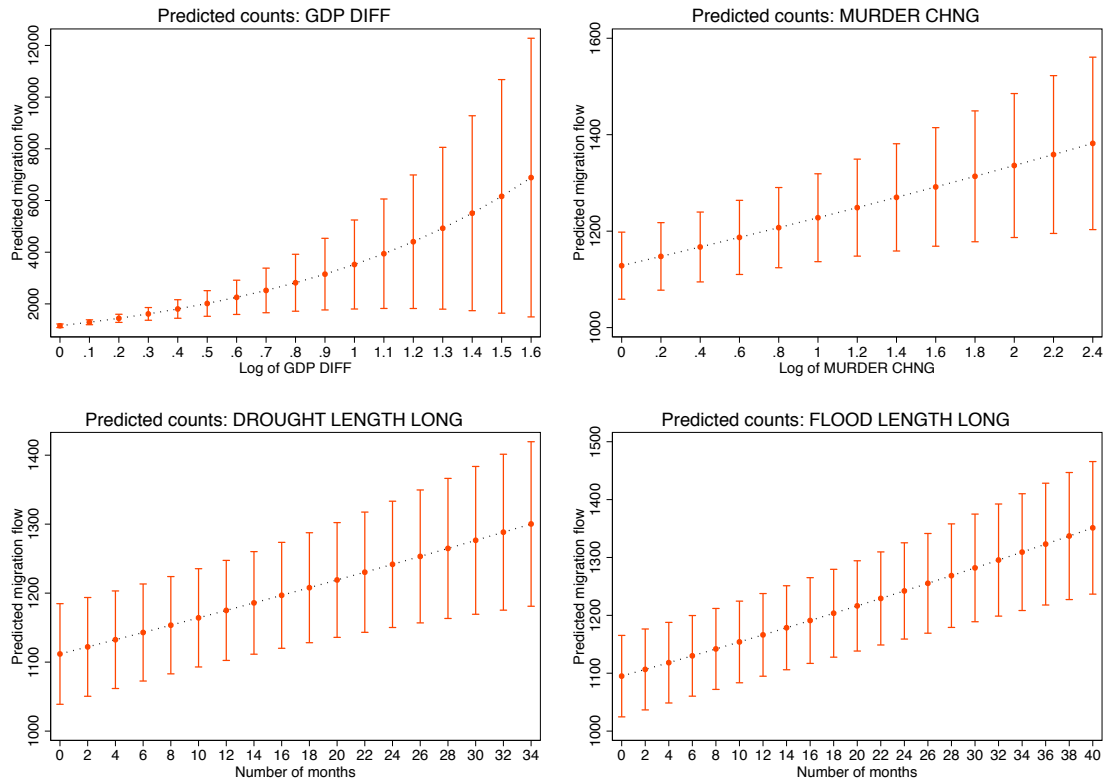
murder rate stayed the same from the beginning to the end of the migration period has predicted average migration flow of 1,128; if we consider the highest increase in murder rates observed in the sample (11 times), the predicted average migration flow increases up to 1,394 which accounts for an increase 1.2 times higher than in the previous case (i.e. 20% higher). Similar effects can be observed when comparing the predicted average migration flow between the lowest and highest values for the length of the longest drought and the total length of flood episodes. An average state been affected by drought lasting 20 months has a predicted average migration flow 11% higher than an average state characterised by no droughts; for an average state experiencing a drought lasting 34 months, the expected migration flow is 19% higher than for a state without any drought. Finally, with regard to floods, an average state experiencing 40 months of moderate and severe floods has a predicted average migration flow 24% higher than that of an average state with no floods.

### 3.5.1 Robustness checks

Robustness checks show that the influence of climatic factors on internal migration does not depend on the stage of development or the importance of agriculture in the state of origin. To account for potential heterogeneity, I interact climatic variables with GDP per capita differentials and the share of GDP in agriculture. Through the latter, I allow the effects of climatic factors to further depend of the level of development of each state and the extent to which their economy depends on agriculture. Similar approaches have also been considered by [Beine and Parsons \(2015\)](#) and [Coniglio and Pesce \(2015\)](#).

Table 3.7 presents the result of an alternative specification in which the length and magnitude of droughts are interacted with the GDP differential

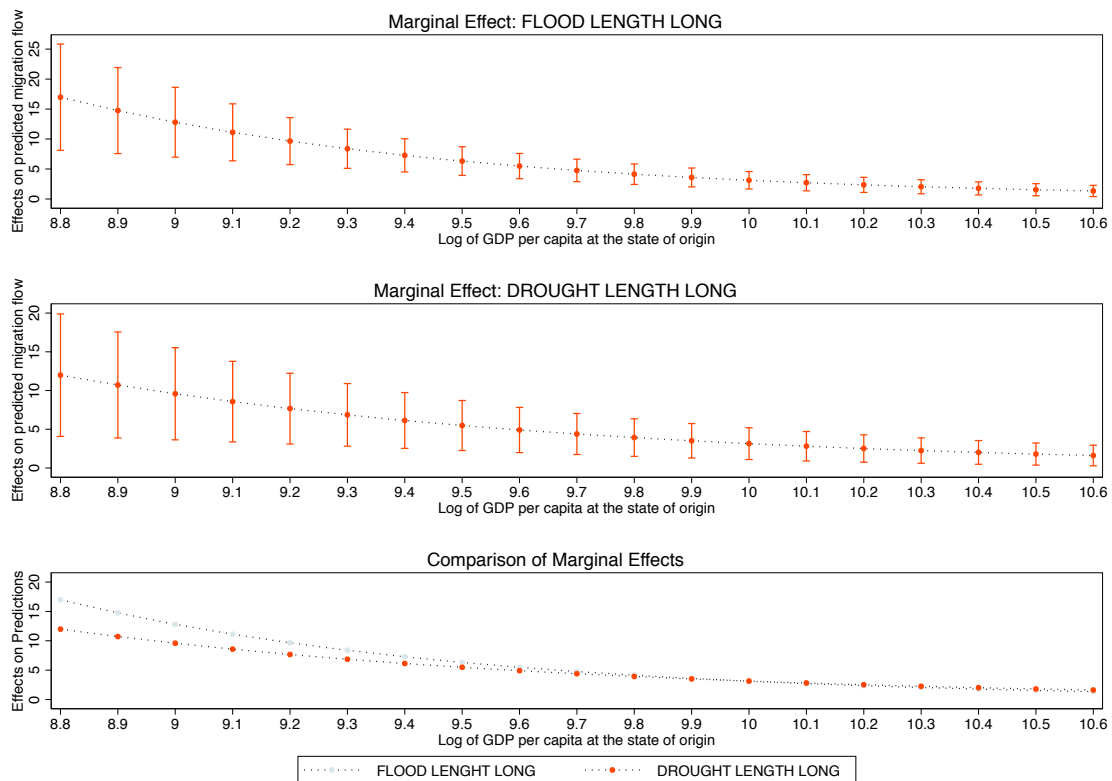


**Figure 3.5** – Predicted average migration flows for different covariates

**Note:** Estimation based on the model presented in Table 3.6 when considering FLOOD LENGTH ALL as the covariate accounting for the extent of floods; all covariates are expressed in logarithmic terms; all covariates for which values are not specified are evaluated at their mean values.

and the percentage of GDP in agriculture in the state of origin. None of these interactions are significant. The estimated coefficient of the length of the longest drought during the migration period remains significant and within the same order of magnitude as in the case of the baseline model when interacted with both variables. The magnitude of the longest drought is significant when interacted with the share of GDP in agriculture. The share of agriculture in the state of origin is negative and significant for both models.

**Figure 3.6** – Marginal effects of the length of droughts and floods across different levels of GDP per capita in the state of origin



**Note:** the estimated effects come from the models presented in Table 3.6 when considering DROUGHT LENGTH LONG and FLOOD LENGTH LONG as the covariates accounting for the extent of precipitation. Confidence intervals at 95%. Remaining covariates are evaluated at their mean values.

Table 3.8 presents the results of the interactions between GDP differential and the share of GDP in agriculture with respect to the number of hurricanes, and the length and magnitude of the longest flood during the migration period. As in the case of droughts, the interactions with GDP differential and share of GDP in agriculture are not significant. However, the interaction between hurricanes and the two measures of floods is significant and positive. Although the interpretation of this result should be done with caution, it

seems to suggest that hurricanes limit migration flows when floods are not present; however, when floods and hurricanes are present in the state of origin, the latter enhance the former and the overall combined effect acts as a push factor for migration.

**Table 3.7** – Results from PPML regression - interaction between droughts and both GDP DIFF and GDP AGRI

|  | (1)                   | (2)                   | (3)                   | (4)                   |
|--|-----------------------|-----------------------|-----------------------|-----------------------|
| LN GDP DIFF <sub>ij,t</sub>                                  | 1.224***<br>(3.51)    | 1.350***<br>(3.64)    | 0.852***<br>(3.55)    | 1.014***<br>(3.92)    |
| LN DISTANCE <sub>ij</sub>                                    | -0.733***<br>(-10.87) | -0.735***<br>(-10.94) | -0.735***<br>(-11.02) | -0.735***<br>(-11.02) |
| CONTIGUITY <sub>ij</sub>                                     | 0.793***<br>(5.87)    | 0.790***<br>(5.86)    | 0.790***<br>(5.90)    | 0.790***<br>(5.90)    |
| LN MURDER <sub>i,t</sub>                                     | 0.122<br>(1.44)       | 0.140**<br>(1.97)     | 0.0926<br>(1.34)      | 0.0874<br>(1.33)      |
| LN MURDER CHNG <sub>i,t</sub>                                | 0.0928**<br>(2.55)    | 0.0673**<br>(2.04)    | 0.106***<br>(4.02)    | 0.0972***<br>(3.70)   |
| LN TERTIARY EDU <sub>i,t</sub>                               | -0.334**<br>(-2.02)   | -0.451***<br>(-3.05)  | -0.459***<br>(-3.34)  | -0.553***<br>(-3.96)  |
| HURRICANE 1-4 <sub>i,t</sub>                                 | -0.0255*<br>(-1.88)   | -0.0369***<br>(-2.68) | -0.0342**<br>(-2.55)  | -0.0448***<br>(-3.28) |
| EARTHQUAKES <sub>i,t</sub>                                   | -0.0146<br>(-0.62)    | -0.0141<br>(-0.61)    | 0.00610<br>(0.27)     | 0.00936<br>(0.40)     |
| DROUGHT LENGTH LONG <sub>i,t</sub>                           | 0.00443***<br>(2.92)  |                       | 0.00674***<br>(2.63)  |                       |
| DROUGHT LENGTH LONG <sub>i,t</sub> *GDP DIFF <sub>ij,t</sub> | -0.00255<br>(-0.41)   |                       |                       |                       |
| DROUGHT MAG LONG <sub>i,t</sub>                              |                       | 0.00220<br>(0.96)     |                       | 0.00817*<br>(1.91)    |
| DROUGHT MAG LONG <sub>i,t</sub> *GDP DIFF <sub>ij,t</sub>    |                       | 0.00125<br>(0.12)     |                       |                       |
| GDP AGRI <sub>i,t</sub>                                      |                       |                       | -0.0682***<br>(-4.60) | -0.0743***<br>(-4.60) |
| DROUGHT LENGTH LONG <sub>i,t</sub> *GDP AGRI <sub>i,t</sub>  |                       |                       | -0.000319<br>(-1.00)  |                       |
| DROUGHT MAG LONG <sub>i,t</sub> *GDP AGRI <sub>i,t</sub>     |                       |                       |                       | -0.000625<br>(-1.40)  |
| Constant   | 11.20***<br>(16.77)   | 11.68***<br>(19.24)   | 11.84***<br>(20.38)   | 12.19***<br>(20.65)   |
| Pseudo R <sup>2</sup>  | 0.876                 | 0.876                 | 0.876                 | 0.876                 |
| Log-likelihood   | -941958.2             | -943161.9             | -940514.0             | -941239.6             |
| Origen FE:   | Yes                   | Yes                   | Yes                   | Yes                   |
| Time-Destination FE:   | Yes                   | Yes                   | Yes                   | Yes                   |
| Observations   | 1984                  | 1984                  | 1984                  | 1984                  |

<sup>1</sup> *t* statistics in parentheses<sup>2</sup> \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.001$ <sup>3</sup> The dependent variable is the migration flow across Mexican states<sup>4</sup> Robust standard errors clustered by origin-destination

**Table 3.8** – Results from PPML regression - interaction between floods and both GDP DIFF and GDP AGRI

|  | (1)                   | (2)                   | (3)                   | (4)                   | (5)                   | (6)                   |
|--|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| LN GDP DIFF <sub>ij,t</sub>                                    | 1.493***<br>(4.64)    | 1.429***<br>(3.94)    | 1.012***<br>(4.24)    | 1.132***<br>(4.39)    | 0.885***<br>(3.81)    | 1.155***<br>(4.64)    |
| LN DISTANCE <sub>ij</sub>                                      | -0.734***<br>(-10.87) | -0.736***<br>(-10.94) | -0.735***<br>(-11.02) | -0.735***<br>(-11.01) | -0.736***<br>(-11.02) | -0.735***<br>(-11.01) |
| CONTIGUITY <sub>ij</sub>                                       | 0.792***<br>(5.86)    | 0.789***<br>(5.85)    | 0.790***<br>(5.90)    | 0.790***<br>(5.90)    | 0.790***<br>(5.90)    | 0.790***<br>(5.90)    |
| LN MURDER <sub>i,t</sub>                                       | 0.189**<br>(2.18)     | 0.151**<br>(2.15)     | 0.188***<br>(3.15)    | 0.114*<br>(1.86)      | 0.190***<br>(3.25)    | 0.145**<br>(2.47)     |
| LN MURDER CHNG <sub>i,t</sub>                                  | 0.0990**<br>(2.54)    | 0.0819**<br>(2.38)    | 0.0990***<br>(3.90)   | 0.0906***<br>(3.40)   | 0.0645**<br>(2.08)    | 0.0705**<br>(2.28)    |
| LN TERTIARY EDU <sub>i,t</sub>                                 | -0.252<br>(-1.64)     | -0.340**<br>(-2.40)   | -0.436***<br>(-3.28)  | -0.537***<br>(-3.82)  | -0.212<br>(-1.53)     | -0.240<br>(-1.64)     |
| HURRICANE 1-4 <sub>i,t</sub>                                   | -0.0344**<br>(-2.39)  | -0.0347**<br>(-2.18)  | -0.0303**<br>(-2.15)  | -0.0460***<br>(-3.11) | -0.0590***<br>(-3.28) | -0.0586***<br>(-2.97) |
| EARTHQUAKES <sub>i,t</sub>                                     | -0.0250<br>(-1.13)    | -0.0236<br>(-1.08)    | -0.00491<br>(-0.20)   | -0.000993<br>(-0.04)  | -0.0316<br>(-1.61)    | -0.0170<br>(-0.78)    |
| FLOOD LENGTH LONG <sub>i,t</sub>                               | 0.00506***<br>(4.63)  |                       | 0.00348**<br>(2.54)   |                       | 0.00428***<br>(4.03)  |                       |
| FLOOD LENGTH LONG <sub>i,t</sub> *GDP DIFF <sub>ij,t</sub>     | -0.00213<br>(-0.34)   |                       |                       |                       |                       |                       |
| FLOOD MAG LONG <sub>i,t</sub>                                  |                       | 0.00315***<br>(2.83)  |                       | 0.00130<br>(0.89)     |                       | 0.00250**<br>(2.06)   |
| FLOOD MAG LONG <sub>i,t</sub> *GDP DIFF <sub>ij,t</sub>        |                       | 0.00168<br>(0.16)     |                       |                       |                       |                       |
| GDP AGRI <sub>i,t</sub>  |                       |                       | -0.0378**<br>(-2.12)  | -0.0602***<br>(-3.33) |                       |                       |
| FLOOD LENGTH LONG <sub>i,t</sub> *GDP AGRI <sub>i,t</sub>      |                       |                       | 0.000225<br>(1.25)    |                       |                       |                       |
| FLOOD MAG LONG <sub>i,t</sub> *GDP AGRI <sub>i,t</sub>         |                       |                       |                       | 0.0000226<br>(0.08)   |                       |                       |
| FLOOD LENGTH LONG <sub>i,t</sub> *HURRICANE 1-4 <sub>i,t</sub> |                       |                       |                       |                       | 0.00468***<br>(4.01)  |                       |
| FLOOD MAG LONG <sub>i,t</sub> *HURRICANE 1-4 <sub>i,t</sub>    |                       |                       |                       |                       |                       | 0.00800***<br>(2.98)  |
| Constant   | 10.97***<br>(17.15)   | 11.31***<br>(19.69)   | 11.72***<br>(20.33)   | 12.16***<br>(20.04)   | 10.88***<br>(20.32)   | 11.00***<br>(19.90)   |
| Pseudo R <sup>2</sup>  | 0.876                 | 0.876                 | 0.876                 | 0.876                 | 0.876                 | 0.876                 |
| Log-likelihood   | -941159.6             | -942615.3             | -940551.6             | -941377.2             | -939414.9             | -941555.6             |
| Origen FE:   | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   |
| Time-Destination FE:   | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   |
| Observations   | 1984                  | 1984                  | 1984                  | 1984                  | 1984                  | 1984                  |

<sup>1</sup> *t* statistics in parentheses

<sup>2</sup> \* *p* < 0.10, \*\* *p* < 0.05, \*\*\* *p* < 0.001

<sup>3</sup> The dependent variable is the migration flow across Mexican states

<sup>4</sup> Robust standard errors clustered by origin-destination

As an additional robustness check, I run the full model considering a subsample that does not contain the corridor Distrito Federal - Mexico. As discussed in the background section, the most important population flow in Mexico takes place between these two states. These results are presented in Table 3.18 and Table 3.19 in the Appendix. Overall, with the exception of some coefficients, the results are very close to those of the full sample. For instance, the coefficient of MURDER is higher and more significant in all specifications when the corridor is not considered. This could be explained by the fact that the increase in criminal activity experienced in the last decade mostly took place outside these two states. Regarding climatic variables, the only significant coefficient among drought variables is that of DROUGHT LENGTH LONG, but its value is lower when the corridor is not considered. In the case of flood variables, their significance is barely affected when considering the subsample, while the values of their coefficients tend to be slightly higher.

### 3.5.2 Indirect channels to internal migration

Floods and drought may further influence internal migration in Mexico through indirect channels. The previous results suggest that floods and droughts have a direct influence on internal migration in Mexico. However, they do not exclude the possibility that the frequency or length of either floods or droughts may further influence internal migration through indirect channels. As previously discussed, climatic changes may have a negative impact on wages in the place of origin and, in turn, influence the decision to migrate to another place. Indeed, studies such as [Munshi \(2003\)](#) and [Feng et al. \(2010\)](#) have shown that climatic factors indirectly influence Mexican migration to the United States. To test for the presence of these indirect channels, I

regress income differentials between destination and origin states expressed in logarithmic terms (i.e. the covariate GDP DIFF used in the previous regressions) on disaster and weather-related variables, while controlling for murder and education. The results of the regressions accounting for drought covariates are presented in Table 3.9 and those accounting for flood covariates are shown in Table 3.10. The change in the murder rate in the place of origin within the migration period is positive but only significant in one of the ten specifications of the model. The rest of the variables are significant in every specification. The share of the population with tertiary education in the place of origin has a negative effect on income differentials: a higher accumulation of human capital in the place of origin has positive impacts on GDP per capita in the place of origin reducing income differential between the origin and destination. With regard to disasters, hurricanes have a positive and robust effect on wage differentials. The effect of earthquakes is positive but only significant when controlling for droughts and the frequency of floods. The robust results from hurricanes suggest that this natural phenomenon puts pressure on wages or income in the place of origin, further widening the income differential. Drought and flood covariates have a similar effect on income differential. These results suggest that climatic changes influence internal migration in Mexico through both direct and indirect channels. Moreover, the results are consistent with the information presented in the background section concerning the negative effects of hurricanes, floods, and droughts on GDP in certain regions of the country.

In light of the previous results, I carry out an exercise considering a different measure accounting for wage differentials. Indeed, considering the potential endogeneity of GDP, I run the full model using a deprivation index as proxy of income or wages. This index accounts for deprivation in a number of

**Table 3.9** – Results from linear regression - effects of droughts on income differential

|                              | (1)                   | (2)                  | (3)                  | (4)                  | (5)                  |
|------------------------------|-----------------------|----------------------|----------------------|----------------------|----------------------|
| LN MURDER CHNG $_{i,t}$      | 0.00378<br>(1.01)     | 0.00533<br>(1.42)    | 0.00468<br>(1.27)    | 0.00389<br>(1.03)    | 0.00343<br>(0.91)    |
| LN TERTIARY EDU $_{i,t}$     | -0.0601***<br>(-2.64) | -0.0476**<br>(-2.04) | -0.0579**<br>(-2.51) | -0.0495**<br>(-2.18) | -0.0533**<br>(-2.41) |
| HURRICANE 1-4 $_{i,t}$       | 0.00553***<br>(5.14)  | 0.00508***<br>(4.43) | 0.00553***<br>(4.96) | 0.00331***<br>(2.97) | 0.00321***<br>(2.86) |
| EARTHQUAKES $_{i,t}$         | 0.0109***<br>(4.66)   | 0.00841***<br>(3.62) | 0.0112***<br>(4.41)  | 0.0111***<br>(4.54)  | 0.0128***<br>(5.00)  |
| DROUGHT FREQ LONG $_{i,t}$   | 0.00246***<br>(4.20)  |                      |                      |                      |                      |
| DROUGHT LENGTH LONG $_{i,t}$ |                       | 0.00157***<br>(9.62) |                      |                      |                      |
| DROUGHT MAG LONG $_{i,t}$    |                       |                      | 0.00262***<br>(8.17) |                      |                      |
| DROUGHT LENGTH ALL $_{i,t}$  |                       |                      |                      | 0.00105***<br>(7.05) |                      |
| DROUGHT MAG ALL $_{i,t}$     |                       |                      |                      |                      | 0.00178***<br>(5.83) |
| Constant                     | 0.136**<br>(2.02)     | 0.0820<br>(1.18)     | 0.109<br>(1.60)      | 0.0948<br>(1.41)     | 0.102<br>(1.58)      |
| $R^2$                        | 0.997                 | 0.997                | 0.997                | 0.997                | 0.997                |
| Origen FE:                   | Yes                   | Yes                  | Yes                  | Yes                  | Yes                  |
| Time-Destination FE:         | Yes                   | Yes                  | Yes                  | Yes                  | Yes                  |
| Observations                 | 1984                  | 1984                 | 1984                 | 1984                 | 1984                 |

<sup>1</sup>  $t$  statistics in parentheses

<sup>2</sup> \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.001$

<sup>3</sup> The dependent variable is the log of income differential in 2005 and 2010

<sup>4</sup> Robust standard errors clustered by origin-destination

dimensions associated to well-being such as income, education, and access to basic services<sup>15</sup>. I express this new variable as the logarithm of ratio of the deprivation index in the state of destination over that of the state of origin. Table 3.11 compares the coefficients of all weather variables between the specifications considering GDP and the deprivation index. The complete set of results from regressing internal migration flows on this new proxy of

<sup>15</sup> This index is produced by the Committee for Social Development Policy Evaluation (CONEVAL). It is a standardised index ranging from -3 to 3, implying low to high deprivation. In order to facilitate the interpretation of this variable, I rescale it from 1 to 10; 1 being the lowest deprivation level and 10 the highest.



**Table 3.10** – Results from linear regression - effects of floods on income differential

|                            | (1)                  | (2)                   | (3)                  | (4)                   | (5)                  |
|----------------------------|----------------------|-----------------------|----------------------|-----------------------|----------------------|
| LN MURDER CHNG $_{i,t}$    | 0.00110<br>(0.28)    | 0.00538<br>(1.43)     | 0.00265<br>(0.67)    | 0.00615*<br>(1.66)    | 0.00314<br>(0.81)    |
| LN TERTIARY EDU $_{i,t}$   | -0.0595**<br>(-2.48) | -0.0564**<br>(-2.44)  | -0.0588**<br>(-2.44) | -0.0578**<br>(-2.47)  | -0.0606**<br>(-2.51) |
| HURRICANE 1-4 $_{i,t}$     | 0.00608***<br>(5.42) | 0.00744***<br>(6.34)  | 0.00687***<br>(6.02) | 0.00755***<br>(6.45)  | 0.00693***<br>(6.07) |
| EARTHQUAKES $_{i,t}$       | 0.00457**<br>(2.29)  | 0.000381<br>(0.21)    | 0.00202<br>(1.08)    | 0.00105<br>(0.56)     | 0.00221<br>(1.14)    |
| FLOOD FREQ LONG $_{i,t}$   | 0.00185***<br>(6.26) |                       |                      |                       |                      |
| FLOOD LENGTH LONG $_{i,t}$ |                      | 0.00186***<br>(13.58) |                      |                       |                      |
| FLOOD MAG LONG $_{i,t}$    |                      |                       | 0.00163***<br>(9.71) |                       |                      |
| FLOOD LENGTH ALL $_{i,t}$  |                      |                       |                      | 0.00157***<br>(11.81) |                      |
| FLOOD MAG ALL $_{i,t}$     |                      |                       |                      |                       | 0.00149***<br>(8.59) |
| Constant                   | 0.117*<br>(1.66)     | 0.0780<br>(1.16)      | 0.105<br>(1.49)      | 0.0776<br>(1.15)      | 0.100<br>(1.44)      |
| $R^2$                      | 0.997                | 0.997                 | 0.997                | 0.997                 | 0.997                |
| Origen FE:                 | Yes                  | Yes                   | Yes                  | Yes                   | Yes                  |
| Time-Destination FE:       | Yes                  | Yes                   | Yes                  | Yes                   | Yes                  |
| Observations               | 1984                 | 1984                  | 1984                 | 1984                  | 1984                 |

<sup>1</sup>  $t$  statistics in parentheses

<sup>2</sup> \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.001$

<sup>3</sup> The dependent variable is the log of income differential in 2005 and 2010

<sup>4</sup> Robust standard errors clustered by origin-destination

wage differential - while accounting for drought and floods - are presented in the Appendix in Table 3.20 and Table 3.21. Results show that the variables accounting for the length and magnitude of droughts are both positive and significant when considering the deprivation index (MARG DIFF). In the case of GDP per capita differential, only the variables considering the length of droughts are significant. Moreover, the values of the coefficients of drought variables are higher under this alternative specification. The opposite happens to the coefficients of flood variables, which are consistently lower than in the GDP-based specification; coefficients related to the magnitude of floods

lose significance under the specification using deprivation as proxy of wages. With regard to the remaining covariates, the first thing to notice is that the coefficient of the deprivation differential is negative and very robust across all specifications. The latter suggests that states with low deprivation tend to be more attractive as potential destinations. The change in murder rates is positive and significant, while the variables accounting for migration costs are robust and have the same signs as in the GDP-based model. An interesting result concerns the effects of hurricanes. When using the deprivation index as a proxy of wages, the effect of hurricanes on migration is positive, but only significant when floods are not controlled for.

**Table 3.11** – Results from PPML regression - comparison between GDP DFF and MARG DIFF

|                              | GDP DIFF             | MARG DIFF            |
|------------------------------|----------------------|----------------------|
| DROUGHT FREQ LONG $_{i,t}$   | -0.00595<br>(-1.32)  | 0.00246<br>(0.59)    |
| DROUGHT LENGTH LONG $_{i,t}$ | 0.00461***<br>(3.33) | 0.00668***<br>(4.90) |
| DROUGHT MAG LONG $_{i,t}$    | 0.00226<br>(0.98)    | 0.00836***<br>(3.83) |
| DROUGHT LENGTH ALL $_{i,t}$  | 0.00209*<br>(1.85)   | 0.00430***<br>(3.71) |
| DROUGHT MAG ALL $_{i,t}$     | -0.000654<br>(-0.34) | 0.00349*<br>(1.80)   |
| FLOOD FREQ LONG $_{i,t}$     | 0.0212<br>(0.94)     | 0.00309<br>(1.07)    |
| FLOOD LENGTH LONG $_{i,t}$   | 0.00526***<br>(5.24) | 0.00383**<br>(2.53)  |
| FLOOD MAG LONG $_{i,t}$      | 0.00311***<br>(2.73) | 0.00157<br>(1.11)    |
| FLOOD LENGTH ALL $_{i,t}$    | 0.00526***<br>(5.38) | 0.00364**<br>(2.34)  |
| FLOOD MAG ALL $_{i,t}$       | 0.00361***<br>(3.01) | 0.00182<br>(1.20)    |
| Origen FE:                   | Yes                  | Yes                  |
| Time-Destination FE:         | Yes                  | Yes                  |
| Observations                 | 1984                 | 1984                 |

<sup>1</sup>  $t$  statistics in parentheses

<sup>2</sup> \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.001$

<sup>3</sup> The dependent variable is the migration flow across Mexican states

<sup>4</sup> Robust standard errors clustered by origin-destination

### 3.5.3 Differences in climatic factors between the state of origin and the state of destination

I conclude the analysis by considering an alternative specification of the full model that accounts for both natural disasters and climatic variables in both the origin and destination states. For the latter, I express all these variables as destination-origin differentials<sup>16</sup>. Building on the results from the previous paragraph, I test two different specifications. The first specification accounts for wage differentials through GDP per capita; the second specification does so through the deprivation index. The results from the latter are presented in Table 3.12, while the results from the former are presented in Table 3.13. In both specifications the differentials of climatic variables are significant and negative. This suggests that climatic factors act as push factors for migration, but also that migration flows are on average attracted to destinations characterised by better climatic conditions. With regard to natural disasters, the first thing to note is that the differential of earthquakes is not significant in both specifications. In the case of hurricanes, results tend to completely differ between the two specifications. Indeed, when using the deprivation index to account for wage differentials, the coefficient of hurricanes is negative and only significant when floods are not accounted for; but when GDP per capita is used instead, the differential of hurricanes is both significant and positive even when floods are controlled for. This result further highlights the potential endogeneity of GDP per capita. Finally, for the remaining covariates, using the deprivation index tends to capture the effects of education and murders since these variables are not significant in this specification. However, changes in the murder rate during the migration period is positive

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<sup>16</sup> Differentials are computed as the difference between the values in the state of destination and the state of origin

and a robust push factor for migration in both specifications.

**Table 3.12** – Results from PPML regression - difference in climatic factors between origins and destinations - deprivation index

|  | (1)                   | (2)                    | (3)                    | (4)                   | (5)                   |
|--|-----------------------|------------------------|------------------------|-----------------------|-----------------------|
| LN MARG DIFF <sub>ij,t</sub>             | -1.684***<br>(-4.07)  | -1.544***<br>(-4.20)   | -1.747***<br>(-4.35)   | -1.108**<br>(-1.99)   | -1.061*<br>(-1.80)    |
| LN DISTANCE <sub>ij</sub>                | -0.735***<br>(-10.99) | -0.735***<br>(-11.01)  | -0.735***<br>(-11.00)  | -0.735***<br>(-11.00) | -0.735***<br>(-10.99) |
| CONTIGUITY <sub>ij</sub>                 | 0.791***<br>(5.89)    | 0.791***<br>(5.90)     | 0.791***<br>(5.90)     | 0.790***<br>(5.89)    | 0.790***<br>(5.89)    |
| LN MURDER <sub>i,t</sub>                 | 0.0204<br>(0.34)      | 0.0646<br>(1.04)       | 0.0432<br>(0.71)       | 0.0980<br>(1.42)      | 0.0874<br>(1.28)      |
| LN MURDER CHNG <sub>i,t</sub>            | 0.0630**<br>(2.23)    | 0.0931***<br>(3.60)    | 0.0829***<br>(3.16)    | 0.0815**<br>(2.53)    | 0.0880***<br>(2.58)   |
| LN TERTIARY EDU <sub>i,t</sub>           | -0.292*<br>(-1.66)    | -0.112<br>(-0.64)      | -0.116<br>(-0.62)      | -0.285<br>(-1.59)     | -0.271<br>(-1.53)     |
| HURRICANE DIFF <sub>ij,t</sub>           | -0.0140<br>(-1.18)    | -0.0271**<br>(-2.21)   | -0.0195*<br>(-1.67)    | -0.0155<br>(-1.32)    | -0.0174<br>(-1.46)    |
| EARTHQUAKE DIFF <sub>ij,t</sub>          | 0.0187<br>(0.80)      | 0.00753<br>(0.32)      | 0.000693<br>(0.03)     | 0.0246<br>(1.08)      | 0.0260<br>(1.13)      |
| DROUGHT LENGTH LONG DIFF <sub>ij,t</sub> |                       | -0.00668***<br>(-4.90) |                        |                       |                       |
| DROUGHT LENGTH ALL DIFF <sub>ij,t</sub>  |                       |                        | -0.00430***<br>(-3.71) |                       |                       |
| FLOOD LENGTH LONG DIFF <sub>ij,t</sub>   |                       |                        |                        | -0.00383**<br>(-2.53) |                       |
| FLOOD LENGTH ALL DIFF <sub>ij,t</sub>    |                       |                        |                        |                       | -0.00364**<br>(-2.34) |
| Constant                                 | 10.92***<br>(17.77)   | 10.44***<br>(16.73)    | 10.40***<br>(15.89)    | 11.01***<br>(17.27)   | 10.91***<br>(17.47)   |
| Pseudo R <sup>2</sup>                    | 0.876                 | 0.876                  | 0.876                  | 0.876                 | 0.876                 |
| Log-likelihood                           | -944580.6             | -941911.7              | -943190.5              | -943827.4             | -943857.7             |
| Origen FE:                               | Yes                   | Yes                    | Yes                    | Yes                   | Yes                   |
| Time-Destination FE:                     | Yes                   | Yes                    | Yes                    | Yes                   | Yes                   |
| Observations                             | 1984                  | 1984                   | 1984                   | 1984                  | 1984                  |

<sup>1</sup> *t* statistics in parentheses

<sup>2</sup> \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.001$

<sup>3</sup> The dependent variable is the migration flow across Mexican states

<sup>4</sup> Robust standard errors clustered by origin-destination

**Table 3.13** – Results from PPML regression - difference in climatic factors between origins and destinations - GDP per capita differential

|  | (1)                   | (2)                    | (3)                   | (4)                    | (5)                    |
|--|-----------------------|------------------------|-----------------------|------------------------|------------------------|
| LN GDP DIFF <sub>ij,t</sub>              | 1.503***<br>(5.32)    | 1.117***<br>(4.44)     | 1.365***<br>(5.02)    | 1.413***<br>(5.25)     | 1.447***<br>(5.41)     |
| LN DISTANCE <sub>ij</sub>                | -0.735***<br>(-11.00) | -0.735***<br>(-11.00)  | -0.735***<br>(-11.00) | -0.735***<br>(-11.01)  | -0.735***<br>(-11.01)  |
| CONTIGUITY <sub>ij</sub>                 | 0.790***<br>(5.90)    | 0.791***<br>(5.90)     | 0.790***<br>(5.90)    | 0.790***<br>(5.90)     | 0.790***<br>(5.90)     |
| LN MURDER <sub>i,t</sub>                 | 0.130**<br>(2.25)     | 0.143**<br>(2.39)      | 0.137**<br>(2.33)     | 0.209***<br>(3.59)     | 0.197***<br>(3.44)     |
| LN MURDER CHNG <sub>i,t</sub>            | 0.0648**<br>(2.29)    | 0.0845***<br>(3.23)    | 0.0740***<br>(2.76)   | 0.0924***<br>(3.24)    | 0.104***<br>(3.63)     |
| LN TERTIARY EDU <sub>i,t</sub>           | -0.463***<br>(-3.24)  | -0.374**<br>(-2.54)    | -0.405***<br>(-2.71)  | -0.282**<br>(-2.04)    | -0.231*<br>(-1.66)     |
| HURRICANE DIFF <sub>ij,t</sub>           | 0.0444***<br>(3.09)   | 0.0232*<br>(1.81)      | 0.0379***<br>(2.92)   | 0.0327**<br>(2.28)     | 0.0297**<br>(2.06)     |
| EARTHQUAKE DIFF <sub>ij,t</sub>          | 0.0185<br>(0.83)      | 0.0123<br>(0.54)       | 0.0106<br>(0.45)      | 0.0235<br>(1.10)       | 0.0253<br>(1.17)       |
| DROUGHT LENGTH LONG DIFF <sub>ij,t</sub> |                       | -0.00461***<br>(-3.33) |                       |                        |                        |
| DROUGHT LENGTH ALL DIFF <sub>ij,t</sub>  |                       |                        | -0.00209*<br>(-1.85)  |                        |                        |
| FLOOD LENGTH LONG DIFF <sub>ij,t</sub>   |                       |                        |                       | -0.00526***<br>(-5.24) |                        |
| FLOOD LENGTH ALL DIFF <sub>ij,t</sub>    |                       |                        |                       |                        | -0.00526***<br>(-5.38) |
| Constant                                 | 11.74***<br>(21.04)   | 11.46***<br>(20.58)    | 11.55***<br>(20.14)   | 11.28***<br>(21.01)    | 11.05***<br>(20.72)    |
| Pseudo $R^2$                             | 0.876                 | 0.876                  | 0.876                 | 0.876                  | 0.876                  |
| Log-likelihood                           | -943259.3             | -942228.3              | -942961.3             | -941346.2              | -941100.3              |
| Origen FE:                               | Yes                   | Yes                    | Yes                   | Yes                    | Yes                    |
| Time-Destination FE:                     | Yes                   | Yes                    | Yes                   | Yes                    | Yes                    |
| Observations                             | 1984                  | 1984                   | 1984                  | 1984                   | 1984                   |

<sup>1</sup>  $t$  statistics in parentheses<sup>2</sup> \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.001$ <sup>3</sup> The dependent variable is the migration flow across Mexican states<sup>4</sup> Robust standard errors clustered by origin-destination

## Conclusions

The objective of this paper is to analyse the effects of climate variability and natural disasters on internal migration in Mexico. To this end, I exploit the information of bilateral migration flows across Mexican states through a gravity-based model. The analysis focuses on the effects of earthquakes, hurricanes, droughts, and floods on migration flows during the periods 2000-2005 and 2005-2010. My results show that, in addition to socio-economic drivers, climatic factors do influence internal migration flows in Mexico.

Income differential and violence are key factors influencing internal migration in Mexico. In line with previous literature, wage differentials is one of the strongest factors driving migration flows. An increase of 10% in wage differentials - measured by GDP per capita - is associated to an increase of 10% to 13% of the average migration flow. This result also holds when considering a deprivation index as proxy of wage differentials: an increase of 10% in deprivation differentials translates into a decrease of the average migration flow ranging between 15% and 17%. To a lesser extent, violence - captured by murder rates - also acts as a push factor: a 10% increase in murder rates within the migration period contributes to a 0.6% to 0.8% increase in migration flows. This effect should not be undermined if we consider the significant increase of violence in Mexico during the past decade: on average, between 2005 and 2010, murder rates increased by a factor of 2.5.

Both droughts and floods act as push factors. The length of droughts has a positive effect on migration flows. An increase of 10 months during the longest drought episode (within the migration period) is associated to an increase of 5% to 7% in the average migration flow. In the case of floods, a similar change taking place in the longest flood episode is associated to an

increase of 4% to 5% in the average migration flow. Moreover, the results also show that destination-origin differentials of both droughts and floods are negative. This suggests that regions with better climatic factors are more attractive for migrants.

The role of natural disasters, and in particular that of hurricanes, is complex and deserves further attention. My results show that earthquakes are not significant in explaining internal migration flows. The latter may be due to the fact that since the strong earthquake that took place in 1985, prevention efforts have translated into a reduction in casualties and economic losses associated to earthquakes. With regard to hurricanes, their effect is negative and significant when using GDP per capita to capture wage differentials; and positive and significant when using a deprivation index and when floods are not controlled for. The latter complicates the interpretation of the role of hurricanes within the framework of this analysis.

My results confirm the presence of indirect channels between climatic factors and internal migration. Indeed, earthquakes, hurricanes, floods, and droughts have a significant effect on wage differentials proxied by GDP per capita. These results are consistent with previous studies analysing the influence of climatic factors on international migration.

A number of caveats and limitations exist regarding the analysis that are worth mentioning. The first limitation is the lack of information regarding shorter migration periods. The only available information on internal migration in Mexico refers to 5-year periods, which does not allow to capture possible returning migration flows following a climatic shock. Moreover, it may diffuse the effects of previous shocks. The second limitation is the level of aggregation. Existing information is mostly limited to the state level. Since



rural areas tend to be more vulnerable to climatic shocks, information aggregated at the state level cannot capture rural-to-urban migration movements taking place within states. In order to better analyse the linkages between climatic factors and internal migration it may be necessary to look at more disaggregated data. An interesting territorial unit for this type of analysis could be the municipal level. Although such information is currently available for the period 2005-2010, using this dataset does not allow to control for time-fixed effects.

### 3.A Appendix: Chapter 3

**Table 3.14** – Population across Mexican states

| State Name            | Total<br>Population | Area<br>(km <sup>2</sup> ) | Percentage<br>of country total<br>(%) | Cumulate<br>Percentage<br>(%) | Population<br>Density<br>(Inhab/km <sup>2</sup> ) |
|-----------------------|---------------------|----------------------------|---------------------------------------|-------------------------------|---|
| Mexico                | 14,739,060          | 22,333                     | 13.76                                 | 13.76                         | 659.97  |
| Distrito Federal      | 8,839,361           | 1,484                      | 08.25                                 | 22.01                         | 5,956.44  |
| Veracruz              | 7,270,413           | 71,856                     | 06.79                                 | 28.8                          | 101.18  |
| Jalisco               | 6,989,304           | 78,630                     | 06.52                                 | 35.32                         | 88.89   |
| Puebla                | 5,624,104           | 34,251                     | 05.25                                 | 40.57                         | 164.2   |
| Guanajuato            | 5,033,276           | 30,621                     | 04.7                                  | 45.27                         | 164.37  |
| Chiapas               | 4,483,886           | 73,681                     | 04.19                                 | 49.46                         | 686   |
| Nuevo Leon            | 4,420,909           | 64,203                     | 04.13                                 | 53.59                         | 68.86   |
| Michoacan             | 3,971,225           | 58,667                     | 03.71                                 | 57.3                          | 67.69   |
| Oaxaca                | 3,551,710           | 93,343                     | 03.32                                 | 60.62                         | 38.05   |
| Chihuahua             | 3,376,062           | 247,487                    | 03.15                                 | 63.77                         | 13.64   |
| Tamaulipas            | 3,174,134           | 80,148                     | 02.96                                 | 66.73                         | 39.6  |
| Guerrero              | 3,143,292           | 63,618                     | 02.93                                 | 69.66                         | 49.41   |
| Baja California Norte | 3,122,408           | 71,546                     | 02.91                                 | 72.57                         | 43.64   |
| Sinaloa               | 2,650,499           | 57,331                     | 02.47                                 | 75.04                         | 46.23   |
| Coahuila              | 2,615,574           | 151,445                    | 02.44                                 | 77.48                         | 17.27   |
| Sonora                | 2,499,263           | 179,516                    | 02.33                                 | 79.81                         | 13.92   |
| San Luis Potosi       | 2,479,450           | 61,165                     | 02.31                                 | 82.12                         | 454   |
| Hidalgo               | 2,415,461           | 20,856                     | 02.25                                 | 84.37                         | 115.82  |
| Tabasco               | 2,045,294           | 24,747                     | 01.91                                 | 86.28                         | 82.65   |
| Yucatan               | 1,909,965           | 39,671                     | 01.78                                 | 88.06                         | 48.15   |
| Queretaro             | 1,705,267           | 11,658                     | 01.59                                 | 89.65                         | 146.27  |
| Morelos               | 1,668,343           | 4,892                      | 01.56                                 | 91.21                         | 341.03  |
| Durango               | 1,547,597           | 123,367                    | 01.44                                 | 92.65                         | 12.54   |
| Zacatecas             | 1,380,633           | 75,416                     | 01.29                                 | 93.94                         | 18.31   |
| Quintana Roo          | 1,290,323           | 42,535                     | 01.2                                  | 95.14                         | 334   |
| Aguascalientes        | 1,133,137           | 5,625                      | 01.06                                 | 96.2                          | 201.45  |
| Tlaxcala              | 1,127,331           | 3,997                      | 01.05                                 | 97.25                         | 282.04  |
| Nayarit               | 968,257             | 27,862                     | 0.09                                  | 98.15                         | 34.75   |
| Campeche              | 791,322             | 57,727                     | 0.074                                 | 98.89                         | 13.71   |
| Colima                | 597,043             | 5,627                      | 0.056                                 | 99.45                         | 106.1   |
| Baja California Sur   | 558,425             | 73,943                     | 0.052                                 | 100                           | 7.55  |

Computations made by the author. **Source:** INEGI, 2010.

Table 3.15 – Correlation across measures of droughts and floods

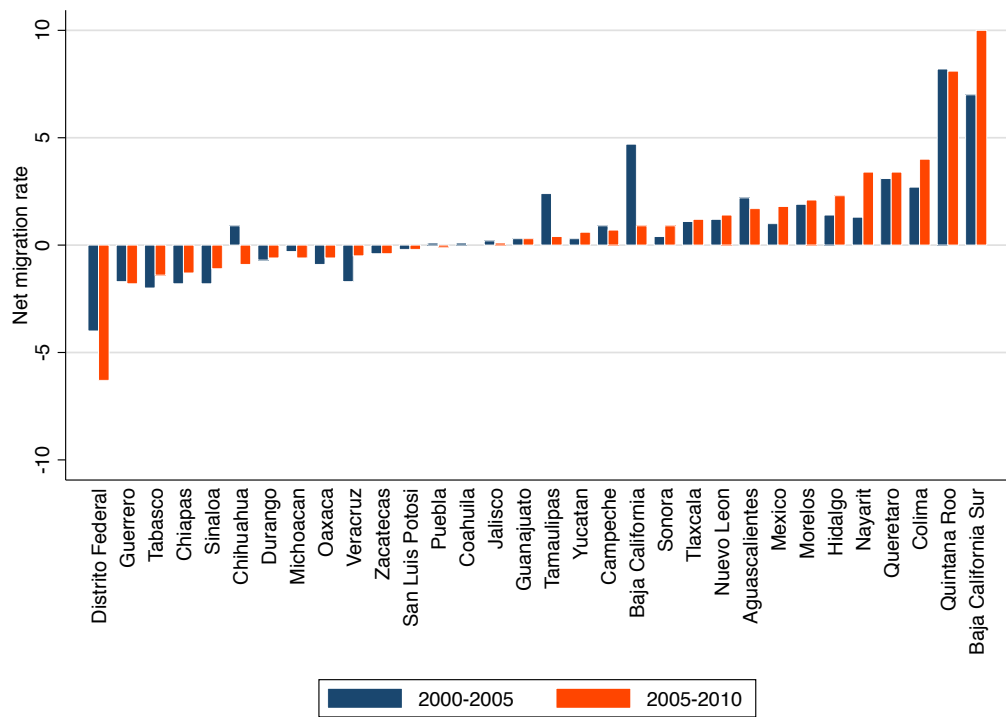
| Variables                                 | HURRICANE 1-4 <sub><i>i,t</i></sub>    | EARTHQUAKES <sub><i>i,t</i></sub>        | DROUGHT FREQ LONG <sub><i>i,t</i></sub> | DROUGHT LENGTH LONG <sub><i>i,t</i></sub> |
|---|--|--|---|---|
| HURRICANE 1-4 <sub><i>i,t</i></sub>       | 1.000                                  |  |   |   |
| EARTHQUAKES <sub><i>i,t</i></sub>         | 0.041                                  | 1.000                                    |   |   |
| DROUGHT FREQ LONG <sub><i>i,t</i></sub>   | 0.147                                  | -0.152                                   | 1.000                                   |   |
| DROUGHT LENGTH LONG <sub><i>i,t</i></sub> | 0.124                                  | -0.097                                   | 0.633                                   | 1.000                                     |
| DROUGHT MAG LONG <sub><i>i,t</i></sub>    | 0.082                                  | -0.138                                   | 0.812                                   | 0.94                                      |
| DROUGHT LENGTH ALL <sub><i>i,t</i></sub>  | 0.275                                  | -0.133                                   | 0.742                                   | 0.938                                     |
| DROUGHT MAG ALL <sub><i>i,t</i></sub>     | 0.245                                  | -0.169                                   | 0.853                                   | 0.894                                     |
| FLOOD FREQ LONG <sub><i>i,t</i></sub>     | -0.108                                 | -0.115                                   | 0.327                                   | 0.478                                     |
| FLOOD LEN LONG <sub><i>i,t</i></sub>      | -0.146                                 | -0.154                                   | 0.257                                   | 0.288                                     |
| FLOOD MAG LONG <sub><i>i,t</i></sub>      | -0.147                                 | -0.127                                   | 0.284                                   | 0.394                                     |
| FLOOD LENGTH ALL <sub><i>i,t</i></sub>    | -0.158                                 | -0.162                                   | 0.246                                   | 0.278                                     |
| FLOOD MAG ALL <sub><i>i,t</i></sub>       | -0.165                                 | -0.138                                   | 0.286                                   | 0.389                                     |
| Variables                                 | DROUGHT MAG LONG <sub><i>i,t</i></sub> | DROUGHT LENGTH ALL <sub><i>i,t</i></sub> | DROUGHT MAG ALL <sub><i>i,t</i></sub>   | FLOOD FREQ LONG <sub><i>i,t</i></sub>     |
| HURRICANE 1-4 <sub><i>i,t</i></sub>       |  |  |   |   |
| EARTHQUAKES <sub><i>i,t</i></sub>         |  |  |   |   |
| DROUGHT FREQ LONG <sub><i>i,t</i></sub>   |  |  |   |   |
| DROUGHT LENGTH LONG <sub><i>i,t</i></sub> | 1.000                                  |  |   |   |
| DROUGHT MAG LONG <sub><i>i,t</i></sub>    | 0.907                                  | 1.000                                    |   |   |
| DROUGHT LENGTH ALL <sub><i>i,t</i></sub>  | 0.94                                   | 0.969                                    | 1.000                                   |   |
| FLOOD FREQ LONG <sub><i>i,t</i></sub>     | 0.509                                  | 0.4                                      | 0.437                                   | 1.000                                     |
| FLOOD LEN LONG <sub><i>i,t</i></sub>      | 0.333                                  | 0.207                                    | 0.242                                   | 0.747                                     |
| FLOOD MAG LONG <sub><i>i,t</i></sub>      | 0.434                                  | 0.302                                    | 0.338                                   | 0.882                                     |
| FLOOD LENGTH ALL <sub><i>i,t</i></sub>    | 0.323                                  | 0.203                                    | 0.24                                    | 0.776                                     |
| FLOOD MAG ALL <sub><i>i,t</i></sub>       | 0.432                                  | 0.304                                    | 0.345                                   | 0.923                                     |
| Variables                                 | FLOOD LEN LONG <sub><i>i,t</i></sub>   | FLOOD MAG LONG <sub><i>i,t</i></sub>     | FLOOD LENGTH ALL <sub><i>i,t</i></sub>  | FLOOD MAG ALL <sub><i>i,t</i></sub>       |
| HURRICANE 1-4 <sub><i>i,t</i></sub>       |  |  |   |   |
| EARTHQUAKES <sub><i>i,t</i></sub>         |  |  |   |   |
| DROUGHT FREQ LONG <sub><i>i,t</i></sub>   |  |  |   |   |
| DROUGHT LENGTH LONG <sub><i>i,t</i></sub> |  |  |   |   |
| DROUGHT MAG LONG <sub><i>i,t</i></sub>    |  |  |   |   |
| DROUGHT LENGTH ALL <sub><i>i,t</i></sub>  |  |  |   |   |
| DROUGHT MAG ALL <sub><i>i,t</i></sub>     |  |  |   |   |
| FLOOD FREQ LONG <sub><i>i,t</i></sub>     | 1.000                                  |  |   |   |
| FLOOD LEN LONG <sub><i>i,t</i></sub>      | 0.939                                  | 1.000                                    |   |   |
| FLOOD MAG LONG <sub><i>i,t</i></sub>      | 0.977                                  | 0.905                                    | 1.000                                   |   |
| FLOOD LENGTH ALL <sub><i>i,t</i></sub>    | 0.928                                  | 0.972                                    | 0.942                                   | 1.000                                     |

**Figure 3.7** – Mexico’s political division: states



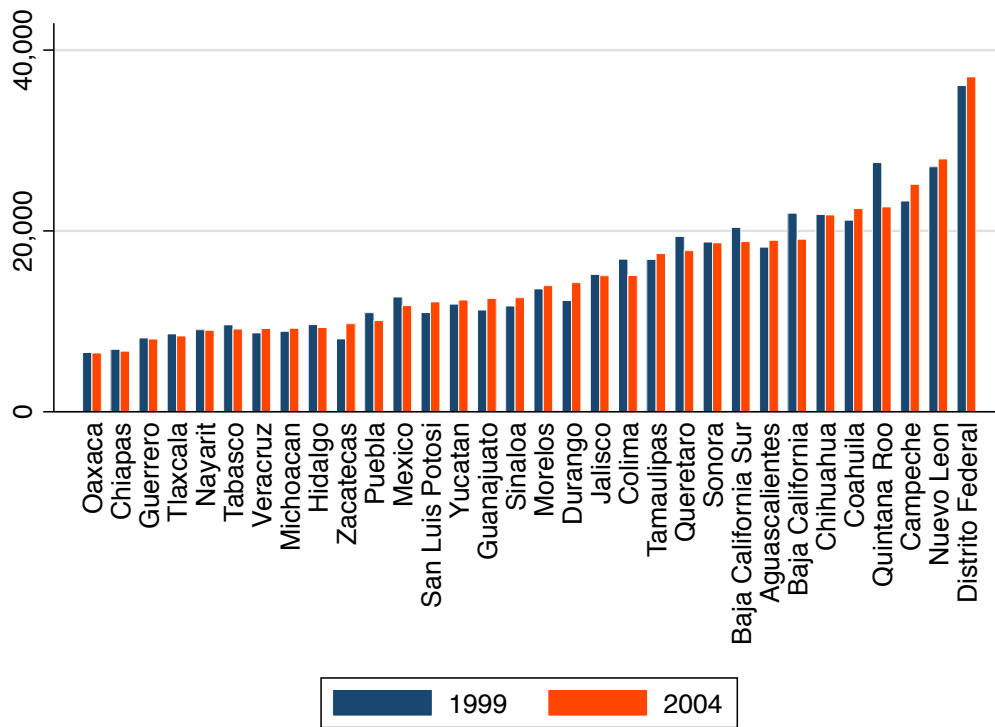
Source: INEGI, 2010.

**Figure 3.8** – Net-migration rates in the periods 1995-2000, 2000-2005, and 2005-2010.



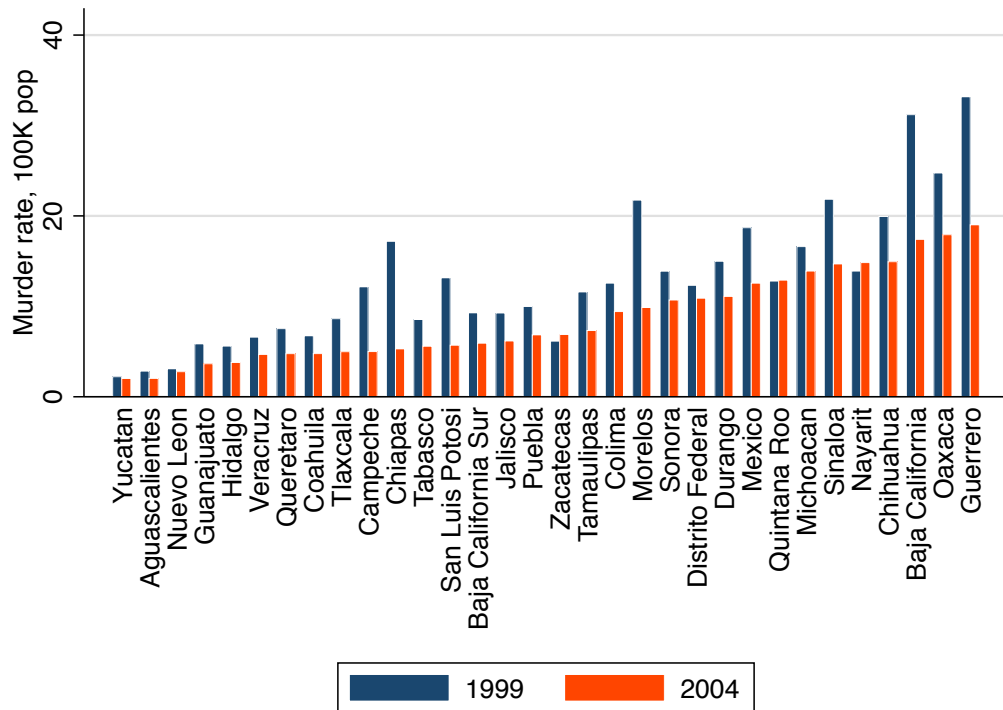
Source: INEGI, 2010; CONAPO, 2010

Figure 3.9 – GDP per capita by region.



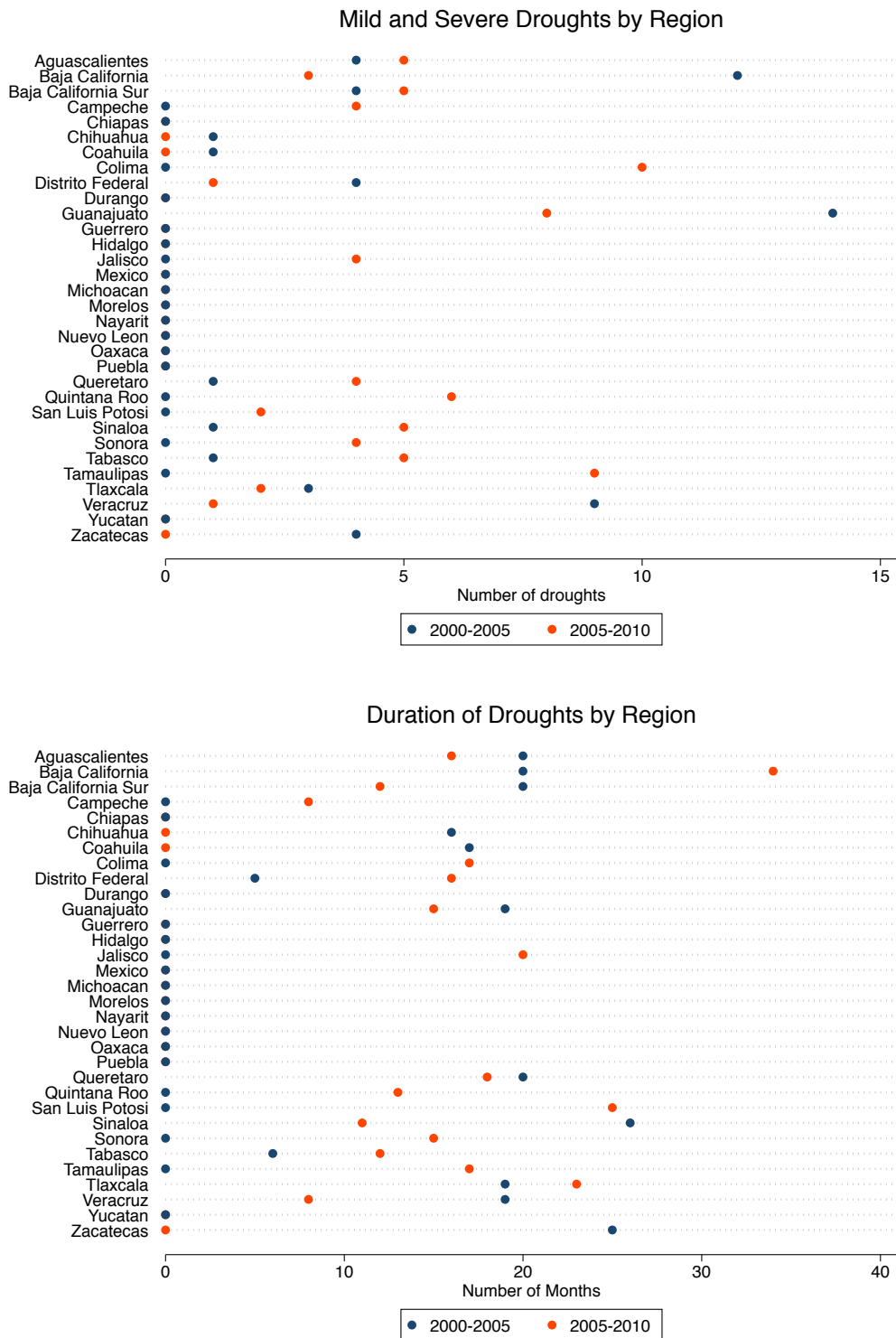
Source: INEGI, 2010.

Figure 3.10 – Murder rate per 10,000 population by region.



Source: INEGI, 2010.

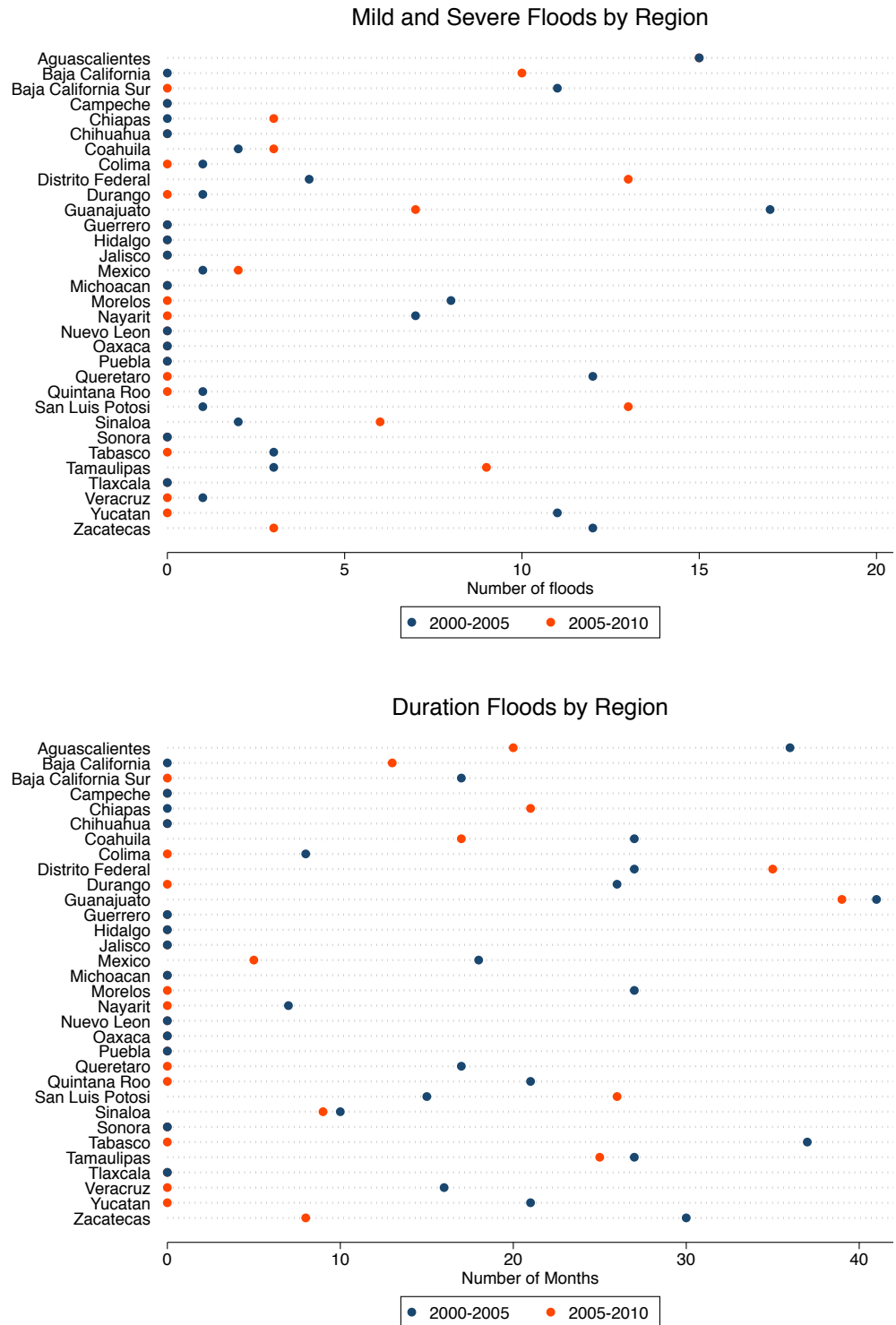
**Figure 3.11** – Number of mild and severe droughts and maximum length of droughts by region.



Source: Willmott and Matsuura (2001).

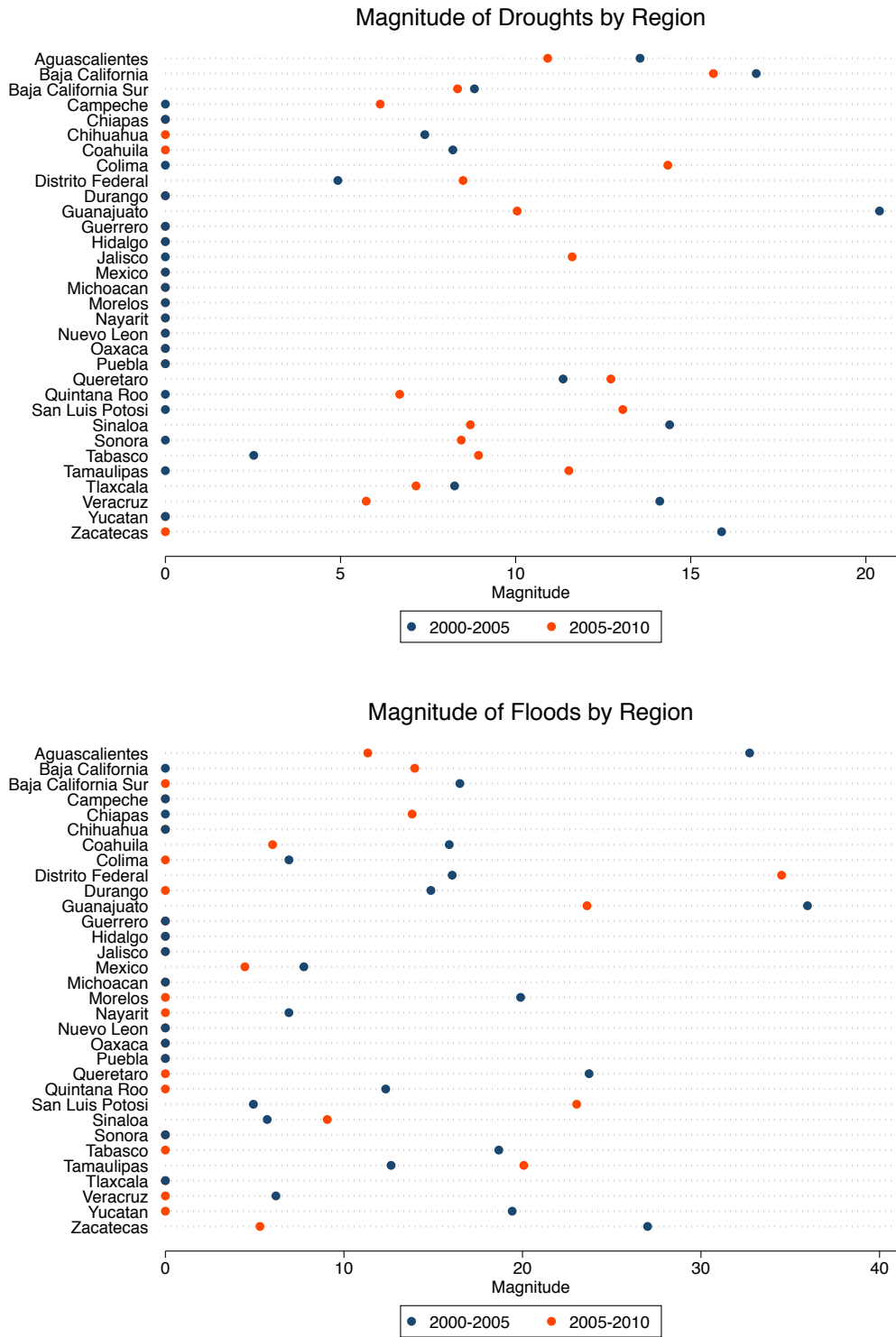


**Figure 3.12** – Number of mild and severe floods and maximum length of floods by region.



Source: Willmott and Matsuura (2001).

**Figure 3.13** – Magnitude of droughts by region (top); Magnitude of floods by region (bottom).



Source: Willmott and Matsuura (2001).

**Table 3.16** – Results from PPML regression - droughts during the migration period

|   | (1)                   | (2)                   | (3)                   | (4)                   | (5)                   |
|---|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| LN GDP DIFF <sub><i>ij,t</i></sub>        | 1.634***<br>(5.30)    | 1.117***<br>(4.44)    | 1.380***<br>(4.82)    | 1.365***<br>(5.02)    | 1.528***<br>(5.32)    |
| LN DISTANCE <sub><i>ij</i></sub>          | -0.735***<br>(-10.99) | -0.735***<br>(-11.00) | -0.735***<br>(-11.00) | -0.735***<br>(-11.00) | -0.735***<br>(-11.00) |
| CONTIGUITY <sub><i>ij</i></sub>           | 0.790***<br>(5.89)    | 0.791***<br>(5.90)    | 0.790***<br>(5.90)    | 0.790***<br>(5.90)    | 0.790***<br>(5.90)    |
| LN MURDER <sub><i>i,t</i></sub>           | 0.114*<br>(1.94)      | 0.143**<br>(2.39)     | 0.136**<br>(2.29)     | 0.137**<br>(2.33)     | 0.129**<br>(2.18)     |
| LN MURDER CHNG <sub><i>i,t</i></sub>      | 0.0676**<br>(2.48)    | 0.0845***<br>(3.23)   | 0.0692**<br>(2.57)    | 0.0740***<br>(2.76)   | 0.0635**<br>(2.31)    |
| LN TERTIARY EDU <sub><i>i,t</i></sub>     | -0.489***<br>(-3.49)  | -0.374**<br>(-2.54)   | -0.445***<br>(-3.07)  | -0.405***<br>(-2.71)  | -0.472***<br>(-3.21)  |
| HURRICANE 1-4 <sub><i>i,t</i></sub>       | -0.0508***<br>(-3.51) | -0.0232*<br>(-1.81)   | -0.0376***<br>(-2.97) | -0.0379***<br>(-2.92) | -0.0455***<br>(-3.43) |
| EARTHQUAKES <sub><i>i,t</i></sub>         | -0.0305<br>(-1.34)    | -0.0123<br>(-0.54)    | -0.0143<br>(-0.62)    | -0.0106<br>(-0.45)    | -0.0207<br>(-0.88)    |
| DROUGHT FREQ LONG <sub><i>i,t</i></sub>   | -0.00595<br>(-1.32)   |                       |                       |                       |                       |
| DROUGHT LENGTH LONG <sub><i>i,t</i></sub> |                       | 0.00461***<br>(3.33)  |                       |                       |                       |
| DROUGHT MAG LONG <sub><i>i,t</i></sub>    |                       |                       | 0.00226<br>(0.98)     |                       |                       |
| DROUGHT LENGTH ALL <sub><i>i,t</i></sub>  |                       |                       |                       | 0.00209*<br>(1.85)    |                       |
| DROUGHT MAG ALL <sub><i>i,t</i></sub>     |                       |                       |                       |                       | -0.000654<br>(-0.34)  |
| Constant                                  | 11.84***<br>(20.75)   | 11.36***<br>(20.31)   | 11.65***<br>(20.45)   | 11.51***<br>(19.86)   | 11.78***<br>(20.05)   |
| Pseudo $R^2$                              | 0.876                 | 0.876                 | 0.876                 | 0.876                 | 0.876                 |
| Log-likelihood                            | -942981.0             | -942228.3             | -943186.2             | -942961.3             | -943248.2             |
| Origen FE:                                | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   |
| Time-Destination FE:                      | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   |
| Observations                              | 1984                  | 1984                  | 1984                  | 1984                  | 1984                  |

<sup>1</sup>  $t$  statistics in parentheses

<sup>2</sup> \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.001$

<sup>3</sup> The dependent variable is the migration flow across Mexican states

<sup>4</sup> Robust standard errors clustered by origin-destination

**Table 3.17** – Results from PPML regression - floods during the migration period

|   | (1)                   | (2)                   | (3)                   | (4)                   | (5)                   |
|---|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| LN GDP DIFF <sub><i>ij,t</i></sub>      | 1.473***<br>(5.13)    | 1.413***<br>(5.25)    | 1.475***<br>(5.24)    | 1.447***<br>(5.41)    | 1.479***<br>(5.27)    |
| LN DISTANCE <sub><i>ij</i></sub>        | -0.735***<br>(-11.00) | -0.735***<br>(-11.01) | -0.735***<br>(-11.00) | -0.735***<br>(-11.01) | -0.735***<br>(-11.00) |
| CONTIGUITY <sub><i>ij</i></sub>         | 0.790***<br>(5.90)    | 0.790***<br>(5.90)    | 0.790***<br>(5.90)    | 0.790***<br>(5.90)    | 0.790***<br>(5.90)    |
| LN MURDER <sub><i>i,t</i></sub>         | 0.131**<br>(2.26)     | 0.209***<br>(3.59)    | 0.145**<br>(2.51)     | 0.197***<br>(3.44)    | 0.147**<br>(2.55)     |
| LN MURDER CHNG <sub><i>i,t</i></sub>    | 0.0715**<br>(2.46)    | 0.0924***<br>(3.24)   | 0.0840***<br>(2.87)   | 0.104***<br>(3.63)    | 0.0885***<br>(3.01)   |
| LN TERTIARY EDU <sub><i>i,t</i></sub>   | -0.389***<br>(-2.76)  | -0.282**<br>(-2.04)   | -0.335**<br>(-2.41)   | -0.231*<br>(-1.66)    | -0.310**<br>(-2.22)   |
| HURRICANE 1-4 <sub><i>i,t</i></sub>     | -0.0391**<br>(-2.53)  | -0.0327**<br>(-2.28)  | -0.0361**<br>(-2.39)  | -0.0297**<br>(-2.06)  | -0.0343**<br>(-2.26)  |
| EARTHQUAKES <sub><i>i,t</i></sub>       | -0.0224<br>(-1.02)    | -0.0235<br>(-1.10)    | -0.0240<br>(-1.09)    | -0.0253<br>(-1.17)    | -0.0252<br>(-1.15)    |
| FLOOD FREQ LONG <sub><i>i,t</i></sub>   | 0.00390<br>(1.51)     |                       |                       |                       |                       |
| FLOOD LENGTH LONG <sub><i>i,t</i></sub> |                       | 0.00526***<br>(5.24)  |                       |                       |                       |
| FLOOD MAG LONG <sub><i>i,t</i></sub>    |                       |                       | 0.00311***<br>(2.73)  |                       |                       |
| FLOOD LENGTH ALL <sub><i>i,t</i></sub>  |                       |                       |                       | 0.00526***<br>(5.38)  |                       |
| FLOOD MAG ALL <sub><i>i,t</i></sub>     |                       |                       |                       |                       | 0.00361***<br>(3.01)  |
| Constant                                | 11.45***<br>(20.52)   | 11.09***<br>(20.73)   | 11.28***<br>(20.90)   | 10.86***<br>(20.35)   | 11.16***<br>(20.56)   |
| Pseudo $R^2$                            | 0.876                 | 0.876                 | 0.876                 | 0.876                 | 0.876                 |
| Log-likelihood                          | -943042.9             | -941346.2             | -942658.7             | -941100.3             | -942469.2             |
| Origen FE:                              | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   |
| Time-Destination FE:                    | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   |
| Observations                            | 1984                  | 1984                  | 1984                  | 1984                  | 1984                  |

<sup>1</sup>  $t$  statistics in parentheses

<sup>2</sup> \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.001$

<sup>3</sup> The dependent variable is the migration flow across Mexican states

<sup>4</sup> Robust standard errors clustered by origin-destination

**Table 3.18** – Results from PPML regression - sample without the Distrito Federal and state of Mexico - droughts

|                                    | (1)                   | (2)                  | (3)                   | (4)                   | (5)                   |
|------------------------------------|-----------------------|----------------------|-----------------------|-----------------------|-----------------------|
| GDP DIFF <sub>ij,t</sub>           | 1.519***<br>(4.65)    | 1.146***<br>(4.43)   | 1.350***<br>(4.56)    | 1.375***<br>(4.98)    | 1.494***<br>(5.17)    |
| DISTANCE <sub>ij</sub>             | -0.595***<br>(-6.18)  | -0.595***<br>(-6.18) | -0.595***<br>(-6.18)  | -0.595***<br>(-6.18)  | -0.595***<br>(-6.18)  |
| CONTIGUITY <sub>ij</sub>           | 1.161***<br>(7.55)    | 1.161***<br>(7.55)   | 1.161***<br>(7.55)    | 1.161***<br>(7.55)    | 1.161***<br>(7.55)    |
| MURDER <sub>i,t</sub>              | 0.191***<br>(2.88)    | 0.224***<br>(3.11)   | 0.208***<br>(2.93)    | 0.207***<br>(2.97)    | 0.194***<br>(2.78)    |
| MURDER CHNG <sub>i,t</sub>         | 0.0647*<br>(1.87)     | 0.0673*<br>(1.92)    | 0.0663*<br>(1.92)     | 0.0683**<br>(2.01)    | 0.0658*<br>(1.95)     |
| TERTIARY EDU <sub>i,t</sub>        | -0.677***<br>(-4.02)  | -0.651***<br>(-3.69) | -0.668***<br>(-3.80)  | -0.641***<br>(-3.59)  | -0.664***<br>(-3.77)  |
| HURRICANE 1-4 <sub>i,t</sub>       | -0.0529***<br>(-3.02) | -0.0366**<br>(-2.46) | -0.0451***<br>(-2.97) | -0.0472***<br>(-3.02) | -0.0512***<br>(-3.22) |
| EARTHQUAKES <sub>i,t</sub>         | -0.00305<br>(-0.12)   | 0.00740<br>(0.30)    | 0.00581<br>(0.23)     | 0.00725<br>(0.29)     | -0.000205<br>(-0.01)  |
| DROUGHT FREQ LONG <sub>i,t</sub>   | -0.00166<br>(-0.34)   |                      |                       |                       |                       |
| DROUGHT LENGTH LONG <sub>i,t</sub> |                       | 0.00374**<br>(2.22)  |                       |                       |                       |
| DROUGHT MAG LONG <sub>i,t</sub>    |                       |                      | 0.00234<br>(0.88)     |                       |                       |
| DROUGHT LENGTH ALL <sub>i,t</sub>  |                       |                      |                       | 0.00151<br>(1.14)     |                       |
| DROUGHT MAG ALL <sub>i,t</sub>     |                       |                      |                       |                       | -0.000196<br>(-0.09)  |
| Constant                           | 11.06***<br>(13.51)   | 10.95***<br>(13.68)  | 10.99***<br>(13.78)   | 10.91***<br>(13.57)   | 11.00***<br>(13.68)   |
| Pseudo R <sup>2</sup>              | 0.768                 | 0.768                | 0.768                 | 0.768                 | 0.768                 |
| Log-likelihood                     | -715548.3             | -715066.7            | -715498.8             | -715434.3             | -715562.2             |
| Origen FE:                         | Yes                   | Yes                  | Yes                   | Yes                   | Yes                   |
| Time-Destination FE:               | Yes                   | Yes                  | Yes                   | Yes                   | Yes                   |
| Observations                       | 1740                  | 1740                 | 1740                  | 1740                  | 1740                  |

<sup>1</sup> *t* statistics in parentheses

<sup>2</sup> \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.001$

<sup>3</sup> The dependent variable is the migration flow across Mexican states

<sup>4</sup> Robust standard errors clustered by origin-destination

**Table 3.19** – Results from PPML regression - sample without the Distrito Federal and the state of Mexico - floods

|   | (1)                   | (2)                   | (3)                   | (4)                  | (5)                   |
|---|-----------------------|-----------------------|-----------------------|----------------------|-----------------------|
| GDP DIFF <sub><i>ij,t</i></sub>         | 1.408***<br>(4.48)    | 1.391***<br>(4.92)    | 1.396***<br>(4.62)    | 1.392***<br>(4.95)   | 1.370***<br>(4.54)    |
| DISTANCE <sub><i>ij</i></sub>           | -0.596***<br>(-6.18)  | -0.596***<br>(-6.19)  | -0.596***<br>(-6.19)  | -0.597***<br>(-6.19) | -0.596***<br>(-6.19)  |
| CONTIGUITY <sub><i>ij</i></sub>         | 1.161***<br>(7.55)    | 1.160***<br>(7.55)    | 1.160***<br>(7.55)    | 1.160***<br>(7.54)   | 1.160***<br>(7.55)    |
| MURDER <sub><i>i,t</i></sub>            | 0.230***<br>(3.44)    | 0.303***<br>(4.14)    | 0.262***<br>(3.58)    | 0.323***<br>(4.68)   | 0.291***<br>(4.09)    |
| MURDER CHNG <sub><i>i,t</i></sub>       | 0.0511<br>(1.46)      | 0.0624*<br>(1.86)     | 0.0512<br>(1.50)      | 0.0640*<br>(1.91)    | 0.0468<br>(1.38)      |
| TERTIARY EDU <sub><i>i,t</i></sub>      | -0.695***<br>(-3.72)  | -0.553***<br>(-3.29)  | -0.683***<br>(-3.78)  | -0.539***<br>(-3.17) | -0.692***<br>(-3.81)  |
| HURRICANE 1-4 <sub><i>i,t</i></sub>     | -0.0491***<br>(-2.84) | -0.0440***<br>(-2.64) | -0.0481***<br>(-2.81) | -0.0418**<br>(-2.52) | -0.0465***<br>(-2.71) |
| EARTHQUAKES <sub><i>i,t</i></sub>       | -0.00206<br>(-0.09)   | -0.00234<br>(-0.10)   | -0.00267<br>(-0.12)   | -0.00394<br>(-0.17)  | -0.00447<br>(-0.20)   |
| FLOOD FREQ LONG <sub><i>i,t</i></sub>   | 0.00475<br>(1.23)     |                       |                       |                      |                       |
| FLOOD LENGTH LONG <sub><i>i,t</i></sub> |                       | 0.00535***<br>(3.79)  |                       |                      |                       |
| FLOOD MAG LONG <sub><i>i,t</i></sub>    |                       |                       | 0.00373*<br>(1.93)    |                      |                       |
| FLOOD LENGTH ALL <sub><i>i,t</i></sub>  |                       |                       |                       | 0.00625***<br>(4.77) |                       |
| FLOOD MAG ALL <sub><i>i,t</i></sub>     |                       |                       |                       |                      | 0.00524***<br>(2.67)  |
| Constant                                | 11.07***<br>(13.86)   | 10.77***<br>(13.86)   | 11.10***<br>(13.85)   | 10.68***<br>(13.74)  | 11.09***<br>(13.93)   |
| Pseudo $R^2$                            | 0.768                 | 0.768                 | 0.768                 | 0.769                | 0.768                 |
| Log-likelihood                          | -715419.0             | -714524.8             | -715241.1             | -714113.6            | -714967.2             |
| Origen FE:                              | Yes                   | Yes                   | Yes                   | Yes                  | Yes                   |
| Time-Destination FE:                    | Yes                   | Yes                   | Yes                   | Yes                  | Yes                   |
| Observations                            | 1740                  | 1740                  | 1740                  | 1740                 | 1740                  |

<sup>1</sup> *t* statistics in parentheses<sup>2</sup> \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.001$ <sup>3</sup> The dependent variable is the migration flow across Mexican states<sup>4</sup> Robust standard errors clustered by origin-destination

**Table 3.20** – Results from PPML regression - marginalisation index - droughts

|                                    | (1)                   | (2)                   | (3)                   | (4)                   | (5)                   |
|------------------------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| LN MARG DIFF <sub>ij,t</sub>       | -1.711***<br>(-4.15)  | -1.544***<br>(-4.20)  | -1.658***<br>(-4.23)  | -1.747***<br>(-4.35)  | -1.744***<br>(-4.17)  |
| LN DISTANCE <sub>ij</sub>          | -0.735***<br>(-10.99) | -0.735***<br>(-11.01) | -0.735***<br>(-11.00) | -0.735***<br>(-11.00) | -0.735***<br>(-10.99) |
| CONTIGUITY <sub>ij</sub>           | 0.791***<br>(5.90)    | 0.791***<br>(5.90)    | 0.791***<br>(5.90)    | 0.791***<br>(5.90)    | 0.791***<br>(5.90)    |
| LN MURDER <sub>i,t</sub>           | 0.0284<br>(0.45)      | 0.0646<br>(1.04)      | 0.0588<br>(0.95)      | 0.0432<br>(0.71)      | 0.0333<br>(0.54)      |
| LN MURDER CHNG <sub>i,t</sub>      | 0.0622**<br>(2.19)    | 0.0931***<br>(3.60)   | 0.0809***<br>(3.08)   | 0.0829***<br>(3.16)   | 0.0706***<br>(2.62)   |
| LN TERTIARY EDU <sub>i,t</sub>     | -0.266<br>(-1.52)     | -0.112<br>(-0.64)     | -0.165<br>(-0.91)     | -0.116<br>(-0.62)     | -0.209<br>(-1.11)     |
| HURRICANE 1-4 <sub>i,t</sub>       | 0.0153<br>(1.39)      | 0.0271**<br>(2.21)    | 0.0255**<br>(2.15)    | 0.0195*<br>(1.67)     | 0.0167<br>(1.47)      |
| EARTHQUAKES <sub>i,t</sub>         | -0.0132<br>(-0.56)    | -0.00753<br>(-0.32)   | -0.000981<br>(-0.04)  | -0.000693<br>(-0.03)  | -0.00568<br>(-0.23)   |
| DROUGHT FREQ LONG <sub>i,t</sub>   | 0.00246<br>(0.59)     |                       |                       |                       |                       |
| DROUGHT LENGTH LONG <sub>i,t</sub> |                       | 0.00668***<br>(4.90)  |                       |                       |                       |
| DROUGHT MAG LONG <sub>i,t</sub>    |                       |                       | 0.00836***<br>(3.83)  |                       |                       |
| DROUGHT LENGTH ALL <sub>i,t</sub>  |                       |                       |                       | 0.00430***<br>(3.71)  |                       |
| DROUGHT MAG ALL <sub>i,t</sub>     |                       |                       |                       |                       | 0.00349*<br>(1.80)    |
| Constant                           | 10.84***<br>(16.92)   | 10.31***<br>(16.33)   | 10.47***<br>(16.18)   | 10.32***<br>(15.54)   | 10.63***<br>(15.78)   |
| Pseudo R <sup>2</sup>              | 0.876                 | 0.876                 | 0.876                 | 0.876                 | 0.876                 |
| Log-likelihood                     | -944528.5             | -941911.7             | -943245.2             | -943190.5             | -944237.5             |
| Origen FE:                         | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   |
| Time-Destination FE:               | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   |
| Observations                       | 1984                  | 1984                  | 1984                  | 1984                  | 1984                  |

<sup>1</sup> *t* statistics in parentheses

<sup>2</sup> \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.001$

<sup>3</sup> The dependent variable is the migration flow across Mexican states

<sup>4</sup> Robust standard errors clustered by origin-destination

**Table 3.21** – Results from PPML regression - marginalisation index - floods

|                                  | (1)                   | (2)                   | (3)                   | (4)                   | (5)                   |
|----------------------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| LN MARG DIFF <sub>ij,t</sub>     | -1.617***<br>(-3.69)  | -1.108**<br>(-1.99)   | -1.541***<br>(-3.25)  | -1.061*<br>(-1.80)    | -1.504***<br>(-3.08)  |
| LN DISTANCE <sub>ij</sub>        | -0.735***<br>(-10.99) | -0.735***<br>(-11.00) | -0.735***<br>(-10.99) | -0.735***<br>(-10.99) | -0.735***<br>(-10.99) |
| CONTIGUITY <sub>ij</sub>         | 0.791***<br>(5.89)    | 0.790***<br>(5.89)    | 0.791***<br>(5.89)    | 0.790***<br>(5.89)    | 0.791***<br>(5.89)    |
| LN MURDER <sub>i,t</sub>         | 0.0237<br>(0.39)      | 0.0980<br>(1.42)      | 0.0327<br>(0.52)      | 0.0874<br>(1.28)      | 0.0349<br>(0.56)      |
| LN MURDER CHNG <sub>i,t</sub>    | 0.0681**<br>(2.30)    | 0.0815**<br>(2.53)    | 0.0723**<br>(2.32)    | 0.0880***<br>(2.58)   | 0.0744**<br>(2.34)    |
| LN TERTIARY EDU <sub>i,t</sub>   | -0.246<br>(-1.43)     | -0.285<br>(-1.59)     | -0.259<br>(-1.51)     | -0.271<br>(-1.53)     | -0.255<br>(-1.49)     |
| HURRICANE 1-4 <sub>i,t</sub>     | 0.0169<br>(1.40)      | 0.0155<br>(1.32)      | 0.0165<br>(1.38)      | 0.0174<br>(1.46)      | 0.0172<br>(1.42)      |
| EARTHQUAKES <sub>i,t</sub>       | -0.0220<br>(-0.95)    | -0.0246<br>(-1.08)    | -0.0220<br>(-0.95)    | -0.0260<br>(-1.13)    | -0.0228<br>(-0.98)    |
| FLOOD FREQ LONG <sub>i,t</sub>   | 0.00309<br>(1.07)     |                       |                       |                       |                       |
| FLOOD LENGTH LONG <sub>i,t</sub> |                       | 0.00383**<br>(2.53)   |                       |                       |                       |
| FLOOD MAG LONG <sub>i,t</sub>    |                       |                       | 0.00157<br>(1.11)     |                       |                       |
| FLOOD LENGTH ALL <sub>i,t</sub>  |                       |                       |                       | 0.00364**<br>(2.34)   |                       |
| FLOOD MAG ALL <sub>i,t</sub>     |                       |                       |                       |                       | 0.00182<br>(1.20)     |
| Constant                         | 10.74***<br>(17.67)   | 10.87***<br>(17.51)   | 10.80***<br>(17.89)   | 10.78***<br>(17.68)   | 10.76***<br>(17.86)   |
| Pseudo R <sup>2</sup>            | 0.876                 | 0.876                 | 0.876                 | 0.876                 | 0.876                 |
| Log-likelihood                   | -944446.4             | -943827.4             | -944442.6             | -943857.7             | -944404.1             |
| Origen FE:                       | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   |
| Time-Destination FE:             | Yes                   | Yes                   | Yes                   | Yes                   | Yes                   |
| Observations                     | 1984                  | 1984                  | 1984                  | 1984                  | 1984                  |

<sup>1</sup> *t* statistics in parentheses

<sup>2</sup> \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.001$

<sup>3</sup> The dependent variable is the migration flow across Mexican states

<sup>4</sup> Robust standard errors clustered by origin-destination





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## **Analysis and evaluation of economic policy instruments for environmental control in Mexico**

The sustainability of water resources in Mexico is challenged, among other things, by inadequate regulation tools, limited enforcement capacity, and the uncertainty related to climate change. This thesis analyses key aspects of these challenges with the overall objective of contributing to the economic literature and providing inputs for evidence-based policy making. The thesis is composed of three chapters.

The first chapter looks at the mechanisms regulating groundwater extraction. In particular, it analyses the distortion caused by electricity subsidies and their effects on groundwater overdraft. It contributes to the existing literature by providing estimates on cross-price elasticities related to irrigation water demand in Mexico. The results of this chapter show that changes in the price of groundwater not only affect the amount of water pumped, but also the allocation of labour and fertilisers.

The second chapter studies the effects of environmental inspections on illegal water extraction across Mexican municipalities. Results show that the main inspection programme led by Mexico's water agency does have an impact on the number of irrigators extracting water without a valid concession. However, further efforts improving the capacity of regional offices are required for this programme to have a substantive effect on water sustainability.

Finally, the third chapter addresses some of the concerns related to climate change by analysing the effects of droughts and floods on internal migration trends in Mexico. Results show that both droughts and floods act as push factors for internal migration. In addition, results also show that income differential, murders, and educational attainments are key drivers for internal migration in the country.

**Keywords:** Mexico, groundwater, overdraft, regulatory mechanisms, illegal water extraction, environmental-induced migration, climate change

## **Analyse et évaluation des instruments de politique économique pour le contrôle environnemental au Mexique**

Le défi de la durabilité des ressources en eau au Mexique est étroitement lié à l'existence d'outils inadéquats de régulation, d'une capacité d'application limitée, et de l'incertitude liée au changement climatique. La présente thèse analyse les principaux aspects de ce défi avec l'objectif de contribuer à la littérature économique et d'alimenter par les faits l'élaboration de politiques. Elle est composée de trois chapitres.

Le premier chapitre analyse les mécanismes de régulation de l'extraction de l'eau souterraine. En particulier, il analyse la distorsion causée par les subventions à l'électricité et leurs effets sur la surexploitation des nappes phréatiques. Il contribue à la littérature en fournissant des estimations sur les élasticités prix-croisés liées à la demande d'eau d'irrigation au Mexique. Les résultats montrent que les changements dans le prix de l'eau souterraine affectent la quantité d'eau pompée ainsi que la répartition du travail et des engrais.

Le deuxième chapitre étudie les effets des inspections environnementales sur l'extraction illégale de l'eau dans les municipalités mexicaines. Les résultats montrent que le programme d'inspection mené par l'agence de l'eau au Mexique a un impact sur le nombre d'irrigants ne possédant pas de concession valide. Toutefois, des efforts supplémentaires sont nécessaires pour améliorer la capacité des bureaux régionaux et permettre au programme d'avoir un effet substantiel sur la durabilité de l'eau.

Enfin, le troisième chapitre aborde certaines des préoccupations liées au changement climatique en analysant les effets des périodes de sécheresse et des inondations sur la migration interne au Mexique. Les résultats montrent que la sécheresse comme les inondations agissent comme facteurs d'incitation à la migration interne. En outre, les écarts de revenu, les homicides, et le niveau d'éducation sont des facteurs clés pour la migration interne.

**Mots-clés :** Mexique, eau souterraine, surexploitation, mécanismes de régulation, extraction illégale de l'eau, migration environnementale, changement climatique