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Deterministic hydrological modelling for real time decision support systems : application to the Var catchment, France

Qiang Ma

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THÈSE DE DOCTORAT

Modélisation hydrologique déterministe pour les systèmes d'aide à la décision en temps réel

Application au bassin versant Var, France

Qiang MA

Polytech Lab

**Présentée en vue de l'obtention
du grade de docteur en**

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When I reviewed my study career in Europe, started from 2011, I arrived at Netherland to do my first Master program, until now I finished my Ph.d thesis, it already 7 years past. After 7 year hard working, I almost succeed to change my major from Geological Information System (GIS) to Hydro-informatics. As young foreigner kid, to change my research direction in Europe, without the help and support from my family and friends, it is impossible for me to get this achievement. Therefore, I would like to show my deepest respect and acknowledgment to all of my professors, friend who I met in Europe and China, and my family members.

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ABSTRACT

Water resource is commonly considered as one of the most important natural resources in social development especially for supporting domestic, agricultural and industrial uses. During the last decade, due to the increase of human activities, such as urbanization and industrialization, the social impacts on the natural environment become more and more intensive. Therefore, recently, water problems compared to before become more complicated. To deal with the complex problem, since 1970s, started from the companies, people recognized that the Decision Support System (DSS) has obvious advantages. Moreover, with the development of computer science and web techniques, the DSS are commonly applied for supporting the local decision makers to manage the region natural resources especially the water resources.

The hydrological modelling in charge of representing the catchment characteristics plays significant role in the Environment Decision Support System (EDSS). Among different kinds of models, the deterministic distributed hydrological model is able to describe the real condition of the study area in more detail and accurate way. However, the only obstacle to limit the applications of this kind of model is pointed to the large data requirement requested by its modelling set up.

In this study of hydrological modelling assessment in AquaVar project, one deterministic distributed model (MIKE SHE) is built for the whole Var catchment with less field information available in the area. Through one reasonable modelling strategy, several hypotheses are conceived to solve the missing data problems within daily and hourly time intervals. The simulation is calibrated in both daily and hourly time scale from 2008 to 2011, which contains one extreme flood event at 2011. Due to the impacts of missing data on both model inputs and observations, the evaluation of modelling calibration is not only based on the statistic coefficients such as Nash coefficient, but also effected by some physical factors (e.g. peak values and total discharge). The calibrated model is able to describe usual condition of Var hydrological system, and also represent the unusual phenomenon in the catchment such as flood and drought event. The validation process implemented from 2011 to 2014 within both daily and hourly time interval further proves the good performance of the simulation in Var.

The MIKE SHE simulation in Var is one of the main parts of the deterministic distributed modelling system in the EDSS of AquaVar. After the calibration and validation, the model could be able to use for forecasting the impacts of coming meteorological events (e.g. extreme flood) in this region and producing the boundary conditions for other deterministic distributed models in the system. The design of the EDSS architecture, modelling strategy and modelling evaluation process presented in this research could be applied as one standard working process for solving the similar problems in other region.

Key words: AquaVar project, DSS, deterministic distributed hydrological model, hydrological assessment, MIKE SHE, Var catchment.

RESUME

Les ressources en eau sont généralement considérées comme l'une des ressources naturelles les plus importantes du développement social, en particulier pour soutenir les usages domestiques, agricoles et industriels. Au cours de la dernière décennie, en raison de l'augmentation des activités humaines, telles que l'urbanisation et l'industrialisation, les impacts sociaux sur l'environnement naturel deviennent de plus en plus intenses. Par conséquent, de nos jours, les problèmes d'eau par rapport à avant deviennent plus compliqués. Pour faire face au problème complexe depuis les années 1970, les gens ont reconnu que le système d'aide à la décision (DSS) présente des avantages évidents. De plus, avec le développement de l'informatique et des techniques web, les DSS sont souvent utilisés pour appuyer la décision locale. Les décideurs pour gérer les ressources naturelles de la région en particulier les ressources en eau.

La modélisation hydrologique en charge de la représentation des caractéristiques du bassin versant joue un rôle important dans le système d'aide à la décision environnementale (EDSS). Parmi les différents types de modèles, le modèle hydrologique distribué déterministe est capable de décrire l'état réel de la zone d'étude de manière plus détaillée et précise. Cependant, le seul obstacle à la limitation des applications de ce type de modèle est pointé vers le grand besoin de données demandé par sa configuration de modélisation.

Dans cette étude d'évaluation de la modélisation hydrologique dans le projet AquaVar, un modèle distribué déterministe (MIKE SHE) est construit pour l'ensemble du bassin versant du Var avec moins d'informations de terrain disponibles dans la zone. Grâce à une stratégie de modélisation raisonnable, plusieurs hypothèses sont conçues pour résoudre les problèmes de données manquantes dans les intervalles de temps quotidiens et horaires. La simulation est étalonnée sur une échelle de temps quotidienne et horaire de 2008 à 2011, qui contient un événement de crue extrême en 2011. En raison des impacts des données manquantes sur les entrées et les observations du modèle, l'évaluation de l'étalonnage de la modélisation n'est pas seulement basée sur des coefficients statistiques tels que le coefficient de Nash, mais aussi des facteurs physiques (p. ex. valeurs maximales et débit total). Le modèle calibré est capable de décrire les conditions habituelles du système hydrologique varois, et représente également le phénomène inhabituel dans le bassin versant tel que les inondations et les sécheresses. Le processus de validation mis en œuvre de 2011 à 2014 dans l'intervalle de temps journalier et horaire confirme la bonne performance de la simulation dans le Var.

La simulation MIKE SHE dans Var est l'une des parties principales du système de modélisation distribuée déterministe de l'EDSS d'AquaVar. Après l'étalonnage et la validation, le modèle pourrait être utilisé pour prévoir les impacts des événements météorologiques à venir (par exemple, des crues extrêmes) dans cette région et produire les conditions aux limites pour d'autres modèles distribués déterministes dans le système. La conception de l'architecture EDSS, la stratégie de modélisation et le processus d'évaluation de modélisation présentés dans cette recherche pourraient être appliqués comme un processus de travail standard pour résoudre les problèmes similaires dans d'autres régions.

Mots clés: projet AquaVar, DSS, modèle hydrologique distribué déterministe, évaluation hydrologique, MIKE SHE, bassin versant Var.

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INTRODUCTION

Study Background

Water resource is commonly considered as one of the most important natural resources in social development especially for supporting domestic, agricultural and industrial uses. During the last decade, due to the increase of human activities, such as urbanization and industrialization, the social impacts on the natural environment become more and more intensive. Therefore, recently, water problems compared to before become more complicated. In summary, those issues related with water resources we recently faced could be generally concluded into three aspects including “Integrated Water Resources Management”, “Disaster Control” and “Environment Protection”.

In a catchment system, the water distribution or water movement is not affected by any signal process, but influenced by multi-hydrogeological processes interacted together. Therefore, to assess or deal with the water issues in one catchment, it often requires massive data to describe the hydrogeological characteristics of the catchment in both temporal and spatial aspects. In the past, due to the technique limitation, the data shortage was the main obstacle among the assessments of water related problems, but now this situation has been changed. With the progress of the new techniques such as computer science, internet and remote sense, it is possible to collect detail information directly in the field of catchment, thus the main challenge is shifted from data collection to data assessment and management as the amount of the monitoring data showed explosive growth.

For the local managers or decision makers, their assessments of water related problems often contain multi objectives such as on one hand to manage the water resources and on other hand to defence the flood disasters, a Decision Support System (DSS) consisted with several deterministic distributed models has obvious advantages of producing detail information and optimizing the organization of massive collected field information. However, depends on the complicity of the assessing catchment system, the difficulties of setting up the deterministic distribution system often lies in using appropriate methods to minimize the uncertainty in order to make the process described by the model simulation more closed to the reality.

This research project contained two main objectives: one is to design a web-based DSS to integrate manage the real time monitoring information and model simulation results and another is to set up one deterministic distributed hydrological modelling system to accurately represent the complex catchment hydrogeological characteristics with less filed survey available. For the first objective, after reviewing the progress of the DSS, a multi-layered DSS was designed in this project to satisfy various requirements asked by different users of this DSS. Moreover, some new concepts from other domain such as dashboards presentation were first introduced in the DSS design to improve its visualization. For the second objective, a new modelling strategy was conceived in this research study to fill the gaps caused by the missing field data and enhance the accuracy of the deterministic distributed hydrological simulation.

AquaVar Project

The unconfined aquifer of the lower Var valley is one of the main fresh water resource of the state of Alpes-Maritimes, which provides the drinking water for around 600 000 residents lived in this region and also supports the industrial and agricultural uses. To optimize the fresh water resource management by producing an integrated water management tool, the local water management authority, Régie Eau d'Azur (REA) started this research project named with AquaVar since 2014 and planned to last for 4 years.

The project of AquaVar emphasizes to design an DSS contains several deterministic distributed models to understand the water cycle in whole Var catchment and also quantifies the river-aquifer exchanges in the lower Var valley. The model simulations were required to cover different temporal and spatial scales of the water management and their results were expected to be able to produce the arguments for supporting the decision-making process regarding the daily operations, reactions to accidental events and influence of future developments. Four functions were proposed at beginning of the project, which should be fulfilled at the end of the research:

- The deterministic distributed models applied in this project should be able to represent the real hydrogeological characteristics of the study area in Var.
- The modelling system should be able to be used for predicting the impacts of future construction projects on river and groundwater hydraulics.
- The models in this project should be able to implement long term scenario simulation to analyze the response of catchment to climate changes.
- The models developed in the AquaVar project should be able to forecast the impacts of extreme meteorological events in the catchment.
- The pollutant transport in the river should also be considered in the modelling system to cover the situation of seawater intrusion and accident chemical pollutant leakage into the river or unconfined aquifer.

Considering the needs of the projects, three deterministic distributed models were determined at the beginning, which expected to satisfy the different requirements of the project:

- A hydrological model will in charge of representing the complex hydrogeological processes in whole catchment including rainfall-runoff process, snow melting, infiltration and evapotranspiration and producing the up boundaries for the models of lower Var valley.
- A river hydraulic model will be set up more focused on the lower Var valley to simulate the surface flow movement and river-aquifer exchange in this specific area.
- A groundwater flow model will be built to simulate the unconfined aquifer also located in the lower Var valley and coupled with the river hydraulic model to have more accurate and detail presentation of the river-aquifer exchanges in this study area.

Objectives of The Research

Previous studies have been carried out to assess the hydrogeological characteristics of Var catchment (Gugliemi, 1993; Guglielmi and Reynaud, 1997; Guinot and Philippe, 2003; Emily et al., 2010; Potot, 2011; Potot et al., 2012). However, those studies either only focused on one specific extreme event occurred in Var (Guinot and Philippe, 2003), or mainly concentrated on the unconfined aquifer at the lower Var valley (Gugliemi, 1993; Guglielmi and Reynaud, 1997; Emily et al., 2010; Potot, 2011; Potot et al., 2012). For the whole catchment scale, there are significant knowledge gaps existed in the hydrogeological assessment of Var. Especially at the upper part of the catchment, due to mountainous terrain with higher elevation, few measurements were implemented at those areas, which leads a serious data shortage. Therefore, a deterministic distributed hydrological model is strongly needed in Var to fill the missing data gaps and integrate represent the complex hydrological processes. Thus, the objectives of this research were defined as follow:

- First of all, the role of the hydrological model in the decision support system and its relationship with other modelling processes should be clearly defined in advance.
- All the information related to the hydrogeological characteristics of Var should be collected and analysed to improve the knowledge of catchment hydrological system.
- Considering the characteristics of the deterministic distributed hydrological model and the data limitation in the project, one suitable modelling strategy should be conceived in the research to overcome the obstacle of missing data.
- Following the suitable mode strategy, a numerical modelling system of MIKE SHE would like set up to integrate represent multi-hydrological processes interacted in the Var catchment. The simulation should be able to accurately describe the long term hydrological phenomenon in Var and also well represent the extreme event occurred in this region.
- Due to the short concentration time of Var catchment, the simulation should be handled with two different time intervals (daily and hourly). The calibrated model should be able to either forecast the impacts of coming scenarios in both daily and hourly scale or produce the reasonable boundary conditions for other models in the DSS, which more focused on the lower Var valley.

Thesis Structure

According to the objectives of the study, this thesis is divided into five consecutive chapters and each chapter unfolds a specific subject explained above. The thesis starts with the discussion about the role of hydrological models in the environment decision support system and the design of the layered EDSS of AquaVar project. Then when the architecture of the AquaVar EDSS is defined, the next chapter is more focused on the selection of the model applied in the EDSS. Among different hydrological models, the deterministic distributed hydrological model (MIKE SHE) has obvious advantages of representing the real hydrological process in more detail and accurate way. In the case of Var catchment, the missing field information causes significant difficulties in the modelling set up process. Therefore to overcome the obstacle, a reasonable modelling strategy should be conceived to find the balance between model accuracy and running time and satisfy the model requirements. In the third chapter, the data assessment is implemented before the real modelling application, which supposes to understand the hydrogeological characteristics of Var catchment in order to define the main hydrological processes, which should be more focused on during the modelling simulation. Based on the assessment of hydrogeological characteristics of Var catchment, following the modelling strategy defined in this project, in the fourth chapter, the modelling set up and calibration process have been introduced in detail. The last chapter presented the modelling results in both daily and hourly time interval. After the calibration and validation, the MIKE SHE application in Var catchment has been proved to be able to represent the real phenomenon in this region and hypotheses applied in the modelling processes could be effectively solve the missing data problem in the deterministic modelling simulation. In the conclusion and perspectives of the thesis have summarized the achievements of this research and gives the guide of the next step of the project, which supposes to integrate all the modelling application in the EDSS of AquaVar.

CHAPTER 1: ROLE OF HYDROLOGICAL MODEL IN REAL TIME ENVIRONMENT DECISION SUPPORT SYSTEM

The water resource is the premier scarcest nature resource, which highly affects social development. The topic related to water issue will be continuously causing controversy over the whole 21st century. The main challenges existed in water domain could be summarized within three aspects: (1) Integrated Water Resource Management (IWRM), (2) Disaster prevention and control and (3) Water environment protection and rehabilitation. In the past, the decisions made in water domain were mainly based on experience assessment with limited historical data. Recently, with the progress of computer science, the Decision Support Systems (DSS) and Real-Time Control (RTC) are widely implemented to answer the water questions and support the decision making process.

Challenges in Integrated Water Resource Management (IWRM)

In recent years, due to the population growth, increase in household income and irrigation development, the water demand doubled every twenty years, more than double the rate of human population growth (ITU-T Technology Watch Report, 2010; Sempere-Payá et al., 2013). Comparing with the management made in the past (for example in 1960s), which based on the assumption of water is infinite resource and mainly concerned on water allocation and distribution, recently, all the managers agree to change this approach for building an efficient and sustainable plan to optimize the utilization of scant water resource (Soncini-Sessa et al., 2003). How to manage the shortage of available water resource with sharply increased water demand is frequently repeated by both national and regional decision makers. However, the decision-making process associated with the utilization of water resources are very complex requiring integrated consideration to optimize the balance between those two aspects (Salewicz and Nakayama, 2004). To answer the question with an IWRM plan, the impact factors of socio-economic, environment and human activities should be all included in the consideration.

Challenges in Disaster presentation and control

Of all the natural disasters, water disaster impacts on the greatest number of people across the world (Moore et al., 2004). Flood is one of the major contributors to personal injury and to property damage (Al-Sabhan et al., 2003). In the speech of Witt given on news conferences at 1998 and 2000, he claimed: “Regardless of whether you believe the cause is global warming or natural changes in weather patterns, there is no disagreement that the frequency and severity of what we call ‘weather events’ are on the rise” (Witt et al., 1998; NOAA, 2000). Moreover, recent researches have improved the understanding of the current flood damage, which is statistically related to precipitation and the relationship is strengthened if the population growth is taken into account (Pielke and Downton, 1999 and 2000). In 21st century, the trend of social development is to become more urbanized. Urban invasion of floodplains will likely continue since the cost of investing there is relatively low (Handmer, 2001). The research studies indicate that “floodplain communities are likely to undergo extreme flood more frequently” (Wade et al., 1999; United Kingdom Climate Impacts Programme, 2001).

Challenges in Water environment protection and rehabilitation

Recently, to produce 40% of worldwide food needs, approximately 70% of surface water and ground water is claimed by irrigated agriculture (Brown, 2001). The water environment has direct impact on human health. To manage the water environment, such as water quality control, the decision-process requires clear representation of current situation and estimation of potential phenomenon, which normally consisted with complicated processes and integrated consideration including influences of social-economic, environment and human activities and the responses of the nature environment (Zhang et al., 2010).

Decision Support System (DSS) applied in water domain

In 21st century, solving the water issues will be the main challenge. With the evolution of computer science, the new techniques of Decision Support System (DSS) and Real-time Control (RTC) are widely applied in the water domain to support the decision-making processes of water management, disaster defense and environment protection.

While the progress of computer science makes our daily life more convenient, it also leads hydrologists to start to think how to bring the advantages of computer applications into water subjects. Comparing with the traditional water science subjects such as hydrology, hydraulic or hydro-statistic, the new subject named hydro-informatics has obvious advantages of representing the reality more accurate, producing more detail results and easy embedding in the new DSS and RTC system, *etc.* By applying the computer tools of hydro-informatics models in DSS, the process of data collection, data assessment, scenarios analysis and results visualization will work more efficiently for supporting the decision making.

In this chapter, it aims to produce an integrated overview of DSS and the role of the hydrological model in this new computer based management system. The content starts with the first section of reviewing the history of DSS evolution from the past until now. Then at the second section, the topic moves to the discussion of evolution of DSS architecture applied in water domain linking with the hydro-informatics technique applications. Based on the new techniques and concepts, a new DSS architecture in water domain will be designed and discussed in the third section. At the end, as the modelling tools play significant role in the new DSS, the role of hydrological model and the criteria of model selection will be identified based on the discussion about different characteristics of various kinds of hydrological models.

1.1. Evolution of Decision Support Systems (DSS)

In 1950s, at business companies, people started to recognize that the computer science must have places in modern business, especially in supporting decision making process. Different with the tradition way of decision making, a new decision making process is defined by Simon in 1960. He classified the decisions in two types including programmed decisions and non-programmed decisions. The programmed decisions could be routine, structured and repetitive. It aims to solve the often occurred problems and no needs to be modified each time. The non-programmed decisions could be novel, unstructured and consequential. Its objective is to overcome the elusive and complex problems never arisen before. Compare to the traditional decision making techniques (Table 1), Simon proposed a three phase trichotomy of decision processes (Figure 1) consisted with “Intelligence”, “Design” and “Choice”. He identified that the “Intelligence” activity should be the first step in the decision making process to “search the environment for conditions calling for decisions”. And then, at second phase, “Design” activity could be implemented to “invent, develop, and analyse the possible courses of actions”. At the end, with “Choice” activity, the users could have the ability to “select a particular course of action from those available” (Simon, 1960).

Table 1: Traditional and Modern Techniques of Decision Making (Simon, 1960)

Types of Decisions	Decision-Making Techniques	
	<i>Traditional</i>	<i>Modern</i>
Programmed: Routine, repetitive decisions Organization develops specific processes for handing them	1.Habit 2. Clerical routine: Standard operating procedures 3. Organization structure: Common expectations A system of sub goals Well-defined informational Channels	1.Operation Research: Mathematical analysis Models Computer Simulation 2. Electronic data processing
Non-programmed: One-shot, ill-structured, novel, policy decision Handled by general problem solving processes	1. Judgement, intuition, and creativity 2. Rules of thumb 3. Selection and training of executives	Heuristic problem-solving technique applied to: (a) training human decision makers (b) constructing heuristic computer programs



Figure 1: Simon’s Model of the Decision Process (Simon, 1960)

In addition, we notified that the concept of Management Information System (MIS) was conceived more or less in same period when [Simon \(1960\)](#) presented his design of “Decision Process”. At the beginning, the main task of MIS was designed to produce the predefined managerial report and to support the tactical decision making with the information techniques such as computer science ([Tian et al., 2005](#)). Unfortunately, even the progress of computer science led to the tremendous growth of computer uses in management activities, during the period from 1955 to 1970, there was no significant improvements on the MIS applications in DSS. The main reasons could be because of when the new concept of MIS was first conceived, (1) the related management activities were not yet clearly defined, (2) the design of the MIS framework was very simple and not efficient and (3) there was no standard framework created to answer general or specific problems respectively.

In 1965, [Anthony \(1965\)](#) developed a taxonomy for managerial activities, which sufficiently different in kind to require development of different system. The first category of the managerial activity was defined as “Strategic Planning”, which “*is the process of deciding on objectives, on the resources used to attain these objectives, and on the policies that are to govern the acquisition*”. The second category was described as “Management Control”, which is “*the process by which managers assure that resources are obtained and used effectively and efficiently in the accomplishment of the organization’s objective*”. And the last category was named as “Operational Control” means that “*the process of assuming that specific tasks are carried out effectively and efficiently*” ([Anthony, 1965](#)).

Even though, with the classification created by [Anthony \(1965\)](#), the planning management became more perspective, the boundaries of those three categories were still not often clear to the decision makers in their real management activities. In 1971, [Gorry and Scott Morton \(1971\)](#) introduced those three descriptions of management activity into the Information System (IS) activity. They summarized the information requirements of those three categories and produced a clear understanding of their boundaries in MIS (Table 2). They found that “The information requirements for management control fall between the extremes for operational control and strategic planning. In addition, it is important to recognize that much of the information relevant to management control is obtained through the process of human activities.” ([Gorry and Scott Morton, 1971](#))

Table 2: Information requirements by decision categories ([Gorry and Scott Morton, 1971](#))

Characteristics of information	Operational Control	Management Control	Strategic Planning
Source	Largely internal	----->	External
Scope	Well defined, narrow	----->	Very wide
Level of Aggregation	Detailed	----->	Aggregate
Time Horizon	Historical	----->	Future
Currency	Highly current	----->	Quite old
Required Accuracy	High	----->	Low
Frequency of Use	Very frequent	----->	Infrequent

Integrated [Anthony’s](#) categories of management activity (1965) and the [Simon’s](#) decision types (1960), [Gorry and Scott Morton \(1971\)](#) built an interesting framework of IS, which examine its

purposes and problems (Figure 2). They applied the terms of “structured” and “unstructured” decisions to replace the “programmed” and “non-programed” decisions, since those two words imply less dependence on computers. Based on dividing line (dash lines) in Figure 2, they named the system supporting the structured decisions as Structured Decision System (SDS) and the system supporting the semi-structured and unstructured decisions as Decision Support System (DSS). This could be considered as the original concept of DSS. In addition, [Gorry and Scott Morton \(1971\)](#) also argued that the characteristics of both information needs and models differ in the DSS environment.

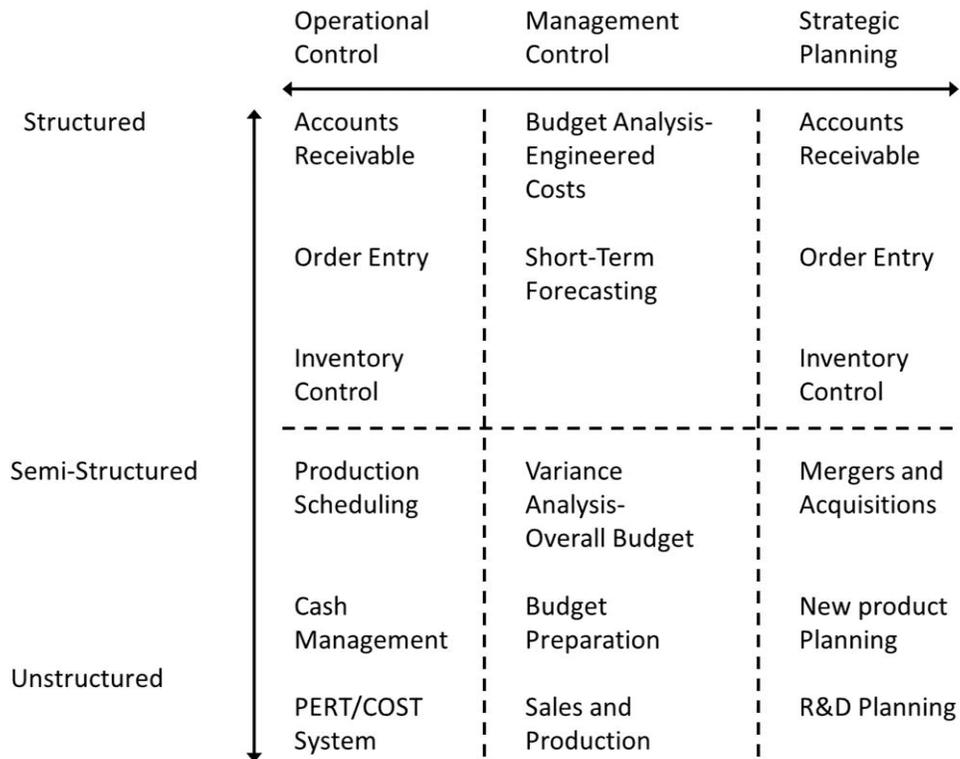


Figure 2: Information system: a framework (Gorry and Scott Morton, 1971)

After the concept of DSS was officially conceived in 1970s, DSS further evolved in 1980s. The original DSS was designed for the individual users to support their decision making for solving signal problem, which are normally not so complicated. Since 1985, the Group Decision Support System (GDSS) or just Group Support System (GSS) was created to support the team problem solving processes by use of a combination of communication and DSS technologies ([Arnott and Pervan, 2008](#)). The network system is introduced into the GSS, which allowed the discussion within groups and distributed individuals. Meanwhile, through the integration of network techniques, artificial intelligence and enterprise information system, a number of sub-fields such as Distributed Decision Support System (DDSS) and Integrated Decision Support System (IDSS) continuously conceived and be introduced into the DSS family. Both the DSS philosophy and techniques had big evolution during this period. Unfortunately, it was evident that most corporate executives did not directly apply DSS in their daily work.

In the late 1980s, the concept of Executive Information System (EIS) was identified in the DSS group, which genuinely extended the scope of DSS from personal or small group to the cooperate level. A EIS can be described as a DSS that “(1) provides a assess to (mostly) summary performance data, (2) has uses graphics to display and visualize the data in an easy-to-use fashion and (3) has a minimum of analysis or modelling beyond the capability to ‘drill down’ in summary data to examine components” (McMurln and Sprague, 2004). Integrated considering the DSS, GDSS (or GSS) and EIS, they were each more compatible with different decision styles than others (Figure 3). The analytic decision makers could benefit from both detailed assessment with DSS and perspective pictures by EIS. For the directive decision makers, the EIS had obvious advantages of fast decision making process. In contrast, the conceptual decision makers might more focus on the exploring a wide assortment of different scenarios, which well supported by DSS and GDSS. And finally, behavioural decision makers appreciated the facility of GDSS to collect the opinions of many stakeholders.

		Propensity to Adopt GDSS	
		Low	High
Propensity to Adopt DSS	High	<p>Analytic</p> <p>Reliance on careful analysis of large volumes of codified data.</p> <p>Interest in both the details of situation and the larger, aggregated profile.</p>	<p>Conceptual</p> <p>Data processing is useful to consider long-term water-if scenarios</p> <p>Some IT applications may be useful for interpersonal relationships</p>
	Low	<p>Directive</p> <p>Limited interest in large-scale data analysis or human relationships.</p> <p>Interest in the aggregated profile of the situation to support a rapid decision making process</p>	<p>Behavioral</p> <p>Limited interest in data processing since information and rules are less important than intuition and relationships.</p> <p>Tools that facilitate communication and consensus-building will be used</p>
		High	Low
		Propensity to Adopt EIS	

Figure 3: Information technology applications and decision styles (Martinsons and Davison, 2007)

When we paused reviewing of the DSS evolution at end of 1980s, with nearly 30 year progress, DSS framework had been extended in different orientations. This extended DSS framework could be specified with five categories recognized by identifying different dominant architectural components. The five categories could be identified with model-driven, communications-driven, document driven, knowledge-driven and data-driven DSS (Power, 2002). The model-driven DSS is the classical DSS, which supports the decision making process by using the computerized system including model simulations or computer based assessment tools. The data information and parameters applied in the model-driven DSS are mainly produced by the decision makers to represent the current situation and assess the different design scenarios. However, it should be clear that the model-driven DSS is usually not data intensive (Power and Sharda, 2007). The communication-driven DSS derived their functionality from communications and information techniques. Its emphasis is sharing the information with all the members to support the group decision making process. Similarly, the document-driven and knowledge-driven DSS are also

more focused on the information interactions such as producing sophisticated documents or giving knowledge-based suggestions to support the final decision making. Nevertheless, the last category named with data-driven DSS has special characteristic of its functionality covering the manipulation and organization of large database.

Here, we recognized that the DSS was conceived with the interaction between computer science and management activities. With the increase of social requirements and evolution of computer technique, more new concepts were kept adding into the existed DSS and made it become more complicated and diverse. DSS was firstly identified as a simple analysis tool, which may only support individual decision making. Until the end of 1980s, it had developed as a complex system consisted with big data assessment, information network, artificial intelligence, etc. There were two changing aspects should be highlighted in the trend of the DSS progress in this 30 years' development and might continue developing not only up to now but also in the farther future:

The first is the changing of DSS main service objects. Due to the evolution of computer science and information technique, DSS began to get more power of assessing more impact factors. The service objects of DSS were kept enlarging from small companies to national departments. And the main objective of the DSS was also changed from solving one specific problem to integrated consider more complicated system consisted with many different processes working independently or integrated.

The second is the extending of DSS framework. With the increase of computer facilities, which increased the model capacity to produce more detail and accurate simulation results in certain level, the key topic of DSS was shifted from "How to get more accurate assessment of the problem?" to "How to improve the communication network to share the analysis results and receive responses from other DSS users?" The role of information interaction in DSS gained more interests by both DSS designers and DSS users (such decision makers or public stakeholders). Building fast, convenient and efficient communication channels linked with all the DSS users was added into the core of the DSS framework. Furthermore, at end of 1980s, the evolution of monitoring technique led to the explosive growth of measured data, which caused new requirement of DSS users to have a well organization of the database. Therefore, the EIS was conceived at this moment to satisfy the new needs of DSS users. In summary, with 30 years' evolution, the DSS framework was extending from model-driven through communication-driven, document-driven and knowledge-driven now to more data-driven.

In 1990s, the DSS was continuously developed in the data-driven orientation. Four useful tools including data warehouse, On-Line Analytical Processing (OLAP), data mining and World Wide Web were introduced in data-driven DSS. Since 1970, Codd (1970) proposed a relational data model for database and predicted the impacts of this data based model on the DSS would keep increased (Codd, 1970). The work of Innom (1992) and Kimball (1996) made the definition of data warehouse become more clearly: "*data warehouse is a subject-oriented integrated, time-variant, non-volatile collection of data which can be considered as a solution for integrating data from diverse operational databases to support decision making processes*" (Innom, 1992; Kimball, 1996). However, building a large data warehouse usually brings the challenges of how to assess the accumulated historical data in a fast and efficient way. To answer this question, applying the OLAP tools in the data warehouse could be one of reasonable solutions. "*On-Line Analytical Processing (OLAP) is a category of software technology that enables analysts,*

managers, and executives to gain insight into data through fast, consistent, interactive access to a wide variety of possible views of information that has been transformed from raw data to reflect the real dimensionality of the enterprise as understood by the user.” (OLAP Council, 1997) Soon after, while the OLAP became a common tool to manage the large database, the concept of data mining defined as a set of artificial intelligence and statistical tool was proposed for more sophisticated data analysis (Edelstein, 1996). Data mining also called database exploration, which aims to find the patterns of data and infer rules from them (Power, 1999).

At the mid-1990s, researchers were exploring the possibilities for the next generation of DSS (Bhargava et al., 1997; Bui, 1997; Gregg et al., 2002). Many of academic researchers and software developers had realized that the Web and Internet technologies could be the center of activity in DSS progress in 21st century. The advantages of developing a web-based DSS were clearly shown in two aspects: Firstly, the Web-based DSS can reduce technological barriers and make it easier and less costly to make decision-relevant information (Power, 1999). Secondly, using Web-based DSS, organizations can provide DSS capability to managers over a proprietary intranet, to customers and suppliers over an extranet, or to any stakeholder over the global Internet (Shim et al., 2002).

Overview of the development of decision support technologies in past 50 years gave us some hints of the coming evolution of DSS in 21st century. Changes may occur in technologies and in the implementation environment – users are becoming more sophisticated and more demanding, organizations are becoming more complex yet more agile and flexible, and global regulatory and competitive factors rapidly change, affecting the design and use of these tools (Shim, 2002). A major trend will be observed is how the Web and internet technologies are supporting more interactivity and collaboration in DSS. Based on the agenda for DSS research made by Keen (1987) and Shim et al. (2002), we expected the development of DSS in the new century may continuously enhanced in the areas of artificial intelligent, information interaction, Web-enable tools and data mining of large database.

1.2. Evolution of Environment DSS (EDSS) Architecture

With global climate change and increasing intensity of social activities, the water crises occur frequently all over the world. In the report published by UNESCO (2006), it claimed that except natural evolution, the main reason of water crises may due to the lack of sustainable method to integrated manager the water resources. Before the concept of DSS was first conceived in 1960s, the managements of water environment were commonly supported by “expert system” where few modelling analysis were involved in the assessment and its decision making process fully depended on the knowledge and experience of decision makers who was called as “expert”. Obviously, the decisions supported by expert system sometimes were more subjective. It was worked well for solving structured problems in the region, which has its local “expert”. But it might not work well for solving unstructured problems never happened in the region before and difficult to be defined as a standard work framework to apply in other places.

Since 1970s, the DSS concept was introduced into management of water environment to replace the “expert system” and support the decision making process in a more objective way. The core of the system was shifted from fully knowledge and experience based to referencing the results of modelling analysis. It evidenced by emerging modelling technology and scenario analysis into DSS of water management. In 1968, Hashemi and Decker (1968) published their work of decision support process for irrigation based on climate information in central Missouri, USA. In this study, statistic models were built to analyze the irrigation requirements and estimate the precipitation possibility during the growth season of crops. The modelling assessment in this study was all based on the historical data collected from 1938 to 1967 in the study area. At the end of this work, two objectives were achieved including: (1) discussion of the feasibility of climate data applied in quantitative fashion for supporting irrigation management and (2) evaluation of the model techniques and determination of their benefits in assessing the historical data and estimating the future scenarios.

From the present point of view, we could recognize that in this study of decision support assessment for irrigation plan, all the modelling analysis was based on the historical records in this certain area. And the estimated scenarios were all produced by simple linear statistical methods based on local records, which might have some uncertainties and are only acceptable in this region. Therefore, even though the irrigation plan produced by this study worked well at that moment, in conclusion, they still highlighted that “*The result is significant savings in irrigation water requirement under the existing condition*”. In addition, if we summarized their working process, it was clearly followed the three phase trichotomy of decision processes defined by Simon (1960) (Figure 4).

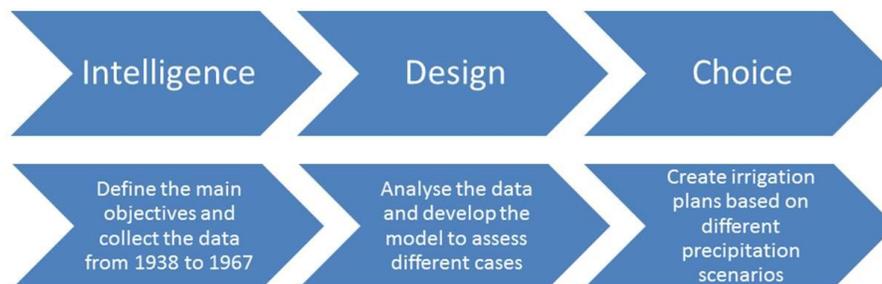


Figure 4: Summarized decision process of irrigation plan in central Missouri, USA (1968).

Due to the limitation of computer facilities at that time, the models built and applied in their study were quite simple. There was no database built during the work process to save and organize the collected information and produced results. Moreover, as results of no communication blocks emerged in this system, it could not invite stakeholders to join the discussion in decision making process and collect the feedbacks. Although there is big space existed and needed to be improved in that system, the study in 1968 could be considered as a good attempt of replacing the “expert system” by DSS, which introduced the modelling analysis as one of the main references to support the decision making process.

After 10 years of DSS progress in water domain, [Kumar and Khepar \(1979\)](#) published their work of building a decision support model for optimal cropping irrigations with water production functions. The model they created was an extended empirical linear relationship model based on the theoretical analysis made by [Pomareda \(1977\)](#) for canal command area. The main objective of this study was aimed to “*demonstrate the usefulness of alternative levels of water use over the fixed yield approach when there is a constraint on water*”. However, comparing with other decision support modelling studies in same period, in this case, the main objective was shifted to solve the structure problems of irrigation without regional limitation. The model designed in this study was no longer as specific case based on local conditions. After testing its sensitivity, the model built in this study could be used as a general function to answer the irrigation questions in a wide area.

In the 1970s, the concept of DSS had not been clearly defined yet and many other aspects were kept adding into DSS family. Therefore, even though the managers attempted to introduce the DSS to replace old “expert system” for solving the problems in a more objective way, few cases were succeed in the water domain applications. One reason could be because of the problems discussed in water environment were often very complicated, which require to have integrated consideration of all independent processes and their interactive effects. Another reason was due to the limitation of computer facility, the model technique was not powerful enough to produce detail and accurate simulation results to support the decision making process. During this period, most of studies in water domain were focused on developing or improving the computer tools for simulating the natural water cycle and support the decision making. The models started to play important role in supporting the decision making process. It started form solving structure problems such as optimizing the irrigation plan to cover the unstructured problems, like flood forecast. From present point of view, in the 1970s, even though the DSS began to gain more interests by the decision maker who worked in water environment area, the concept of “system” were not really built in their working process. At that time, most of decisions made in water

domain were supported by signal decision assessment instead of applying an integrated “system”. The decision assessments were made either depended on “expert” experience or referenced with simple model estimation based on linear statistical analysis with regional historical records under several assumptions or certain hypothesis.

Guariso et al. (1985) developed first DSS in water resource management and applied it to manage the Lake Como in northern Italy. In this study, first they clearly identified the link between the “expert system” and DSS which “*the analyst must first learn from the past experience of the manager and synthesize it into a simple operating rule*”. Secondly, they defined their decision making process into four steps including: (1) *Conceptualization* (which lead to data analysis); (2) *Identification* (which lead to determining the operating rules); (3) *Relaxation* (which lead to analyzing the main future from historical operating rules) and (4) *Optimization* (which lead to selecting the best solution for the managers) (Figure 5). Obviously, in their working process, step 1 and step 3 were both related to data assessment. The analyst in those two steps “*had considerable freedom in interpreting data, simplifying problems and suggesting solutions*”. And the analysis in step 2 and 4 might be more modelling based.



Figure 5: The decision support process of Como Lake defined by Guariso et al., (1985).

The decision assessment presented in their work could produce three different solutions for alleviating flood problem in Como Lake. The operating rules defined in the project were programmed and run on the microcomputer, which is used by the managers in their daily work. In the paper they published, it highlighted in the working process there were links between the rain gauge telemetering network and the decision assessment. In spirit they had not presented their work like an integrated system with graphs of design framework and architecture, from their paper content, we could notice the whole working processes could be summarized with the architecture of DSS showed in Figure 6. This could be considered as the first DSS architecture designed to solving the problems in water environment.

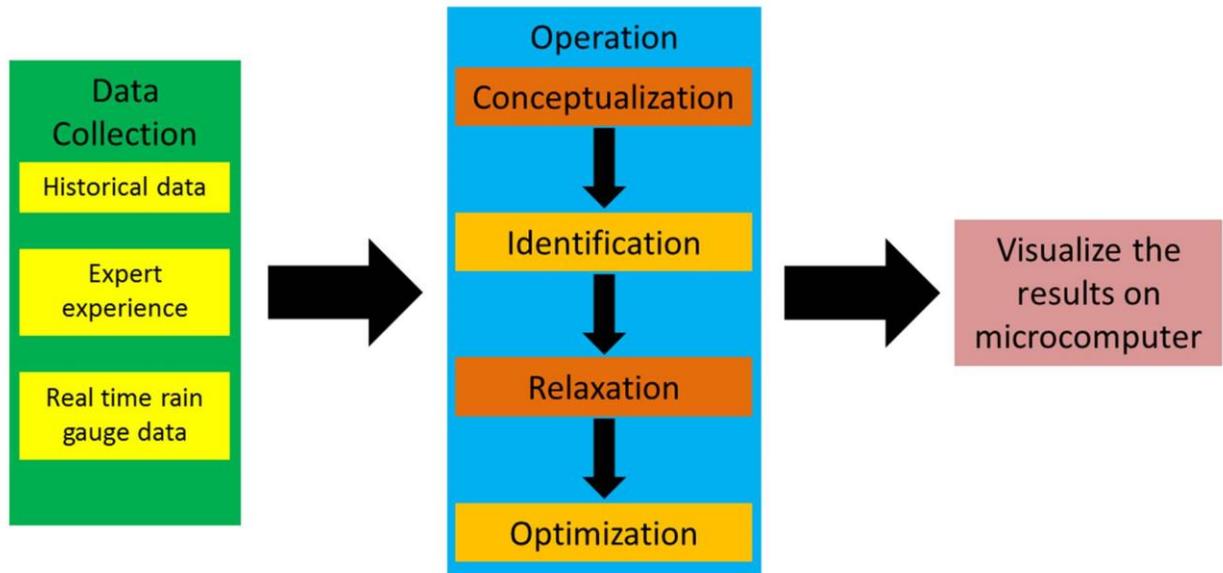


Figure 6: The DSS architecture applied in the case study of water management in Como Lake, Italy

However, with the development of modelling techniques in water domain, computerized tools were widely accepted by the managers as one of the main references supporting their decision making. To implement the modelling assessment, the data collection plays irreplaceable role of setting up the model and evaluating the model accuracy. Moreover, when the modelling tools had the capacity to cover more complicated topics, the results produced by the simulation might become more specialized and complicated, which could not be easy understood by the decision makers who do not have related background. Especially in the management of environment, the improvement of results visualization was highly required in the DSS applications.

Rizzoli and Young (1997) clearly defined the Environment DSS (EDSS) as the DSS applied to solving the environment problems that “*integrate models, or databases, or other decision aids, and package them in a way that decision makers can use*”. The system architecture consisted with three blocks of “Database”, “Operation” and “Results visualization” was commonly accepted by the decision makers to replace the signal decision assessment made in the 1980s.

Haastrup et al. (1998) published their work of building a decision support system for urban waste management. The architecture of their DSS was described in Figure 7, which is similar as the structure we summarized from the work in 1985. It contained three blocks including: “Databases”, “Data and Models Management System” and User Interface System”, which respectively linked to the “Data Collection”, “Operation” and “User Friendly Communication Interface”, described in the work at 1985.

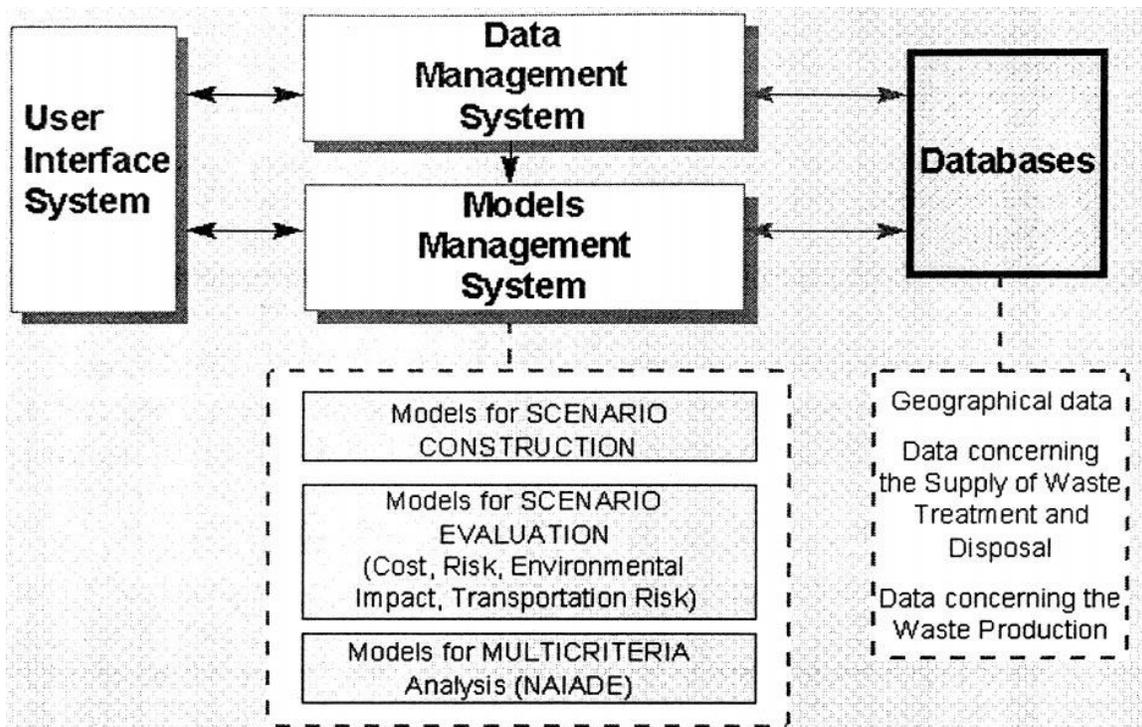


Figure 7: Complete structure of DSS (Haastrup et al., 1998)

Comparing with the work of decision support assessment made in the 1980s, the architecture and its three main components were clearly defined in the framework of this system, and the channels emerged in the system, which linked each of them were not unidirectional but bidirectional. The information interaction was strongly emphasized in the system. Besides, not as before only one single statistical modelling tool was applied in the decision support assessment, but multi-objectives models were created for dealing with various types of field data. The operation stage became more complex with numerous driving factors taken into account such as cost, risk and even environment impacts.

Due to the increase of EDSS complexity, how to present the modelling results in an intuitive and easy-to-understand way was a big challenge in EDSS applications. If the simulation results are directly presented with series of numbers, it might confuse the decision makers who did not have professional background. Hence, to simplify and reorganize the results with maps, graphs and tables with index replacing the numbers could be easily accepted by general decision makers (Figure 8).

In spite of simplifying the modelling results from presenting series of numbers to show in maps, graphs, and tables, could improve system visualization, the information transported from modelling assessment to the decision makers was still not clear and direct enough. In this case, the maps presented in user interface did not have detail information to help the decision makers to quickly define the locations to implement the measures. And the graphs shown in the system were quite conceptual that may still confuse the managers. Moreover, as the decisions supported by this system would have impacts on the citizens, the feedbacks from the stakeholders and public users were necessary for updating the existing system. Unfortunately, from the paper published by the authors, it did not highlight this point in the block of "Databases".

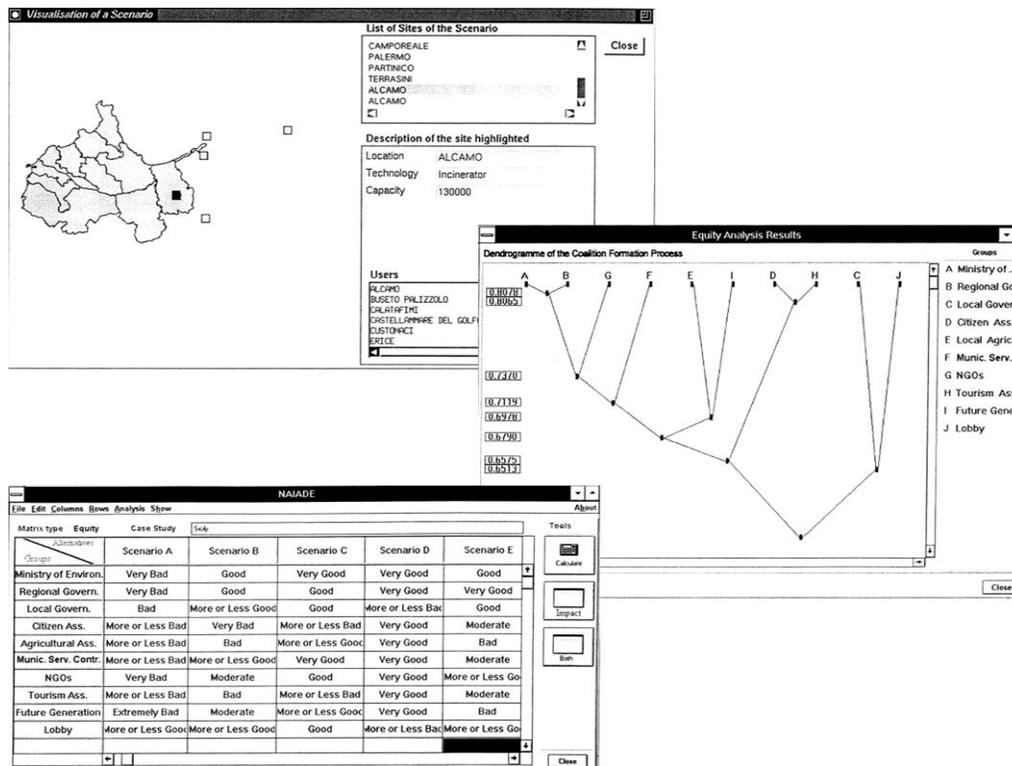


Figure 8: Modelling results presented in DSS with user friendly interface (Hastrup et al., 1998)

At the beginning of new century, Cortés et al. (2000) improved the definition of EDSS as “an intelligent information system that ameliorates the time in which decisions, expressed in characteristic quantities of the field of application”. People further noticed that, in principle, EDSS had the capability to make the decision making process more efficient and reduce the risks resulting from impacts of human societies on natural environment. However, after numerous EDSS applied in the real management works, the users found it difficult to ensure that all the participants involved in the decision making process had the theoretical background of the methodologies applied in the supporting system. It may let the general managers to be confused or to have misunderstanding with the modelling results and make the decision making process become more time consuming. Therefore, in technical, the requirement of increasing the acceptance and confidence level of the assessment results was relatively high.

At same time, the design issues raised with development of integrated EDSS (Lam and Swayne, 2001). The question of whether the EDSS should be designed as a specific system tailored to the need of one single application or it should be generalized from the beginning caused a hot debate. In the study of generic integration of EDSS made by Denzer (2005), he agreed with opinion of generalizing the EDSS from start with the reason of it might be more effective and payed off for a long time. To realize this task, the components in the EDSS should be more interconnected. The developers might face two main challenges including how to link different software together and how to present the results produced from different tools in a standard and easy-to-understand format. Denzer (2005) proposed to design a generic integration EDSS composed of “generic services through generic communication infrastructures”. All the components and interfaces should be enough generalized. Moreover, in technical, he suggested four main techniques could

be emerged in the EDSS including modelling assessment, Geological Information System (GIS) techniques, artificial intelligence and data management (Figure 9). The links between each of them could be technically realized by developing generalized user interfaces.

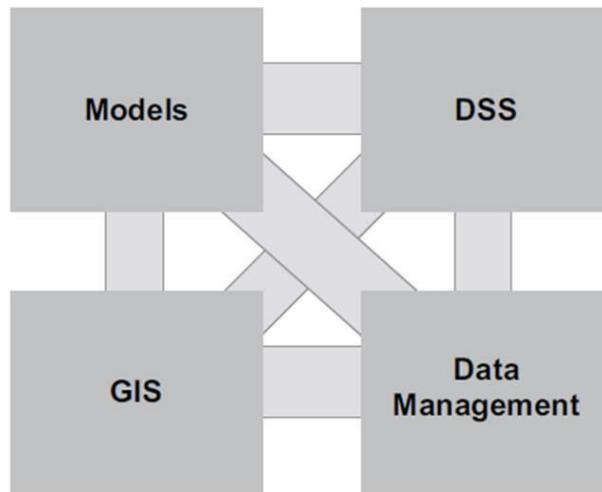


Figure 9: Building blocks of EDSS (Denzer, 2005)

In water environment, the data collected to support the modelling assessment had a special characteristic, which was commonly spatial distributed. Therefore, as the GIS techniques had the capacity to present the data or results in a comprehensive way (Koutsoyiannis et al., 2003), it was widely accepted by both modelers and decision makers to be applied in DSS visualization.

Mbilinyi et al. (2007) created a GIS-based DSS for identifying potential sites for Rain Water Harvesting (RWH) in Makanya catchment, Tanzania. To have an integrated consideration of RWH, both the quantity and quality of the field data should be relative high. From the suggestion of FAO (2008), to have integrated assessment, the best strategy was to find the combination of various techniques and practices from different aspects (Figure 10).

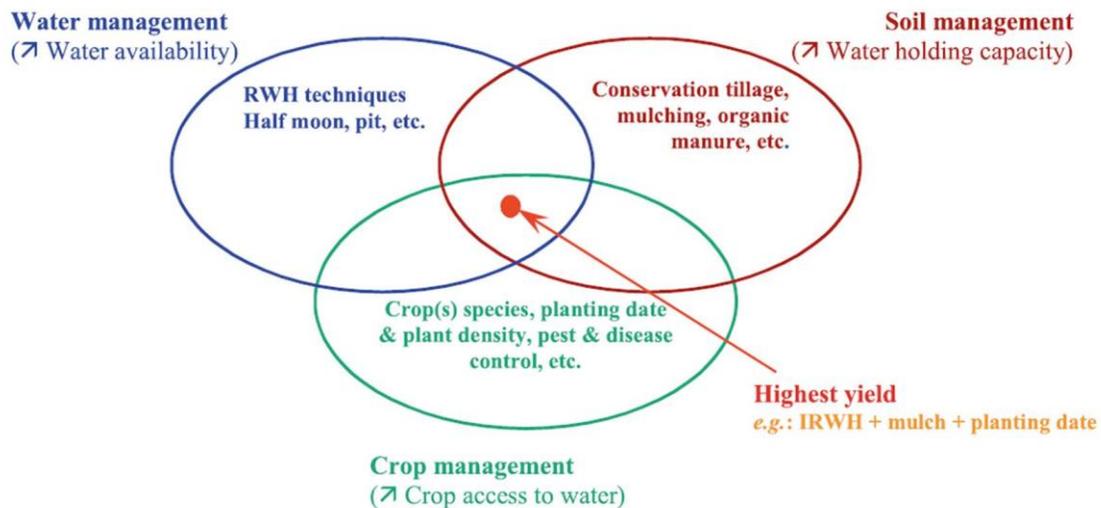


Figure 10: Integrated water–soil–crop management strategies (FAO, 2008)

By taking the advantages of GIS techniques, all the data collected in their DSS database were special distributed. With integrated assessment of surface elevation maps, soil type maps, rainfall interpolation maps and land cover maps, the results produced from this DSS were also shown in maps, which supported an intuitive view to the decision makers and made the decision making process become more efficient (Figure 11). Similar studies could also be found from the work made by *Mwenge Kahinda et al. (2009)* of RWH assessment in South Africa.

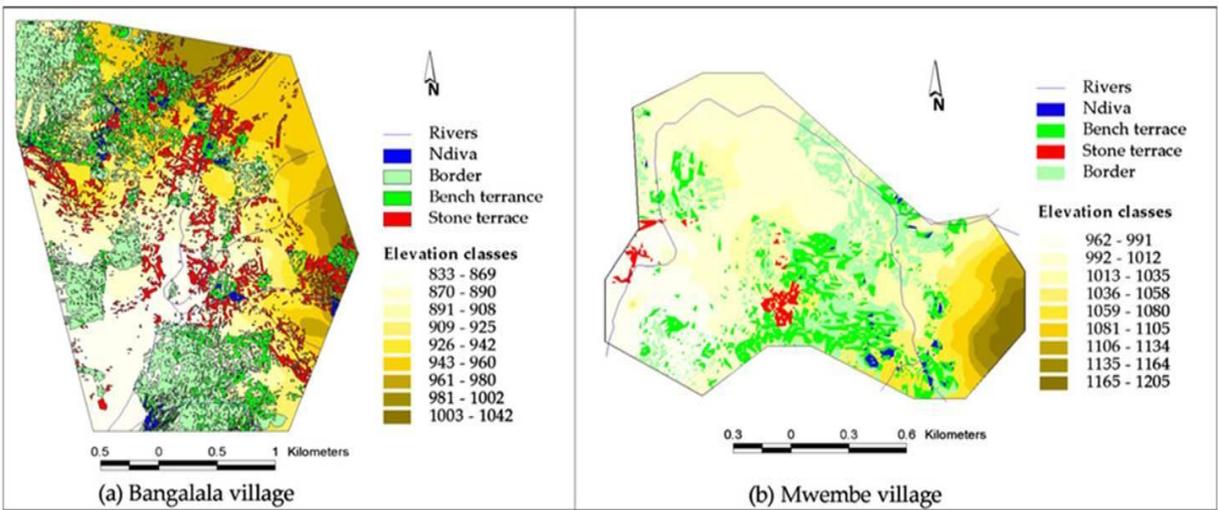
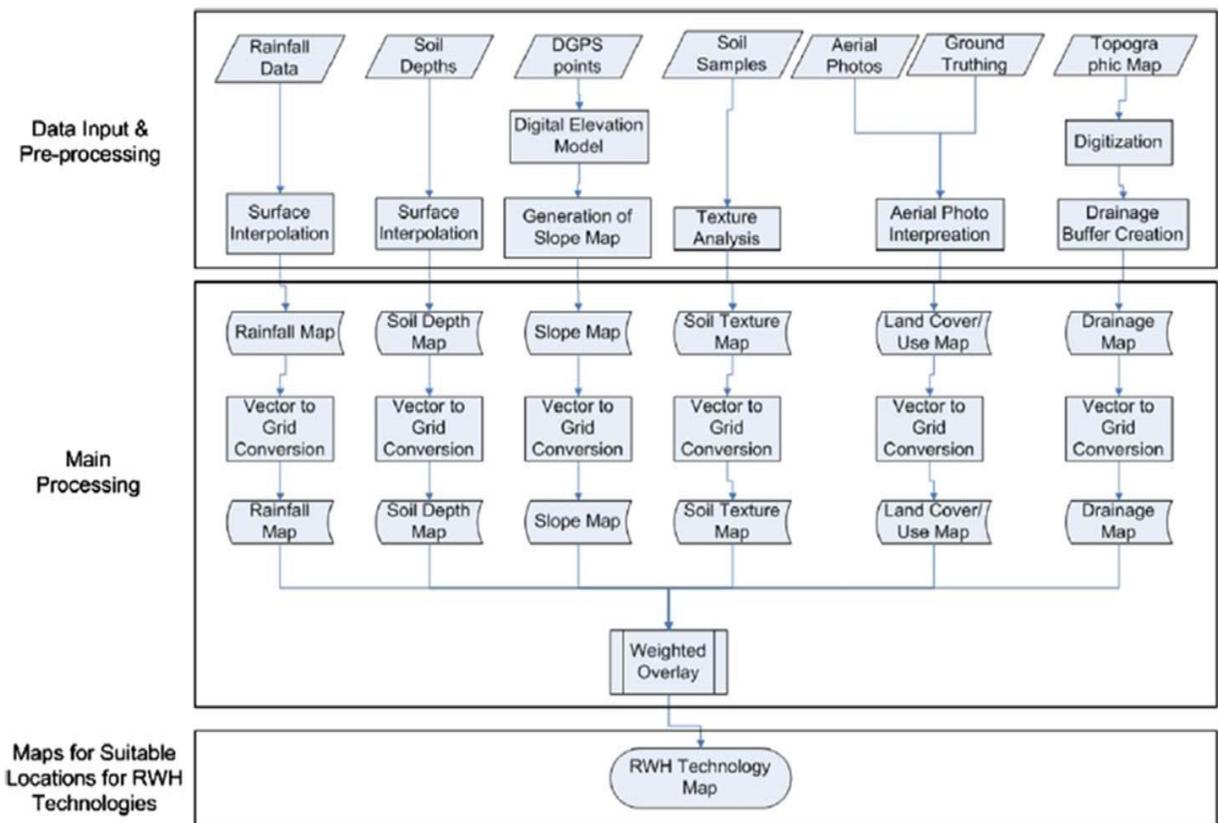


Figure 11: DSS architecture and production of potential RWH (Mbilinyi et al., 2007)

As we concluded from the DSS evolution, recently the information interaction through data, knowledge modelling results and communication among scientists, decision makers and stakeholders were significant emphasized in the design of DSS architecture. On one hand, with the development of monitoring techniques, a significant amount of field data can be easily collected every day by a wide range of sensors distributed over the study area. According to the report of [Smits et al. \(2009\)](#), daily environment data collection was over 25 terabytes in 2009. Consequently, these large amounts of data may locate in distributed computing environment and should have possibility to be integrated together in the DSS. On the other hand, despite progress of introducing the GIS techniques into DSS application made the decision makers be benefited from their easy-to-understand visualization, there was still a growing awareness among the DSS developer community that new approaches and tools should be able to allow more decision makers, potential public users, and stakeholders, to clearly understand the current situation, supervise and participate to the decision making process ([Var Asselt et al., 2001](#)).

Current development trends of DSS in water environment may focus on application of building a Web-based DSS. Firstly, the internet techniques had obvious advantages of fast and integrated dealing with numerous distributed data and information. Secondly, the assessment or decisions published on the website could significantly improve the communication between the decision makers and stakeholders.

[Salewicz and Nakayama \(2004\)](#) had a discussion about how to implement the Web-based DSS for managing international rivers. They identified the audiences for the Web-based DSS could be *“those without direct experience in modelling who want to qualitatively assess the consequences of various policy alternatives in their river basin interest”*. And at the end, they pointed due to the significant progress of data monitoring, collection and storage of data in the DSS required not only technical infrastructure, but also efficient assessment. However, beyond technical problems associated with incorporation of existing building blocks in DSS, the relationship and links between each component need to be discussed more detail.

[Xie et al. \(2005\)](#) made a research related to Web-based DSS architecture. They agreed that the Web-based DSS had the capacity to overcome the limitation of traditional DSS, which had poor maintainability, poor flexibility and less reusability. Moreover, three questions were suggested to be taken into account carefully during the design of Web-based DSS:

- What is the appropriate research framework for Web-based DSS?
- How can providers publish and share their decision resources on the Web?
- How can consumers or decision-makers find and access their preferred decision resources to assist them to solve decision problems?

Clearly, to build a DSS aimed to make the decision resources more shareable and accessible on the Web was one of the main objectives of their work. To achieve this task, they proposed the DSS architecture designed with three logic layers including user logic, business logic and data logic (Figure 12). The system runs with the Browser/broker/server mode with a broker applied to

link automatically the browser and the server, which was “*easier to integrated new decision resources and extended to a more powerful system*”.

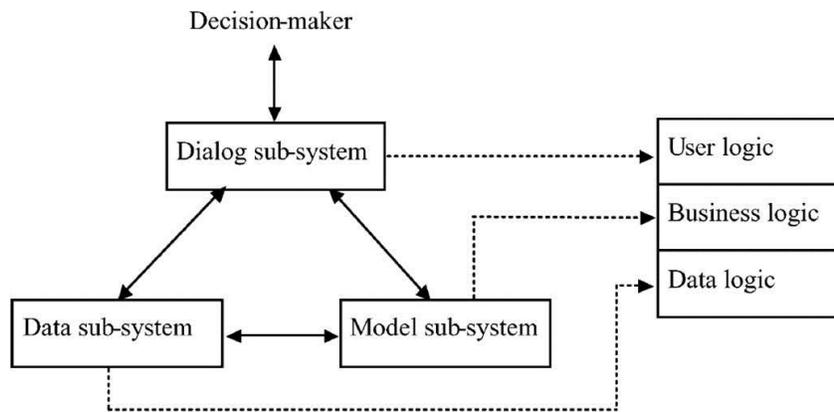


Figure 12: The logic layer for a DSS application (Xie et al., 2005)

Zhang and Goddard (2007) introduced the concept of layered architecture from software engineer to the EDSS. They proposed a “*4 layered software architecture design*” for Web-based EDSS to provide a hierarchical view to organize and specify the data and related tools from multidisciplinary sources (Figure 13).

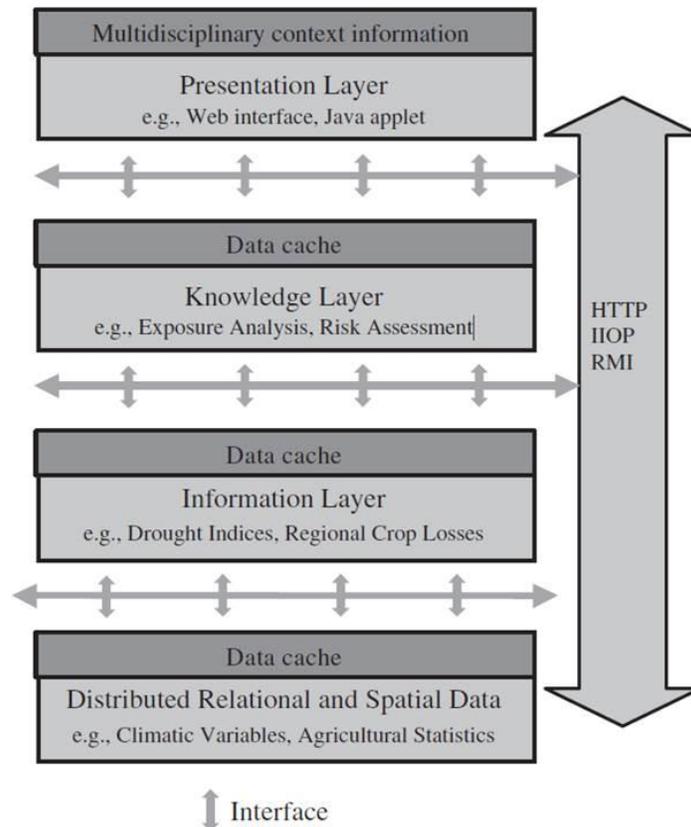


Figure 13: A four-layer software architecture for Web-based DSS (Zhang and Goddard, 2007)

The data collected for supporting the decision making process could be classified based on their meta-information and context information. It can be grouped into the layers of “Data”, “Information” and “Knowledge”. Besides, all the information contained in those three layers could be represented in the “Presentation Layer”. Despite the data was separated into different layers, the authors noticed that, in the real work: “*Higher layers sometimes need to access lower layers that are not adjacent.*” Therefore, they created the large vertical interface arrow at the right of the figure to describe “*the ability of high-order layers (up layers) to make requests to non-adjacent, low-order layers (down layers)*”. Differing from traditional DSS design methods that applied informal box-and-line descriptions, the layered formalization can help the developers and decision makers to analyze architecture behavior and detect design errors in early time. However, this architecture could not address the problem related to implementation of service-based or component-based DSS.

To implement a distributed service-based or component-based DSS application, the authors introduced one framework called “3CoFramework”, which had three major roles: component, connector and coordinator (Figure 14).

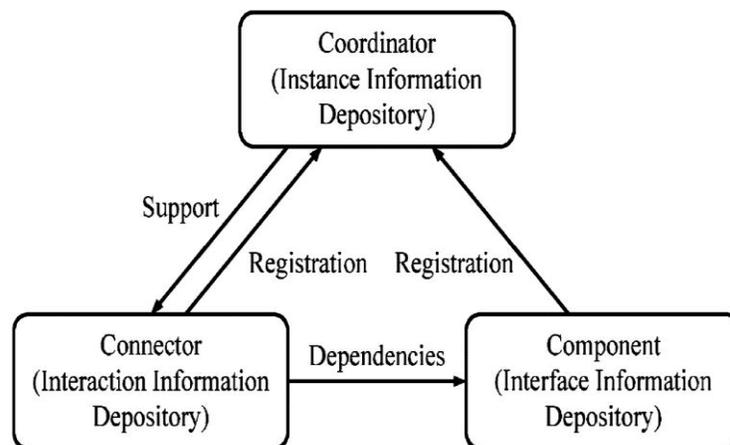


Figure 14: The relationship between component, connector and coordinator (Zhang and Goddard, 2003)

The *component* was “an independent computational or storage unit at a higher level than an object”. The definition of connector came from Shaw et al. (1996) which “*Connectors mediate interactions among components, they establish the rules that govern component interaction and specify and auxiliary mechanisms required.*” And the coordinator “*integrates and manages components and connector at run-time*”. The layered software architecture with 3CoFramework presented above created a tight connection among each component in the system. The relationship between the layered software architecture and the component-based framework in a Web-based DSS were showed in Figure 15.

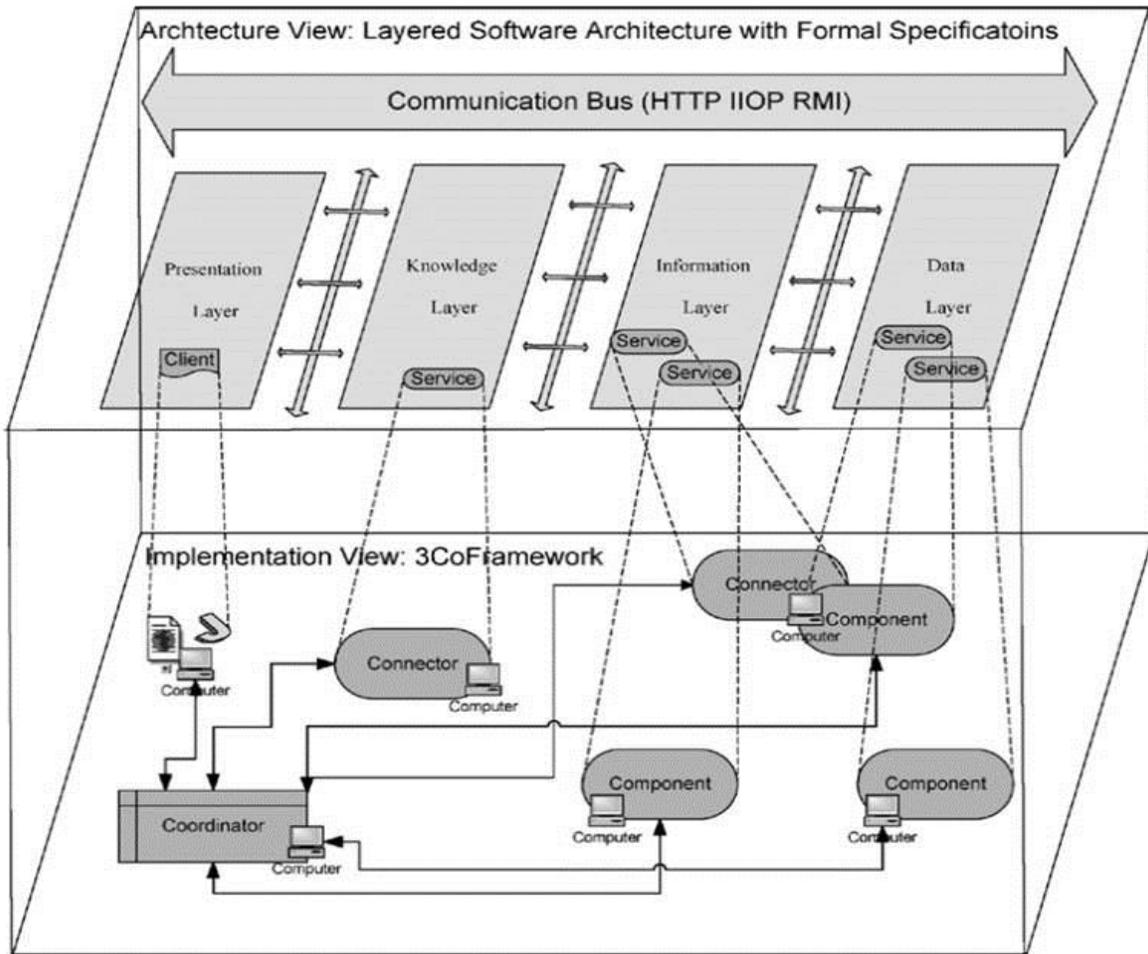


Figure 15: The relationship between layered architecture and 3CoFramework (Zhang and Goddard, 2007)

In conclusion, recently, when the increase of computer facilities help the EDSS application jumped out of the limitation of modelling techniques, the main challenge of building the DSS in water environment was changed to more focusing on optimizing the data organization and improving the information interaction. When the EDSS evolution already existed in technical such as the GIS and Web techniques were widely applied in real application, it was reasonable to have changes appeared in conceptual like the progress of EDSS architecture from 1D view of box-and-line to a 3D view of designing the EDSS architecture with different layers.

1.3. Real Time EDSS Architecture for River Basin Management

Throughout the evolution history of human society, most of big cities were originated in large river basin. The water resource was the most significant driving factor, which has direct impacts on social development. To build a sustainable management plan for solving water problems, the EDSS plays an important role of integrated considering different processes and their influences in water environment system. Overcome the limitation of computer facility, recently, EDSS with GIS and Web techniques was commonly accepted by the decision makers to support their decision making process and share the information between managers and stakeholders.

However, at 2013, to clearly identify the potential DSS end users and their knowledge of integrated management, climate change and DSS, Santoro et al (2013) designed a survey within 31 public institutions whose management and/or administrative competences regard coastal area in Veneto and Friuli Venezia Giulia, Italy. We were quite surprised to notice that although most of respondents (37%) agreed that “*An office with planning functions composed by different administrative bodies*” was the most suitable authority to coordinate an integrated management strategy, more than 50% respondents in Veneto confessed that they had “*a little*” knowledge about the integrated management and around 40% of total respondents agreed that they had no idea about what is that. In addition, people found that due to the climate change processes, the coastal institutions were mostly worried about its hydrodynamic impacts such as “*Increase of damages due to extremes events*”. And the top three vulnerable areas in the coastal management which required DSS were “*Beaches and dunes*”, “*Deltas and estuaries*” and “*Hydrological systems*”.

It is clear that the requirements of DSS for solving water issues were quite urgent and necessary. Unfortunately, there is one obstacle, which frequently repeated before needed DSS designers to pay more attention during the development of DSS. It is the communication gap among the DSS developers, the modelers, the decision makers, and the stakeholders. It was already often appeared in the DSS applications and made the decision makers failed to use it in their daily work. Despite the GIS techniques bridged the experiences and knowledge interactions between each of the participants and empowered the non-expert users to achieve their own goals (Haklay and Tobón, 2003; Schlossberg and Shuford, 2005; Kahila and Kytä, 2009), there were still big challenges for the managers and stakeholder to quickly read and catch the premier or important information from large and complex database and assessment results. Therefore, in our study, we tried to introduce the “dashboards visualization” into DSS design to share and represent the data and assessment results in a more digestible way

In the past, the dashboards were confined in physical area, which commonly applied to record the water or electricity assumptions of individual users. Recently, the managers noticed the convenient of presenting the information with dashboards and took this concept out of physical space (Lee et al., 2015). The new concept of dashboards visualization was already widely applied in the urban management such as the “Urban dashboards” in “Smart City”.

In the new century, due to the evolution of RTC techniques, the rise in availability of monitoring data had encouraged the governments, academia and private companies to invest in ways to analyze, operationalize and communicate the vast amounts of information being created by services and operations. To the extent, there has been a growing trend of the managers adopting

online dashboards as instruments in which both public officials and the general public can interact with data and information in order to have a better understanding of the operating dynamics of the managing area (Kitchin, 2014). These virtual dashboards available from anywhere using personal computers or mobile device screens could help make complex and regional phenomena seem digestible by using raw data visualizations or simplified the indicators/benchmarks. For instance, the IBM built the Intelligent Operations Center for Smart Cities (IOS) in Centro de Operacoes Rio de Janeiro, which allowed for citywide monitoring for operations from diverse city agencies. It followed a dashboards design that in many ways reflected other solutions derived from the business intelligence and analytics expertise of the company (Smarter cites software, 2015). But it might cause an inherent danger of obfuscating or reducing the importance of causes that were not easily sensed or modeled (Kitchin et al., 2015).

Despite the dashboard had obvious advantages of sharing the information in DSS visualization, the other classical visualization techniques such as maps, figures, tables and reports should not be neglected in the DSS design framework. How to manage the balance between information complexity and expertise for different users was a serious question caused lots of debates during the evaluation of DSS design. Here, instead of applying some new technique-based solutions, we proposed a management-based solution to overcome this challenge.

In DSS application, with different objectives, the DSS end users can be categorized into three main user groups named with “Public”, “Professional”, and “Expert”, respectively. The users in “Public” group normally did not have solid professional background and rich experience of solving relevant problems. They could be the novice users of DSS who did not join the assessment and decision making process but had the right to review and download data and some parts of analysis/modelling results. Their main objective of using this DSS application could be to enhance their knowledge and understanding of the current situation, potential risks and the decisions made by the managers. Usually the users in this group could be the students, researchers or the local residents and stakeholders. The users in the “Professional” group should be the main DSS end users who had related background and experience. They used DSS in their daily work to analyze the data and modelling results, design scenarios for future forecast and make the decisions with certain technical and social references from the DSS monitoring or assessment. Compare to the users in “Public” group, the “Professional” users such as the engineers or decision makers were more closed to the core of the DSS. They could have higher permission in the system, which allowed them to review and update the data and run the models emerged in the DSS to satisfy their certain needs or requirements for supporting decision making process. At the end, the users in the third group named as “Expert” could be the modelers or programmers who had the same permission level as “Professional” users in the DSS visualization. But in the whole DSS framework, they might have higher permission to access the system and modify the models and database emerged in DSS. One of their responsibilities in the DSS could be in charge of updating and protecting the system.

To conveniently and efficiently satisfy various requirements asked by different groups of users, we introduced the layered structure of DSS visualization (Figure 16). Among the three user groups, the DSS might give them different permission levels to review the information showed in different layers. Temporarily, we designed “Three layers structure” for the EDSS visualization, but for more complex DSS, the number of layers could be extended depending on system complexity and users’ requirements.

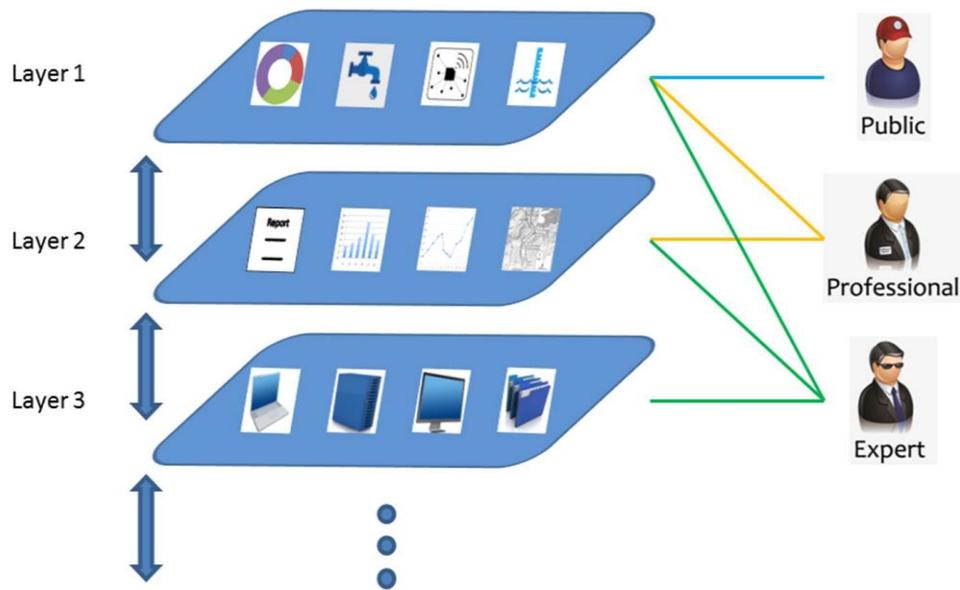


Figure 16: Layered structure of DSS visualization

From the top to the bottom, the complexity and expertise of the information presented in the layers showed an increasing trend. The information displayed in deeper layers was much closer to the “Raw Information” such as “Raw data from field survey”, “Specific assessment results” or “Original modelling outputs”. To read the deeper layer’s information, it required users had professional background and relevant experience. Therefore, the third layer might only open to the users in “Expert” group who were in charge of managing the whole system in their daily work. The information interacted from down to up layers would be transferred and simplified following standard formats or certain processes. Therefore, in the second layer, the raw data, specific assessment results and modelling outputs would be organized and shown in figures, tables, maps and reports. It allowed the “Professional” users who were the main DSS end users to easily catch the emphasis of the information and to get fast responses to make the decisions for solving certain problems. Then, in the top layer, the data of real time monitoring and some parts of the modelling results would be continued to simplified and summarized into dashboards and presented to the DSS users. In fact, the information in the top layer could be published to all the DSS users. Compare to the second layers, the dashboard presentation in first layer would be more user friendly and easily to be understood by the “Public” users.

Due to the evolution of information techniques, the DSS architecture was also updated from signal program-based to multiple layers-based. The new DSS applications with layered architecture had obvious advantage of efficiently organizing and dealing with large database and complicated assessments. However, there were still some insufficient exposed in the information interaction of layered DSS applications. We would like to introduce the platform-based DSS architecture with Web and RTC techniques to replace the layered structure for solving problems in water environment. Our designed architecture of platform-based EDSS could be seen as a combination of classical box-and-line structure and layered concepts. Its main structure may look as similar as the box-and-line but consisted with four main parts named with “Data”, “Monitoring system/Analysis”, “Operation Center” and “Visualization”. Different with classical box-and-line

structure, the working process among those four parts were not unidirectional. The interaction between each of them was emphasized in the design of this EDSS architecture (Figure 17).

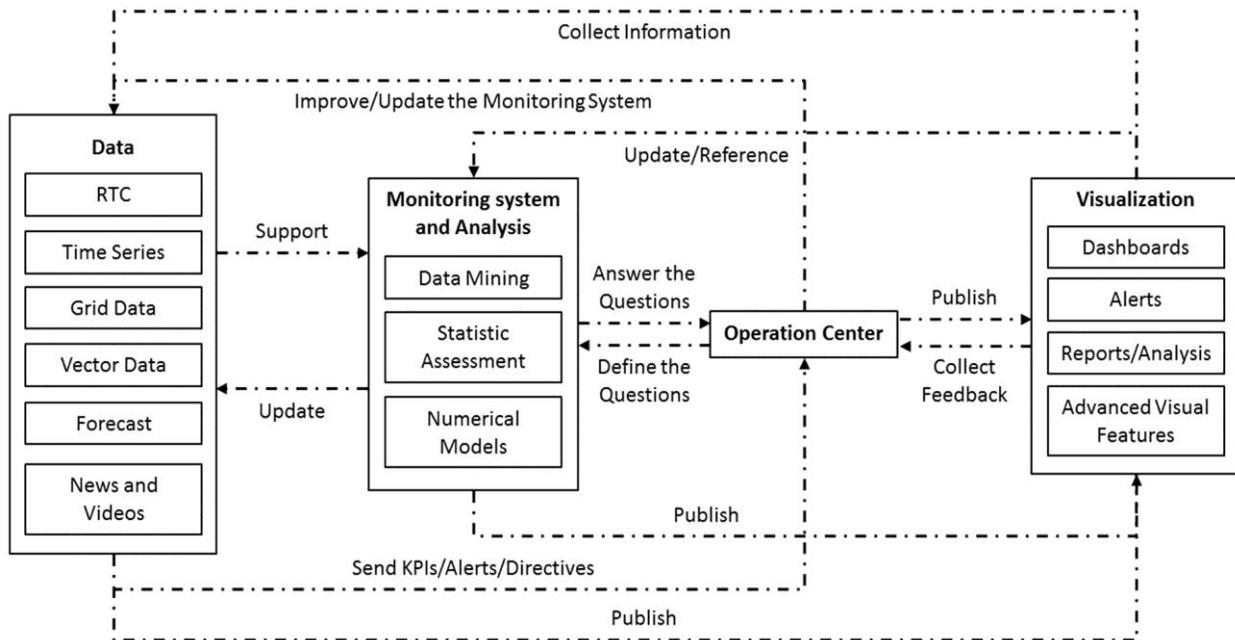


Figure 17: Design of platform-based EDSS architecture

Each part emerged in the system was designed as an open and diversified platform consisted with several working layers. In principle, all the platforms may have the capacity to publish and collect the information to/from the users. However, due to the expertise and complexity of the information in different layers may not easily accept by all the EDSS users. The platform layers may conditionally open to the users who have certain permission. Similar to the design of user groups in DSS visualization, the users who had more professional background and experience in facing certain problems may have higher permission level to access/modify more layers on the platform.

In the EDSS application, the data organization (database) plays significant role in the system. Here, we organized the layers in the “Data” platform based on the different data types. The platform could be set up with the top layer of collecting RTC data, which could clearly represent the current situation and easily to be understood. Part of information collected in this layer could be directly sent to the “Operation Center” through certain formats such as Key Performance Indicators (KPI), predefined alerts, and directives, or immediately published on “Visualization” platform. The second layer of “Data” platform could be the collection of time series information such as stream discharge and water level, which were the historical records in the region plus and update from RTC data. This information could be sent to the platform of “Monitoring System and Analysis” to satisfy the assessment or modelling requirements then answer the questions defined from “Operation Center” and support the decision making process. In addition, compare to the RTC layer, the time series layer might not be updated in real time. Normally it would be refreshed within a defined time interval. After the layer of time series, deeper layers such as “Grid Data” and “Vector Data” were mainly designed to collect the information from field survey (e.g. geological maps, land use maps) and management planning made by the decision makers

(e.g. design of urban management). The information contained in those layers had their own protection level, which could not be freely open to all the DSS end users. Besides, due to the limitation of techniques and project budget, those data could not be monitored in real time and be updated frequently. Moreover, the maps information collected and stored in those layers could be noticed as the main input of the “Monitoring System and Analysis”, the important reference to “Operation Center” and meaningful materials written in the reports.

Compare to the other layers in “Data” platform, the forecast layer has special characteristics of its information collection and interaction. Firstly, the information collected in this layer may have two different sources. It could be either collected from the work of other institutes (e.g. weather forecast from some meteorological departments) or updated with the EDSS estimations or simulations. Secondly, due to the uncertainty of forecast, we suggested that instead of transferring all the information directly to other platforms, it might be better to set up a simple analysis or selection before implementing the information interaction. However, the channels of information transmission started from forecast layer could be linked with all the other platforms including “Monitoring system and Analysis”, “Operation Center”, and “Visualization”.

In general, the forecast could be classified into two categories of long term forecast and short term forecast. The first selection would be based on different types of forecast. For the long term forecast, as its uncertainty might be relatively higher than the short term forecast, it is necessary to send this information first to the “Monitoring system and Analysis” to make more detail assessments and simulations for identifying its impacts and the natural responses of implementing certain measures before directly presenting this information on the platform of “Operation Center” or “Visualization”. For the short term forecast, which is usually related to the disasters such as flood or heavy rainfall event, the EDSS should have the capacity of determine the coming situation automatically based on certain references stored in the database. For instance, the modelers in charge of setting up the models in the EDSS can run some simulations in advance to estimate the impacts of some design scenarios (e.g. simulation of flood caused by 100 year return period rainfall), then store the results in the database as references. When the EDSS received the short term forecast, the program emerged in the system would make quick analysis automatically based on certain threshold defined in the references. If the forecast result achieved certain threshold, the system would immediately send the signal with certain format (such as alerts) to the “Operation Center” to notify the decision makers thinking about relevant measures. At the same time the alerts published on “Visualization” should be also implemented. However, if the forecast result did not achieve the threshold, the information might be only represented on the platform of “Operation Center” and “Visualization” with general format to let both decision makers and users notice the coming phenomenon. However, the information interaction of forecast results from “Data” platform should be controlled also be controlled by the decision makers who had the right to define the format when published the information on the “Visualization” platform. The main objective of applying this working process was aimed to reduce the impacts of the forecast uncertainty and to inform the public on time.

Moreover, with new monitoring techniques, in order to anticipate reaction and ensure an efficient management with various information sources became more feasible. How to link the EDSS with public services becomes a hot topic gaining more interests by managers. In 2012, IBM published their Intelligent Operations Center architecture of supervision platform as a good example for urban management (IBM, 2012). Based on that, we would like to introduce the adapted

architecture showed in Figure 18, which clearly presented the information interaction among each parts emerged in the DSS and links between DSS and city “Service Bus”.

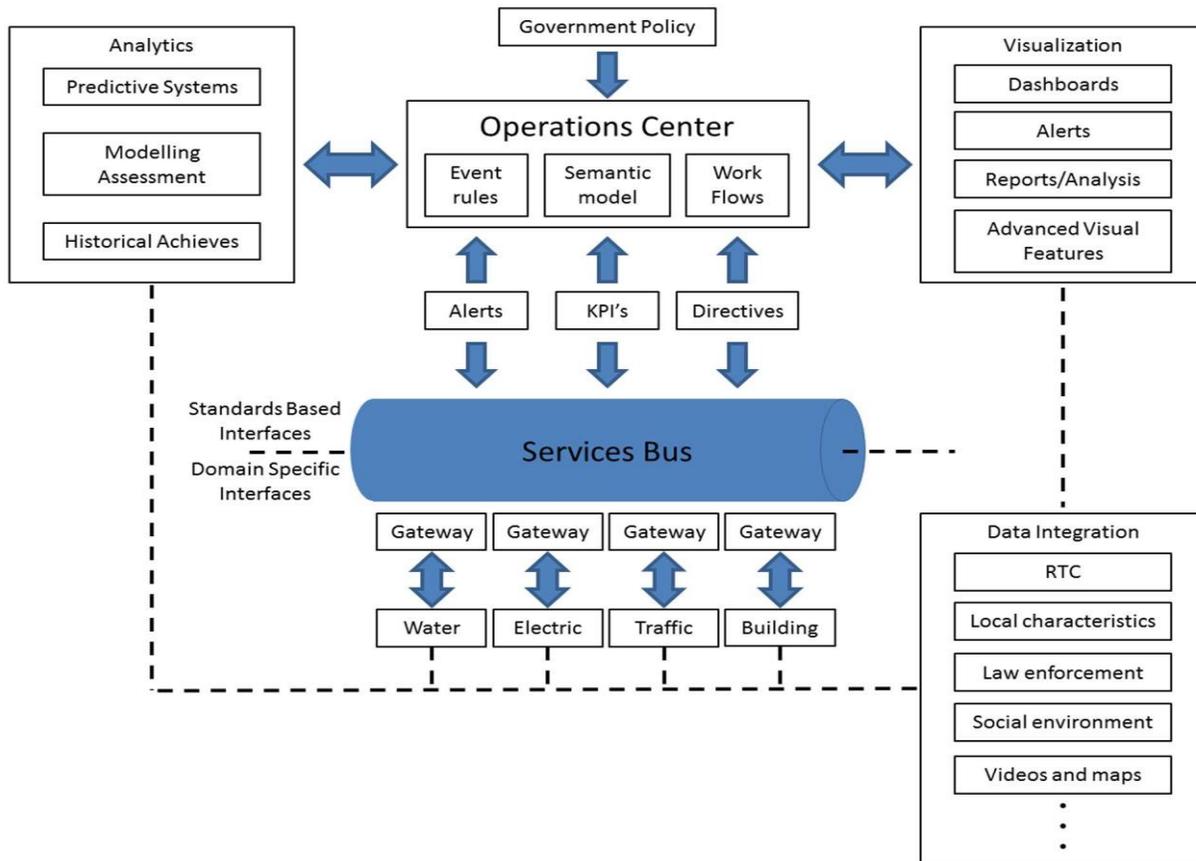


Figure 18: Concept of supervision platform dedicated to urban monitoring and management (adapted from IBM, 2012)

The role of the “Service Bus” was identified by IBM (2012), which handles both internal and external messages and provided a loosely coupled interface for exchanging data and operations in Service-Oriented Architecture (SOA). Here we would like to extend the efforts of the “Service Bus”, which also has direct links with the public services (such as police or firemen) in the management area.

When the “Service Bus” received the information from “Data” platform, it could reorganize the data with their characteristics and linked to related public services (such as “Water”, “Electric”, etc.). Then the “Service Bus” would make the first decision of transferring the information to the “Operation Center” through what kind of data formats. For instance, when the “Service Bus” received the information has characteristic according to the “Event rules”, it could send the alerts to the “Operation Center” to inform the decision makers. Then the “Operation Center” could make the decision of confirming or refusing this alert. If the decision makers agreed that there is a serious event coming, the “Operation Center” could send back the alerts to the “Service Bus” and distribute this information to relevant service through the “Service Bus” in certain format to let the public services be informed and prepared for the coming event.

1.4. The Role of Hydrological Models in EDSS and Criteria of Model Selection

Modelling allows improvement of understanding past and current phenomenon and prediction of several expected future scenarios, thus, is an important reference for supporting the decision making process (Rizzoli and Young, 1997). In the management of water environment, the hydrological modelling tools play significant role in integrated assessing various hydrological processes and their interactions such as evapotranspiration, runoff generation and water exchange between surface and underground. However, due to the complicity of the hydrological system, very often, it requires a rank of models or a modelling system to implement the assessments. Unfortunately, this joint modelling system of hydrological simulation was often very demanding regarding data and can be operated only by especially trained experts (Krysanova et al., 1998; Taylor et al., 1998; Arnold and Fohrer, 2005).

In the past, because of the techniques limitations and the requirement of having short response time in decision making process, some simple empirical approaches were commonly applied in the environment management (Johnes, 1996; Kunkel and Wendland, 2002; Berlekamp et al., 2007). Most of them were aimed at providing the target variables at the policy scale in form of long term average and lack the capacity of considering nonlinear and dynamic characters of hydrological processes and therefore may fail at unobserved basins or in the prognosis of changes (Haberlandt, 2010).

A recent alternative is to apply some kind of metamodeling framework, where the major processes are modelled with tailor-made concepts depending on process complexity, available data and modelling purpose (Haberlandt et al., 2001; Shrestha et al., 2007; Quinn et al., 2008). Today, there are numerous hydrological models available for simulating water environment components at different spatial and temporal scales, which often caused the DSS designers to be confused by their different characteristics. Thus, to provide an efficient assessment process in the EDSS, it is necessary for the DSS designers having a clear overview of hydrological modelling concepts and their different characteristics.

Hydrology is a subject of great importance to human and environment, which deals with all phases of the earth's water (Chow et al., 1988). Various definitions about the hydrological system were developed but in a simplified way, it can be said as a set of physical, chemical and/or biological processes acting upon an input variable or variables, to convert it (them) into an output variable (or variables) (Xu, 2002). This continuous converted process can be named hydrologic cycle, which occurs continuously in nature. The three important phases of the hydrologic cycle are evapotranspiration, precipitation and runoff (Raghunath, 2006).

Xu (2002) defined the hydrological model is a simplified representation of a complex system, which has a lot of hydrological variables e.g. rainfall, runoff, evapotranspiration, temperature, etc. Furthermore, Brooks et al. (2013) cleared the efforts of the hydrological models are mainly used for simplified representing actual hydrological system, predicting hydrological responses of human activities and allowing people to study the function and interaction of various inputs to gain a better understanding of hydrological events. As results of the limitation of computation capacity, the hydrological processes consisted in one watershed was looked as the basic analysis unit for setting up the hydrological simulation in the model. It could be also looked like a basic simplification when interrupting the spatial continuum of hydrological system.

A watershed (or catchment) could be explained with a division by topographic or groundwater as shown in Figure 19, which defined as the terrain area contributing surface stream flow into a river network or any points of interest (Linsley et al., 1949; Chow et al., 1998; Dingman, 1994; 2002; Brutsaet, 2005). Hence, when talking about hydrological models, we often imply that this model simulates hydrological process for a small area or a catchment.

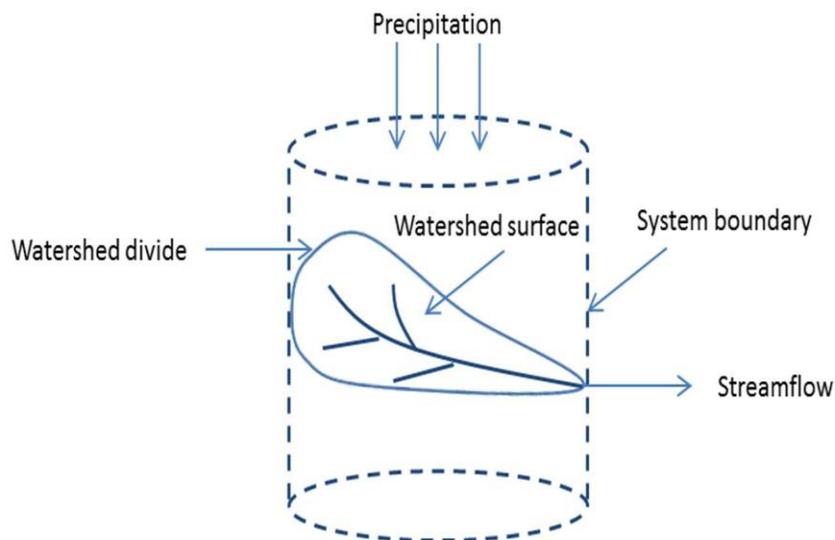


Figure 19: The watershed as a hydrological system (Chow et al., 1988)

Until now, there are numerous hydrological models developed with different theories to simulate catchment's hydrological phenomenon. Based on their characteristics, capabilities and limitations, the existing hydrological models could be classified into different categories. The modelling classification is expected to be helpful not only for engineers and hydrologists, but also for the DSS designers and managers to clearly understand model characteristics before deciding to employ them into their work (Harun et al., 2012). Overview many modelling discussion, we would like to introduce the classification defined by Singh (1988) who distinguished hydrological models as material and symbolic at first step (Figure 20).

Depending on the way of simulation, the hydrological model could be first identified into two classes of "Material" and "Symbolic" models. From the definition of Chow et al. (1988), the material models followed the way of using similar system to physically represent the real situation. It could be further divided into two sub categories. One is the scale (laboratory) model, which often implemented in the laboratory and described the real system on a reduced scale. Another is the analog model, which used other physical substances to introduce the characteristics of prototype. Even through the material model usually has quite high costs and is not convenient for construction, it still has obvious advantages of assisting the researchers to understand the phenomenon of an unfamiliar field or constructing experiments for typical system (Xu, 2002).

Obviously, for the symbolic model, it followed the way of representing the real situation with symbolic system. In principle, it could be further divided into two sub categories of

nonmathematical and mathematical. But, in literature, this kind of model is only considered on mathematical aspect. Like the name of this sub category, the mathematical model is operated based on mathematical relations between the input and output variables. It could provide a certain freedom for the developers to set up the model with their own purposes. Due to its characteristics of simplicity, easy to change and implement, the mathematical models gained more interests by the hydrologists and has been developed widespread in the past 30 years. Recently, when we talked about the hydrological models emerged in the EDSS, it very often points to the mathematical hydrological models implemented with numerical program or software.

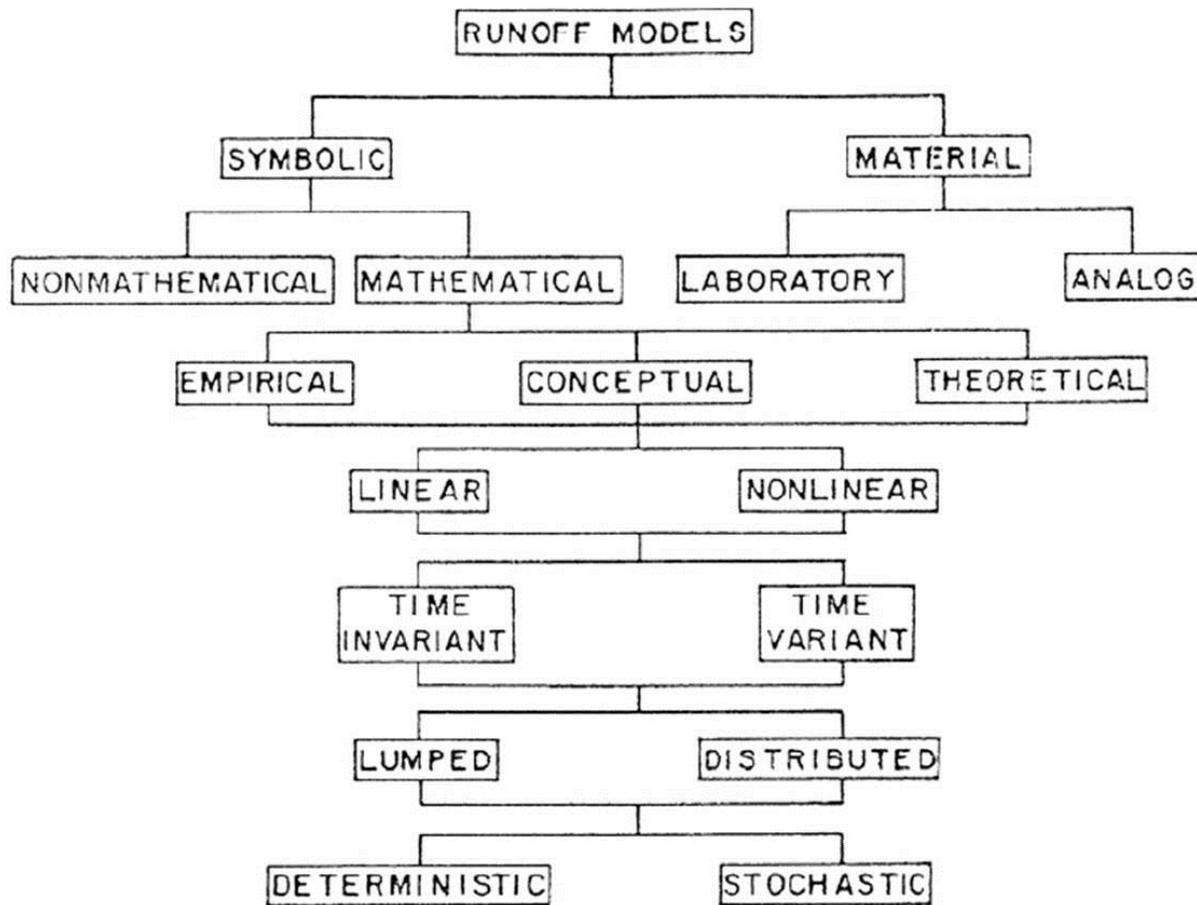


Figure 20: Hydrological model classification (Singh, 1988)

Relied on the different degrees of representing concerned physical phenomenon in hydrological system, the mathematical hydrological models can be identified into 3 main classes including “Empirical model”, “Theoretical model” and “Conceptual model”. The “Empirical model”, which also called as “Black box model” is most independent with the physical process. It is fully based on the experimentation or observed input and output correlation (Oogathoo, 2006). Obviously, the design structure of this kind of model is highly depends on the measurements for the model output variables (Willems, 2000). Therefore, the model parameters involving in the calculation may not have the physical meaning and only be estimated by using concurrent measurements of input and output. This kind of model could be assessed as the simplest hydrological model and usually be constructed very quickly.

Although empirical models were already succeed in many assessments to provide fast and accurate answers of certain questions, there are main weak points of empirical models still limited its application range. Firstly when this kind of model already built in one specific catchment with a certain time interval, it might be difficult to be applied in other catchments, which have different characteristics. Secondly, since the design of this model is highly depends on the relationship between observed inputs and outputs, hence, when there are significant changes happened in the control area, the model may not produce the accurate simulation results with the previous functions. Therefore, this kind of model is commonly used for establishing general catchment characteristic or quickly evaluating the phenomenon in catchment. In addition, the Artificial Neural Networks (ANN) could be seen as the later development of empirical model (Xu, 2002).

Compared to the “Empirical model”, the “Theoretical model” also called “White box model” conversely are derived from physical laws. It has a logical structure similar to the real phenomenon. In theory, all or most of its parameters could be measured in the reality. Although it has complex structure and often requires numerous data to support the simulation, it is expected to have the capacity of representing truly the catchment characteristics and supplying entire view of the hydrological processes existing in the analysis area for the model users.

The intermediate type of “Empirical model” and “Theoretical model” is named with “Conceptual model” also called “Grey box model”. Generally speaking, conceptual model is considered by the physical law but in higher simplified form (Singh, 1988). Some of it parameters do not have true physical meaning (Rochester, 2010). It combined the advantages of “Empirical model” and “Theoretical model”, which have similar physical structure as the reality, relatively shorter running time and easily to be implemented with the changes in the simulation. However, as results some of its parameters could be not easily measured in the field or directly defined from data assessment, this kind of very common model needs to be calibrated and validated carefully.

Moreover, except classifying the hydrological model based on the degree of representing physical phenomenon, it is also possible to identify the mathematical models with their linearity, temporal characteristics, spatial characteristics and relation between model variable and random.

Lewarne (2009) defined that the linear models are set up with the simple correlation between inputs and outputs, but for the nonlinear model, there is a chaos and an irreversibility that makes this model more difficult to study. Besides, with different temporal characteristics, hydrological models could be categorized in different way. With different simulation duration, the models could be classified with event based model and continuous model contains several events in the simulation. Obviously, the event based model may only focus on the special event with short time phase, and the continuous models covered longer time situation of the study catchment. Moreover, when the relationship between model inputs and outputs does not change with time, the model could be called as the “Time invariant model”. On the contrary, it is called “Time variant model”. Most hydrologic systems are time-variant due to variations in solar activity during the day and seasonal variations during the year. For simplicity, they are assumed to be time invariant (Jones 1997).

As we already explained that the hydrological model is representing the hydrological process happened in the catchment with certain functions, to represent the catchment spatially, different model may follow different structure. In terms of spatial discretization, there are three main categories consisted in the hydrological model classification: “Lumped model”, “Semi-distributed model” and “Distributed model” (Figure 21).

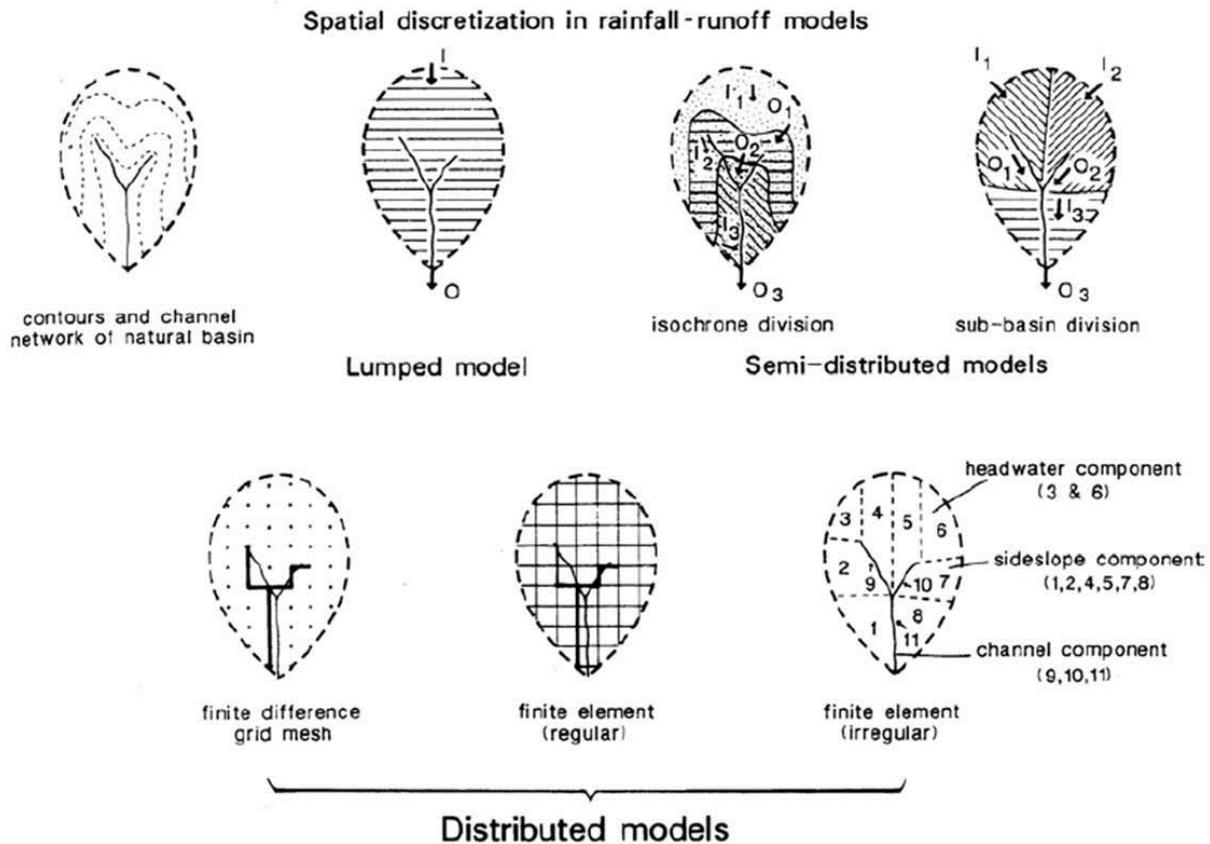


Figure 21: Graphic representation of geometrically-distributed and lumped models (Jones, 1997)

In general, the model, which homogeneously simplifies the distributed characteristics of the catchment in the simulation called the “Lumped model”. In this kind of model, even though the parameters may have their relevant physical meaning, but instead of determining their values from catchment physical characteristic, in most of cases, they were defined through model calibration (Chow, 1972; Madsen, 2003). Moreover, consequently, the lumped model could not classify the hydrological processes precisely and merely assess the catchment responses simply at the outlet without obviously counting for individual sub-basin responses (Cunderlik, 2003).

In contrast, the “Distributed model” is the model representing the catchment by simplifying the whole study area into many sub units. This kind of model maintains the physical details with certain resolution and considers the distributed nature of hydrological properties such as soil, land use, and slopes (Refsgaard, 1997; Vansteenkiste et al., 2013). In principle, the parameters applied in the distributed model calculation could be obtained from the catchment data or from field survey. For this reason, this model is evaluated to be able to simulate the hydrological processes in a catchment more accurately and more concretely.

Moreover, compared to the lumped model, which often supply the simulation results only at the outlet of the catchment, the distributed model has the obvious advantage of producing the simulated relevant hydrological components (such as water level or discharge) anywhere in the catchment. However, the disadvantages of this distributed model are also obvious. Firstly, [Refsgaard \(1997\)](#) noted that more detailed physically based and spatially distributed models are assumed to give a detailed and potentially more correct description of the hydrological process in the catchment. But in reality, it is very difficult for the model developers to satisfy all the model requirement of distributed data in high resolution. The balance between simulation accuracy, detail, and data availability, always courses big discussion during the model set up process. Secondly, as results of the model produced distributed simulation results, it is not easy to find the spatial data for model calibration or validation ([Beven, 1996](#)). This leads to the quality estimation of distributed model in the whole catchment being mostly unable, so the calibration and validation are able to merely carry out against the data at several gauging stations.

The “Semi-distributed model” is an intermediary of two kinds of the models above, which is partly permitted to change the space with division of catchment into an amount of sub basin. The level of the data requirement of this model is in between the distributed and lumped model.

[Chow et al. \(1988\)](#) defined the hydrological model into two categories of deterministic model and stochastic model. The deterministic model is the model implementing the simulations without any random elements. On the contrary, the stochastic model contains several or at least one random element in the calculation. Evidently, the deterministic model is agreed to be more suitable in order to make a forecast within short time period while the stochastic model is frequently applied to create a prediction for longer time ([Chow et al., 1988](#); [Harun et al., 2012](#)).

After reviewing the characteristics of different hydrological models, in EDSS design, the selection for implementing the hydrological model in the system should follow certain criteria including project objectives, real condition of the study area and data availability ([Ng and Marsalek, 1992](#); [Plate, 2009](#)). The general criteria could be summarized in four fundamental requirements ([Cunderlik, 2003](#)):

- Required model outputs
- Hydrological processes need to be taken into account
- Availability of input data
- Project budget

Moreover, towards to the large catchment, which as complex hydrological system including many physical processes interactively affected with each other, the understanding of its hydrological mechanics is almost inextricable. In Table 3 , [Vo \(2015\)](#) summarized the standard of model selection recommended by WMO for simulating the hydrological cycle according to catchment scale, which indicated that the distributed deterministic hydrological model is

expected to represent the real hydrological system more accurately than other kinds of models especially when the catchment topography showed significant variation.

Table 3: Standard of model selection proposed by WMO (summarized by Vo, 2015)

Model type	Question 1	Catchment size?		
		Small (headwater)	medium	large
	Catchment model	lumped	semi distributed	distributed
	Routing	mostly not needed	hydraulic/hydrology	hydraulic, hydrology, gauged to gauge correlation
	Question 2	Catchment relief?		
	Flat/plain	Moderate/hilly	Pronounced/Mountainous	
Catchment model	lumped	semi distributed	distributed	
Model features	Question 3	Does soil wetness effect flood generation?		
		no	to some extent	yes
	Soil water budget feature required	not need	recommended	need
	Question 4	Is snowmelt important for flood generation?		
		no	to some extent	yes
	Snow module	not need	recommended	need
Question 5	Is river regulation (reservoir/lake/diversions) affecting floods?			
	no	to some extent	yes	
Storage module	not need	recommended	need	
Data requirements	Question 6	What is the predominant flood causing rainfall?		
		Seasonal	frontal/advective	convective
	Recommended data resolution	daily	daily/hourly	hourly/sub-hour
	Question 7	What is the required lead time?		
	short	medium	long	
Required rainfall data	Observed rainfall	Rainfall nowcast is recommended (e.g. radar)	Rainfall nowcast and/or forecast from NWP is required	
Constraints	Question 8	Is distributed/gridded data available?		
		no	yes	
		Lumped model is only option	Semi-distributed/distributed model is feasible	
	Question 9	What is the level of capacity of the service?		
	low	intermediate	high	
	Only simple tool feasible (correlation, etc.)	Run lumped/black box simple model	All option available	

In addition, to satisfy the requirement of EDSS, the criteria of hydrological model selection may contain more conditions. [Haberlandt \(2010\)](#) claimed that “The selected approach should be of moderate complexity in order to allow a robust application of the model by water managers and

fast computations”. Moreover, he emphasized that the selected hydrological model implemented in the EDSS should be sensitive to simulate the management changes such as land use change (Table 4).

Table 4: Requirements on hydrological models to be used as part of DSS (Haberlandt, 2010)

No.	Criterion	Requirements
1	Spatial scale	Highly distributed approach required
2	Temporal scale	Daily time step with continuous long term applicability
3	Degree of determination	Conceptual approach with prognostic capabilities; use of parameters ,which are related to physical catchment properties
4	Target variables	Infiltration, percolation, evapotranspiration, at least three runoff components, river discharge
5	Complexity, handling	Moderate complexity with modest number of parameters; robust approach; easy handling
6	Efficiency	Fast computing required
7	Performance	Sufficient performance on monthly time step, small bias for long term behavior
8	Sensitivity	Climate, soils, land use, agricultural management e.g. crop rotations

In conclusion, we would like to clear the criteria of hydrological model selection for our designed platform based EDSS:

- The model should have the capacity to integrate consider multi- hydrological processes in the catchment and estimate their interaction.
- The simulation time for the model should be relatively short in case of applying in the forecast of extreme events.
- The model should have standard input data format, which allows the EDSS easily transferred the information from database to the modelling system.
- The model should be sensitive enough to represent the impacts of the management changes.
- As the hydrological model is one of the main assessment tools in the EDSS but not the only one, the model should be able to produce the simulation results with general format, which could be widely accepted by other assessment tools.
- The model should be user friendly which allows the managers who do not have solid modelling background to make simple changes to satisfy their needs.

CHAPTER 2: MODEL STRATEGY OF APPLYING DETERMINISTIC DISTRIBUTED HYDROLOGICAL MODEL

In the design of EDSS, the water resource management problems with a multi-period feature are often associated with mathematical hydrological models that integrate considered various constraints and variables depending on the level of detail required to reach a significant representation of the system (Loucks et al., 1980; Yeh, 1985). Obviously, accurately forecasting the future phenomenon and estimating the impacts of implementing relevant measures decided by managers on local natural environment are the key objectives of EDSS. When all data collected in the project are fixed and no level of its uncertainty is taken into account, the water resource problem could be considered as a dynamic multi-period network flow problem. Then the objective of EDSS could be achieved by assessment based on efficient optimization algorithms (Kuczera, 1992; Sechi and Zuddas, 1998; 2000). However, in reality, the water resource problems are typically characterized by a level of uncertainty regarding, among other things, the value of hydrological exogenous inflows and demand patterns (Pallottino et al., 2005). The traditional stochastic approach, which produces a probabilistic description of unknown elements on the basis of the historical data which may only be acceptable when a substantial statistical base is available and reliable probabilistic laws can adequately represent parameters' uncertainty and their possible outcomes (Infanger, 1994; Kall and Wallace, 1994; Ruszczyński, 1997). Consequently, when there is insufficient statistical information on data estimation or probabilistic rules are not available in the project, the scenario analysis implemented by deterministic distributed hydrological model could be applied as the main assessment approach to replace the stochastic analysis.

Besides, compared with other approaches, the deterministic distributed hydrological modelling approach has obvious advantages of detail and accurately describing the real phenomenon and being sensitive to represent any chances caused by implementing relevant measures. At the same time, it is also necessary to notice that compared with other hydrological models such as empirical one, the running time of deterministic distributed hydrological simulation is relatively longer and its data requirement is often much higher and more complicated. Those two conditions significantly limit the application of deterministic distributed hydrological model in EDSS. For example, in case of representing the hydrological processes in a study catchment which has poor data availability (e.g. an ungauged catchment) or satisfying the managers' objective, which required to have fast modelling responses (e.g. estimation of flood events), instead of setting up the deterministic distributed models, the empirical models were commonly selected as the premier assessment tool for achieving those tasks during last decade.

Recently, with the increase of computer facility, the running time of the deterministic distributed simulation has been significantly reduced. Then the model could be implemented for more aspects including flood forecast and real time control. Unfortunately, for another question of how to satisfy the complicated data requirements for setting up model, it is still difficult to find a clear answer. And the topic about how to deal with this issue was continuously discussing among the hydrological modelers, managers and EDSS designers until now.

In theory, the deterministic distributed hydrological model could integrate represent various physical processes interacting in the hydrological system based on the distributed information of

many geological and hydrological components (like surface elevation of the catchment, rainfall distribution and distributed soil property in the study area) as the inputs for setting up the model and the related parameters involved in model calculation. But in real projects, not all the physical components can be measured directly and produced with distributed format. For instance, one of the main hydrological processes existing in the catchment water system is the rainfall-runoff. To represent correctly this process in a deterministic distributed hydrological simulation, the surface topography and the rainfall distribution over whole catchment are two main inputs required in modelling set up. By using the new techniques from remote science, catchment surface topography could be described by Digital Elevation Model (DEM), which can be directly collected from some institutes or downloaded from public website. In contrast, for the rainfall distribution over the study area, it is often difficult to be freely and directly achieved. In most of cases, the rainfall time series are recorded with certain time interval at the gauging stations distributed in the study catchment. Therefore, how to transfer the rainfall measurements from certain locations to a distributed format covering whole study area is often confusing the hydrological modelers. Even through there are many mathematic methods available to deal with this question, due to the fact that study areas may have special characteristics such as significant elevation variation or typical meteorological conditions, modelers are requested to have deep and relevant assessments to define the most suitable interpolation method in their study area.

Moreover, for other hydrogeological elements required in setting up the deterministic distributed model like distributed soil property in the catchment, either field survey is similar as precipitations, which are only measured at certain locations in the catchment, or very often due to the technique or budget limitation, there is no field measurement available (ungauged). At this time, the interpolation approach may be not sufficient to produce reasonable distributed information for setting up the model. It may require some extra assumptions to be introduced in the data preparation. However, if these assumptions may solve the issue of data shortage, it could also cause the increasing of modelling uncertainty. Due to the characteristic of deterministic distributed hydrological model, the model calculation follows the physical laws. Thus, through the model calibration process, those elements could be recalibrated. But the calibration process often consumes longer time with numerous times of running simulations.

In this chapter, both the complicated data requirement and challenges in the deterministic distributed modelling set up process were discussed in detail. Depending on the modelling objectives and on the complicity of the catchment hydrogeological characteristics, the data collection may have significant variation. Furthermore, the topic of Prediction of Ungauged Basin (PUB) problems was also assessed in this chapter. After reviewing the feasible approaches dealing with this problem during last decade, with the new technique developed recently, the modelling strategy of setting up deterministic distributed hydrological model in an ungauged catchment was conceived at the end of the chapter.

2.1. Data Requirements of Deterministic Distributed Hydrological Models

The hydrological system in one catchment often contains various physical processes, which are not only working independently but also have effects on each other to make the system become more complicated and difficult to be represented by numerical simulation. Theoretically, the deterministic distributed hydrological model based on physical laws has the capacity to properly describe all the existing processes interacting in the catchment. However, due to the high data quality and quantity requested by its modelling set up, the data requirement is very few fully satisfied in real cases. Therefore depending on the modelling objectives, the modelling structure is often simplified by applying certain hypothesizes to reduce the pressure of data collection.

For instance, to build an EDSS of IWRM, the flood risk management often plays significant role in the system. In general, a successful flood risk assessment often requires the modelling analysis to achieve two main objectives including the production of detailed and accurate estimation for coming risks and has fast modelling responses of representing the influences due to natural, artificial and management changes. To reach those two tasks, the data collection for setting up the deterministic distributed hydrological model could have important variation. It could be complicated in case of collecting all physical characteristics of the catchment in distributed format or be simplified of focusing on several main factors based on reasonable assumptions. For example, in case of simulating extreme flood event, among all the hydrological process in the catchment water system, the rainfall-runoff process plays a significant role. Therefore, to represent the situation during the extreme flood, the data collection could be mainly concentrated on collecting only the catchment surface topography and the precipitation during the event. These two factors could be considered as the minimum data requirement of hydrological modelling assessment in a catchment Besides, with special conditions, this simple data collection could also work well: (1) in case of simulating of worst situation in the urban or industrial area, which does not consider the infiltration and drainage impacts or (2) in case of simulating the water system in a catchment, which has special geological characteristic with negligible water exchange between surface and underground. However, in most common cases with numerous hydrological processes integrated work in the water system, the minimum data collection may not be sufficient to set up the deterministic distributed hydrological model and to produce reasonable results. At this time, if there is still no field survey available, some hypothesis of simplifying the catchment characteristics should be introduced in the modelling set up with a series of tests implemented in advance.

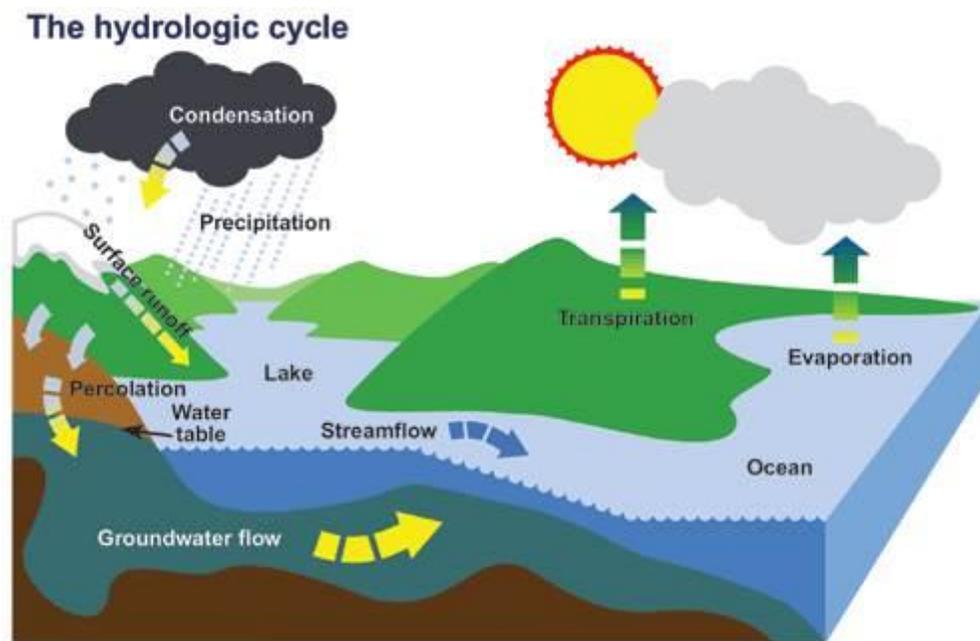


Figure 22: Hydrological cycle (www.ec.gc.ca).

Here we would like to first have an overview of the general data requirement of setting up the deterministic distributed hydrological model. Beginning with reviewing the hydrological cycle shown in Figure 22, the system could be analyzed in a 3D view started from evapotranspiration, which could be considered as the process of taking water from land surface, vegetation or open water body, and returning it back through the atmosphere. Then the water comes back to the ground surface with precipitation process to produce streamflow and surface runoff. Meanwhile, a part of precipitation could infiltrate into soil and through the soil to recharge the groundwater. Moreover, the water exchange process also exists between streamflow and groundwater. Therefore, to create an acceptable presentation by deterministic distributed hydrological simulation to describe the hydrological cycle in a catchment relying on its hydrogeological characteristics, most of these processes with their special data requirements should be taken into account in the data collection.

To represent the process of evapotranspiration in deterministic distributed hydrological modelling simulation, with different mathematic formulas applied in its calculation, the data requirement could be slightly different. The evapotranspiration process mainly contains two sub processes: evaporation and transpiration.

On one hand, the evaporation is pointed to the water evaporated from the top soil, land surface or open water body to the atmosphere, which is controlled by the geological and meteorological characteristics of the catchment including: soil property and water contain, accumulation of surface water and air temperature or sunshine duration. On the other hand, the transpiration is often related to the water transported from the vegetation to the atmosphere, which is affected by air temperature, humidity, vegetation types and root depth. In case of simulating the evapotranspiration process in the deterministic distributed hydrological model, the collected information covering all the physical aspects mentioned above is never completely achieved. Moreover, the mathematic formulas applied in the model calculation usually follow the process

of estimating the potential evapotranspiration first, and then based on the potential evapotranspiration calculates the actual evapotranspiration. This could be considered as a simplification of representing the complicated evapotranspiration process in the modelling simulation. However, even though the process is simplified in the model, the data requirement in the deterministic distributed model is still high. For example, in spite of selecting the simplest formulas in the modelling set up, it is still necessary to support a series of distributed air temperature with a certain time interval.

For the rainfall-runoff process, which could be considered as the most significant hydrological process in the catchment water cycle, the minimum data requirement could at least included a series of precipitation distribution during the assessment period and the catchment surface topography. Moreover, in some cases, where the study catchment has large vegetation area this leads to take into account the interception during the rainfall period. The Leaf Area Index (LAI) could be either collected from field survey or estimated based on the vegetation types define by land use map.

In catchment hydrological system, the water movement through soil is one of the most complicated processes, which caused various difficulties and uncertainties during the model simulation. Generally, the soil water movement could be defined with several processes consisting with infiltration, water movement through top soil (e.g. unsaturated zone) and deep soil (e.g. saturated zone) and water exchange between streamflow and groundwater flow. To handle these processes, the soil property including the hydraulic conductivity in x, y, z directions, saturated soil water content, soil wilting point, and soil field capacity, are often required in distributed format by the deterministic distributed hydrological model.

In conclusion, to summary the key points of data requirement for setting up the deterministic distributed hydrological model: firstly the inputs should be better collected in a distributed format covering the whole catchment. Secondly depending on the study objectives and on the numerical schemes applied in the model, the model structure could be simplified and its data requirement could be significantly resumed. To produce a reasonable simulation result representing the catchment hydrological system, the minimum data collection should be more focused on surface topography information, soil property, and series of meteorological information including precipitation and air temperature.

2.2. Challenges of Building a Deterministic Distributed Hydrological Models

Compared to other hydrological models, the deterministic distributed hydrological model has special characteristics of (1) applying/producing the distributed inputs/outputs and (2) simulation based on physical laws, which leads to some parameters involved in the calculation having physical meanings. Hence, the challenges of setting up this kind of model are often related to how to produce/define the “distributed” data/ parameters.

Firstly, the most common challenge faced by the modelers’ daily work of setting up this kind of model is to transfer the data collected from “point” measurements (e.g. rainfall time series recorded in gauging stations) or “line” measurements (e.g. profile of geological layers surveyed at different cross sections) into the 2D or even 3D distributed format. The simple way to achieve this task is to apply a suitable mathematic method to implement the interpolation. However, to find a suitable or acceptable mathematic method applied in the modelling catchment is often not easy and needs a series of tests and assessments.

Moreover, before the hydrological modelers starting to do the interpolation testes, it is necessary for them to understand that some methods recently commonly applied in hydrological and meteorological interpolation may not be originally conceived or designed to work in those area. For example, to interpolate the rainfall based on the records from different stations in the catchment, one common approach could be interpolated the rainfall with Kriging methods. But when we reviewed the history of this method, we found that it was not conceived for this purpose of rainfall interpolation:

“Theoretical basis for the Kriging was developed by the French mathematician Georges Matheron in 1960, based on the Master’s thesis of Danie G.Krige, the pioneering plotter of distance-weighted average gold grades at the Witwatersrand reef complex in South Africa. Krige sought to estimate the most likely distribution of gold based on samples from few boreholes.”(Wikipedia)

Obviously, if the modelers want to apply a method, which was designed for other objectives, they have to clear its using conditions and limitations. And double check if the selected method, which is not originally conceived to achieve their tasks could produce reasonable results to satisfy their objectives.

Secondly, for some information not available in the project (no measurement or few field survey), how to make a reasonable assumption to estimate the missing data or parameters in distributed format is also a big challenge for the hydrological modelers in the modelling set up processes. For instance, the function presenting the groundwater movement in the deterministic distributed hydrological model often asks the soil depth as one of the main factors and boundary of the calculation. The soil depth has significant impacts on both the soil water storage and soil water movement. Unfortunately, depending on the project budget, technique limitation, geological characteristics and area of the study catchment, often this information cannot be collected through distributed format. In this case, the modelers have to make an assumption based on limited references to produce a distributed soil depth over the catchment. Obviously, this inputs information has its physical meaning, which in theory could not be simply modified during the calibration process. Therefore, during the modelling calibration, these parameters are often

modified at last after all the other experience parameters calibrated. However, every time after modifying this information, all the other relevant parameters should be recalibrated this often consumes lots of time for running numerous simulations.

Besides that, a challenge related to the distribution data production could also shown in how to define the suitable resolution satisfying the balance between simulation running time and accuracy of modelling results. Theoretically, the more detail information are input in the model simulation, the more accurate the results are produced by the model. Unfortunately, this is only working with very ideal cases with all information measured from the field survey and defined by the modelers is accurate and without any uncertainty. However, in reality, it is impossible to avoid the uncertainty during the field measurement and the estimation of model parameters. Besides, in some other cases, due to the uncertainty or even the errors existed in the field survey, with higher resolution inputs, the model results may become worse than using coarse resolution inputs. Moreover, the resolution of the simulation also has huge impacts on the model running time. Obviously, the higher resolution model needs more time to run. After testing many simulation cases of deterministic distributed models, we found that the simulation running time is exponentially growing up with the increasing of model resolution. In most cases, when the EDSS requires the hydrological model to have fast responses, the modelers need to find the balance between the model accuracy and the model running time.

In conclusion, to summary the main challenges often faced by the hydrological modellers during the modelling set up process of deterministic distributed hydrological simulation in the EDSS, the following questions should be answers with a series tests in advance:

- What is the suitable method to do the interpolation based on the data measurements in the study?
- What is the reasonable hypothesis to produce the distributed inputs/parameters in the catchment?
- Which data resolution could be acceptable to accurately represent the reality?
- How to find the balance between the model accuracy and the model running time to satisfy the requirements of the managers?

2.3. Approaches of Solving Problems of Prediction in Ungauged Basin (PUB)

The continuous streamflow time series data is one of the most significant driving factors often asked by the managers to support their decision making process of managing water resources at their interest catchment and its mitigation of natural hazards (Blöschl et al., 2013). In theory, with the development of monitoring techniques, compared to the past, more field information could be caught in detail and in time. However, a series of studies declare that current measurement networks are declining and impacts of anthropogenic changes and climate amplify this issue (Abimbola et al., 2017). The usual practice that consists in optimizing the hydrological model with hydrological data becomes impossible for catchments with limited field information (He et al., 2011).

In the past, the catchment which defined as “ungauged” could be considered as a catchment “with an inexistent or inadequate, in terms of quality or temporal scale, records of its streamflow” (Sivapalan et al., 2003). Moreover, He et al. (2011) extended this concept of “ungauged catchment” to “a catchment undergoing climatic or human-induced changes that will modify their hydrological response with the consequence that existing streamflow records become non-representative of their response”. Even though the criterion of ungauged catchment has obvious extension, the main factor is still focused on the data quality and quantity related to streamflow in the study catchment. Since 2003, the International Association of Hydrological Sciences (IAHS) launched a concerted effort on investigating the “Prediction in Ungauged Basin”, the PUB problems was gaining more attention by both the water managers and hydrological researchers.

Since the concept of PUB conceived, until now, a variety of approaches range from purely empirically-based to purely physically-based was developed and applied to deal with this problem. It could be summarized and classified into three main groups including (1) spatial interpolation approach, (2) index modelling approach and (3) hydrological modelling approach.

The spatial interpolation approach could be considered as simple estimation based on feasible gauged information from neighbors of ungauged catchment (McIntyre et al., 2005; Oudin et al., 2008; Patil and Stieglitz, 2012; Shu and Ouarda, 2012; Yongqiang et al., 2014; Zhang and Chiew, 2009). For instance, the simplest interpolation approach could be the mathematical average approach which applied same weights for each donor to predict runoff and reduced uncertainty in the ungauged catchment (McIntyre et al., 2005; Oudin et al., 2008; Zhang and Chiew, 2009). Moreover, in 2012, Patil and Stieglitz (2012) applied the inverse distance weighting (IDW) interpolation approach to estimate the daily streamflow in ungauged catchment. It applied different weights for different donors based on the distance between donors and ungauged places. In the same year, Shu and Ouarda (2012) selected spatial interpolation approach together with weighted drainage area and weighted physiographical descriptors to predict daily streamflow and found the results produced by this interpolation approach is much better than directly applying the simple mathematical average approach. Yongqiang et al. (2014) made a comparison among different spatial interpolation approaches commonly used for solving PUB problems (Nearest neighbor, Spline, IDW and Kriging). They found that “the spline method performed worst, indicating that it is not suitable for predicting hydrological signatures. Besides, both IDW and Kriging approaches which put higher weights on nearer donors and low weights on more distant donors were noticeably better than the nearest neighbor approach.” At the end of their study, in the further assessment between IDW and Kriging approach, the results produced by IDW

approach showed slightly better performance. In addition, besides the interpolation analysis, they also highlighted that “it is worthwhile to sue multiple donors for solving the PUB problems”.

The second approach is implemented by index modelling which establishes relationships between catchment characteristics and hydrological signatures in one or several gauged catchments then applied these relationships to estimate the streamflow in ungauged catchment (Li et al., 2010; Yongqiang et al., 2014; Zhang and Chiew, 2012). Yongqiang et al., (2014) made the analysis of index modelling approach, they found that “for important long-term aggregated signatures, such as mean annual streamflow and runoff coefficient, the index model perform better than the spatially interpolated methods. For other signatures – such as concavity index, flow standard deviation, and seasonality ratio – derived from flow time series, use of spatial interpolation methods gives better results.”

However, among numerous approaches developed for predication runoff time series in ungauged catchment, the major one commonly selected in solving this problem is implemented by hydrological modelling especially the Rainfall-Runoff (RR) model (Parajka et al., 2013). In theory, this modelling approach could also be divided into two categories: physically-based and empirically-based.

The physically-based approach aims to estimate streamflow by utilizing a conceptual understanding of the physics describing various parts of the hydrological cycle by approximating physical processes (Booker and Woods, 2014). To achieve the tasks, assumptions about physical processes are necessarily required to apply this understanding (Beven, 1997). The data requirement of this approach often requests spatially distributed data (Blöschl and Sivapalan, 1995; Singh and Fevert, 2006) and time series data of the meteorological and hydrological conditions (Clark et al., 2008; Singh, 1995). It may cause much analysis and debates about data needs, parameter assignment and calibration and uncertainty assessment of physically-based hydrological simulations (Beven, 1997; Gupta et al., 2006).

Different to the physically-based approach, the empirically-based approach ails to estimate hydrological indices by quantifying patterns between observed hydrological indices and catchment characteristics (Book and Woods, 2014). A variety of techniques including linear regression (e.g. Engeland and Hisdal, 2009) or machine learning techniques (e.g. Booker and Snelder, 2012) are commonly applied to achieve the task of pattern estimations. Compared to the physically-based approach, on advantage of empirically-based approach is that its relative simplicity has allowed it to be transferred to ungauged catchment through regionalization (e.g. Castellarin et al., 2004), generalization or dissimilarity modelling (e.g. Book and Snelder, 2012).

In practice, many physical-based models have empirical components and many empirical models incorporate some level of knowledge about physical processes (Booker and Woods, 2014). A balance between model complexity and data availability should be discussed in advance for applying physically-based and empirically-based approaches in the study (Fenicia et al., 2008; Jakeman and Hornberger, 1993). Most of the physically-based modelling approaches require parameterization, and are known to perform best when calibrated against observed data (e.g. Clark et al., 2008; McMillan et al., 2013). Similarly, for independent variables applied in the empirically-based approach, the form of fitted empirical relationships could be interrogated to ensure consistency with physical principles (e.g. Book and Snelder, 2012). Moreover, unexpected

results from some regionalization studies predicting hydrological statistics and hydrological model parameters showed that spatial proximity could be more effective predictor than catchment attributes (Merz and Blöschl, 2005; Parajka et al., 2005). Therefore, there is still much to learn from regionalization studies, though it is not yet clear how to improve the performance of methods that use catchment attributes.

The regionalization methods applied in the hydrological modelling approach for ungauged catchment could be concluded with three categories: (1) Regionalization of model parameters, (2) Constraining hydrologic model simulations by regionalized signatures and (3) Transferring model parameters from hydrologically similar catchment (Singh et al., 2014).

The method of regionalizing model parameters relates the calibrated parameters of hydrological model with catchment characteristics using regression (Kokkonen et al., 2003; Oudin et al., 2010; Parajka et al., 2005). When the relationships are established from gauged catchments, the model parameters for ungauged catchments could be estimated with its physical/climatic characteristics. However, it is necessary to recognize that strategies based this method have been criticized for ignoring the covariance among model parameter estimates (Bárdossy, 2007; McIntyre et al., 2005; Oudin et al., 2008; Parajka et al., 2007), and are restricted due to parameter identifiability issues (Beven and Freer, 2001) and model structural error (Wagener and Wheater, 2006). The second method related to the regionalized signature is when regionalizing model parameter which invariably faces with problems and dependence of the calibrated parameters on the performance metrics used (Bárdossy, 2007). It regionalizes the streamflow signatures and calibrates the model to these estimations then to provide an alternative approach. The third method relies on the assumption that the same parameter set should be successful in physically and climatically similar catchment (Merz and Blöschl, 2004; Oudin et al., 2008; Parajka et al., 2005; Zhang and Chiew, 2009). It is clear that all the strategies offer their own strengths and weaknesses (Wagener and Montanari, 2011). For the first and third methods, their weaknesses generally rise from the need for modelling calibration (Beven and Freer, 2001). Singh et al. (2014) made the study about hydrological model parameters transferring based on the similarity in several catchment properties and streamflow signatures. They pointed that “the dominant controls on successful model parameter transfer vary significantly with spatial scale of the analysis, with the region of interest, and with the objective function used”. Besides that, in their study, it highlighted: all three types of catchment properties including climate, soils and land use emerged as important controls and runoff ratio did not emerge as the most important control on parameter transfer. The signatures describing low and medium flow aspects of the hydrograph were equally (or more) important.

Recent studies pointed that prediction from physically distributed models is associated with high levels of uncertainty in ungauged catchment (Razavi and Coulibaly, 2012). Most of the study related to PUB topic selected the conceptual or semi-distributed model as the main hydrological assessment tools mainly due to their less data requirements. However, even though the data needs for setting up the hydrological model could have significant variation which highly depended on the characteristics of the model itself and strategy of modelling process, most of the effective values of the parameters applied in the model could not be measured directly and often obtained by calibrating the model with the observed runoff (Beven, 2012). After a decade of research on PUB problems, it still remains a considerable challenge to calibrate runoff models for data scarce catchment (Hrachowitz et al., 2013). A series of studies explored the minimum length of a runoff

time series necessary to obtain robust model calibration. Some authors assumed that a short and intensive field campaign could be carried out in the catchment of interest to collect data for model calibration (Sandra et al., 2017). There is a general agreement that model performance tends to improve with an increased length of calibration data, much smaller data sets have been shown to be of comparable value as long continuous time series (McIntyre and Wheater, 2004; Melsen et al., 2014; Perrin et al., 2007; Seibert and Beven, 2009; Seibert and McDonnell, 2013; Singh and Bárdossy, 2012). For instance, Seibert and Beven (2009) reported that approximately sixteen runoff measurements randomly picked within one hydrological year could already provide information for an acceptable model calibration and maximum flows or a combination of maximum and recession data contained more information than minimum or mean flow. Moreover, Seibert and McDonnell (2013) pointed that one fully gauged event or ten observations during different high flow situations has similar information values as three months of continuously measured data. Some study even declared that event based sampling strategies results in better model performances than strategies with measurements at fixed time intervals (Juston et al., 2009; McIntyre and Wheater, 2004; Seibert and McDonnell, 2013) and model calibration with limited number of runoff measurements performed best in relatively wet catchment (Perrin et al., 2007; Sun et al., 2017). In addition, the consideration of hydrological variability and hydrologically important processes was found to be essential for the calibration process and the results simulation uncertainty (Harlin, 1991; Konz and Seibert, 2010; Singh and Bárdossy, 2012; Vrugt et al., 2006).

2.4. Strategy of Setting up Deterministic Distributed Model in Ungauged Catchment

Among numerous discussions and studies of using modelling tool for solving PUB problems, the applications of deterministic distributed model did not gain much attention by the hydrological modelers in the real case study. The main reason which we already discussed before could be the higher data requirement and complicity of the model structure. However, it is also necessary to notice that most of the cases of solving PUB problems were mainly focused on streamflow estimation which simplified or even ignored the impacts of other hydrological processes existed in the catchment.

Recently, the requests of water management in one catchment are not limited by assessing the phenomenon of streamflow. The managers take more attention on having an integrated view of the water distribution caused by all main hydrological processes in the catchment and impacts of implementing relative measures on natural environment. Obviously, to achieve those new tasks in environment management, the advantages of applying deterministic distributed model are in evidence. Therefore, due to the special characteristics of deterministic distributed model, here, the description of the ungauged or poor gauged catchment could be extended and updated as follow:

The ungauged or poor gauged catchment could be defined as the catchment which has less or no information to well describe the main hydrological processes in its control area.

However, even though with this extended definition of “ungauged catchment”, most of the catchment in the world could be concluded in this categories, compared to the previous definition, it could be considered as a starting point which changed the mind of modelling study in PUB problem from data-driven to objective-driven. Due to the development of hydro-informatics and monitoring techniques, several approaches were designed to overcome the data issue faced by the hydrological modelers during the process of setting up deterministic distributed model. Therefore, when the impacts of the data limitation show a decreasing trend, through reasonable modelling strategy, the deterministic distributed hydrological model could be more commonly applied in the hydrological assessment. In this case, the integrate management could be also benefited. Here, we would like to conclude a suitable modelling strategy of setting up this kind of model for ungauged catchment with complex geological, meteorological and hydrological conditions (Figure 23).

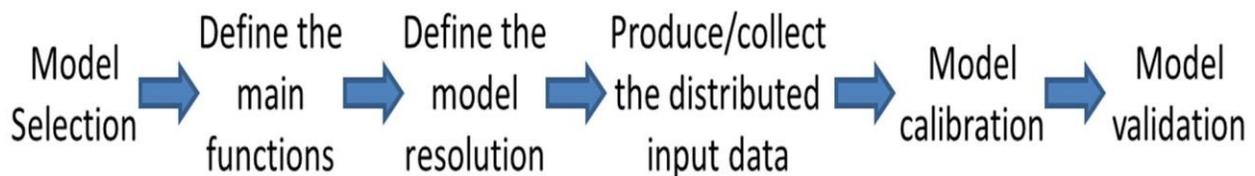


Figure 23: Working process of setting up deterministic distributed hydrological model in an ungauged catchment.

A good modelling approach in one ungauged catchment should be started from a reasonable model selection. With different objectives, various models now are available in the market, so the needs for us is through a serious discussion to select the most suitable model to satisfied our

tasks. We suggested that a reasonable modelling selection of deterministic distributed model should at least consider following characteristics:

- (1) The model should be available to physically represent all the possible hydrological processes in the catchment.
- (2) The model should be sensitively responded to any changes from the inputs of physical factors.
- (3) The modelling results should be easily used by other numerical analysis such as applying as inputs for other hydraulic models.

The first characteristic could be considered as the basic requests from the management, and the other two are mainly focused on having an integrated modelling system applied in the EDSS. Then, the second step of setting up the model could be the function selection in the model structure. In most of the deterministic distributed hydrological models, the simulation works with various hydrological functions working integrated. Hence, based on the characteristics of the catchment, different functions which represent hydrological processes having significant impacts in the catchment should be included in the modelling process. And for the insignificant hydrological processes, the related functions in the model could be neglected or simplified to reduce the data requirements and running time assumption.

For the deterministic distributed hydrological model, the complicity of the model structure and accuracy of the model results are highly affected by the model resolution which commonly control by the data collection in the catchment. With the new techniques of remote science, the DEM is widely applied in the hydrological modelling study as the main input to represent the terrain of the catchment surface in the model. For instance, [Dadiyorto et al. \(2015\)](#) made a study of improve the DEM quality through Artificial Neural Network (ANN). Based on a part of high resolution data as the reference, the quality of DEM covered whole study area with coarse resolution could be significant improved through ANN application (Figure 24).

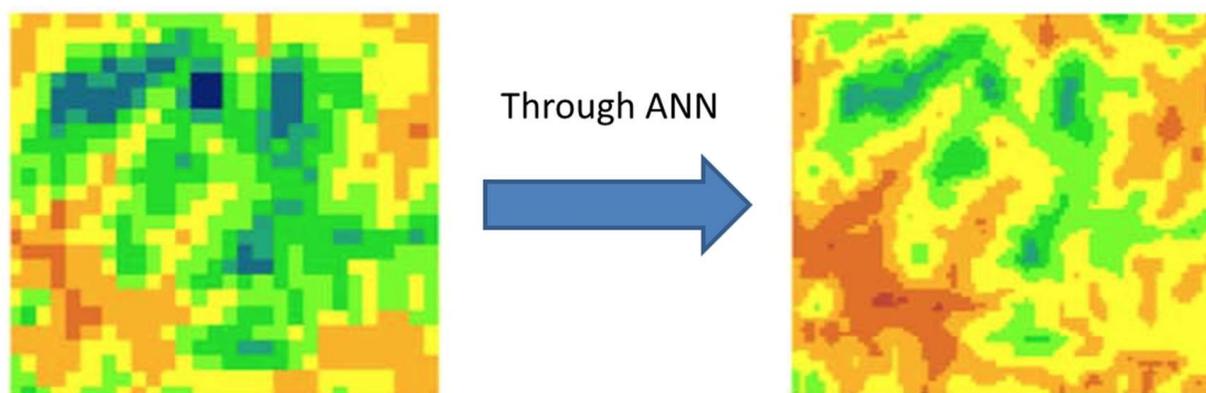


Figure 24: DEM improvement through ANN (Dadiyorto et al., 2015).

Therefore when the limitation of the data collection for high resolution DEM has been significant reduced, the main question asked in the modelling set up process is concentrated on how to define the suitable modelling resolution for hydrological assessment at interested catchment. Our

suggestion is to taking a series of tests which integrated consider following criterions before running the model for real cases:

- (1) Is the model with selected resolution could well represent the real catchment phenomenon such as the river channel, terrain of the catchment surface or artificial structures implemented in this area?
- (2) Is running time of the model with selected resolution accepted by the management purposes?

In some cases, especially for the catchment which has big area with mountain terrain, the width of the stream river channel could have significant fluctuation. It could be varied from several meters to hundreds meters. In this case, the higher resolution DEM (e.g. 2m ×2m) could be considered as the main input to represent the river channels in the catchment. But with this high resolution input, the model running time would be exponentially increased. When the main objective more focused on representing or forecasting the situation which has short responses time (e.g. extreme flood), the high resolution model run with longer simulation time could not be accepted. However, in contrast, when the modelers seek for shorter running time and apply coarse resolution in deterministic distributed simulation, the accuracy of its modelling results will be significantly reduced. The balance between the model accuracy and running time should be discussed seriously to define the suitable resolution satisfied our working objectives.

In addition, one point should be clear here is in most of the deterministic distributed hydrological modelling cases, the model resolution is not only controlled by the resolution of the topography data which normally is the DEM, but also impacts by other inputs of the model such as the rainfall distribution, snow cover and soil property. How to make the distribution of inputs based on point survey realized by gauging stations is the core topic caused a series of discussions. In general, there could be three main approaches available for solving this problem: uniform approach, station based approach and special interpolation approach.

The uniform approach assumed the catchment has homogeneous characteristic over the whole area. It strongly reduces the data requirements and often be applied in small catchment which has less terrain variation or used to describe the catchment's property with less spatial sensitive. The station based approach could be considered as an improvement based on uniform approach. It divides the study area into different sub-catchments controlled by the gauging stations and assumed that in those sub-catchments, it has homogeneous characteristics as same as measured at the gauging station. This approach works well in the middle size river basin or a catchment not has so complicated hydrological system. However, for the large river basin which as unneglectable terrain variation and complex hydrological system both uniform and station based approaches may not represent the real phenomenon accurately. In this case, the distributed information based on gauging information through reasonable interpolation method could be applied to satisfy the data requirement of setting up the model. Among numerous discussions of spatial interpolation, the methods like Kriging and Inverse Distance Weight (IDW) often give different weights of the donors based on other physical characteristics such as distance or elevation difference have better interpolation results than other mathematic methods and widely be applied in the hydrogeological modelling approach. In sprit of that, a series of tests among different data interpolations is still necessary before setting up the model. We could like to point

that these tests may not only focus on the comparison among different methods, but also the impacts of different interpolation resolution.

The last two working process of the deterministic distributed modelling approaches are the calibration and validation. Compare to the classical modelling calibration process, due to the data limitation, for the ungauged catchment modelling, not only the conceptual parameters but also the physical parameters should be calibrated carefully. And in the time series data applied in the calibration process, we suggested to better have at least two flood events and one draught during the simulation period.

CHAPTER 3: AQUAVAR AT FRENCH MEDITERRANEAN REGION

During the last decade, with the intense increasing of the social activities especially urbanization and industrialization, the water impacts of the human life becomes more and more significant. Compared to the previous management strategy which mainly focused on the quantity control and optimization, in the new century, the challenges faced by the local managers is how to manage both the quality and quantity of the water resources distributed in their interested catchment.

The modelling assessment could be considered as the main analysis tool for the topic related to water resources management. Since 1970, with the progress of computer science, the new subjects named with hydro-informatics has conceived and developed to deal with the rapid increased of geological, hydrological and meteorological information (Diersch and Kolditzn 1998; MoDonald and Harbaugh, 1984; Verruijt, 1970). With the development of modelling techniques and application, an integrated modelling system contains a series of models in both hydrological and hydraulic domain are designed and commonly applied in EDSS to produce integrated view of the water system in the catchment. Compared with working independently, the models work together may have more advantage of achieving complex functions according to the needs (Geofrion, 1989). However, the modelling diversity in the system could also be reflected during whole the modelling process from construction of the simulation to application of the models and made the system become more complicated Therefore, the researchers and engineers should more carefully consider their objectives and needs of the projects in order to select the efficient and suitable modelling tools to satisfy the management requirement.

In this chapter, a real application of deterministic distributed hydrological modelling simulation in EDSS was introduced with the project of AquaVar implemented at French Mediterranean region. Through the design of EDSS architecture discussion in the first chapter, this study is one of the core modelling processes which includes the scientific study of an integrated deterministic distributed hydrological model and its application in the field of EDSS working with other specific hydraulic models. The contents of the chapter started at the general introduction of the AquaVar project including its main objectives and design. Then the main challenges of the hydrological modelling assessment of this study were discussed in the second section. Before selecting the suitable modelling tool to achieve our tasks, a detail analysis of the catchment characteristics should be implemented in advance. In the section 3, the geological, hydrological and metrological characteristics of the Var catchment were deeply discussion to have a more detail view of the physical condition of the catchment. The chapter ended by the reviewing of some historical natural disasters recorded in the Var catchment.

3.1. AquaVar Project

The water resources in the Var catchment especially at the unconfined aquifer distributed in the downstream of the watershed is the main fresh water resources for the department of Alpes-Maritimes. It supplied the water for most of the social activities including industrial, agricultural and domestic uses for the Nice Côte d'Azur conurbation and also many communities located in the same region contains a total population around 600 000. To optimize the fresh water resources management in the catchment, local water agency Régie Eau d'Azur (REA) set up this project named with AquaVar to develop an integrated EDSS consisted with hydrological, hydraulic and groundwater modelling assessments for supporting their decision making process. The project of AquaVar has been initiated since 2014 and planned to last at 4 year until 2018.

The project emphasizes understanding the water system of Var catchment in both temporal and spatial aspects and the quantification of river-aquifer exchange at the low Var valley. The achievements of the project was expected to be able to provide arguments supporting the decision making process regarding the daily operation, reactions to accidental events and influences of future developments. Besides that, the study results and working process could also be applied to optimize the current water management plan and benefits the economic, social and ecological profits.

To achieve the final two main tasks including integrated understanding of water system cover whole catchment and river-aquifer exchange especially at the low part of the watershed, there are four main function designed to be fulfilled in order to meet the needs of local water managements:

- The modelling system developed in AquaVar project should be able to use for predicting the future impacts on the local environment, such as implementing constructions or river morphology evolution induced by sediment transportation.
- The modelling assessment should have the capacity to have reasonable simulation of the long term scenario in order to represent the impacts of climate changes.
- The modelling system should be capable to represent the historical extreme events records in the catchment and use for estimating the impacts of coming meteorological events including flash floods and droughts events in at least sub-catchment scale.
- The pollutant transpiration should also be considered in the model simulation in cases of seawater intrusion and accidental chemical pollutant leakage into the river or unconfined aquifer.

Integrated considering the requirement of the AquaVar project, the modelling system is thus designed with 3 individual models covered hydrological, hydraulic and groundwater aspects and a coupling interface was also designed to have more detail simulation for the river-aquifer exchanges (Figure 25).

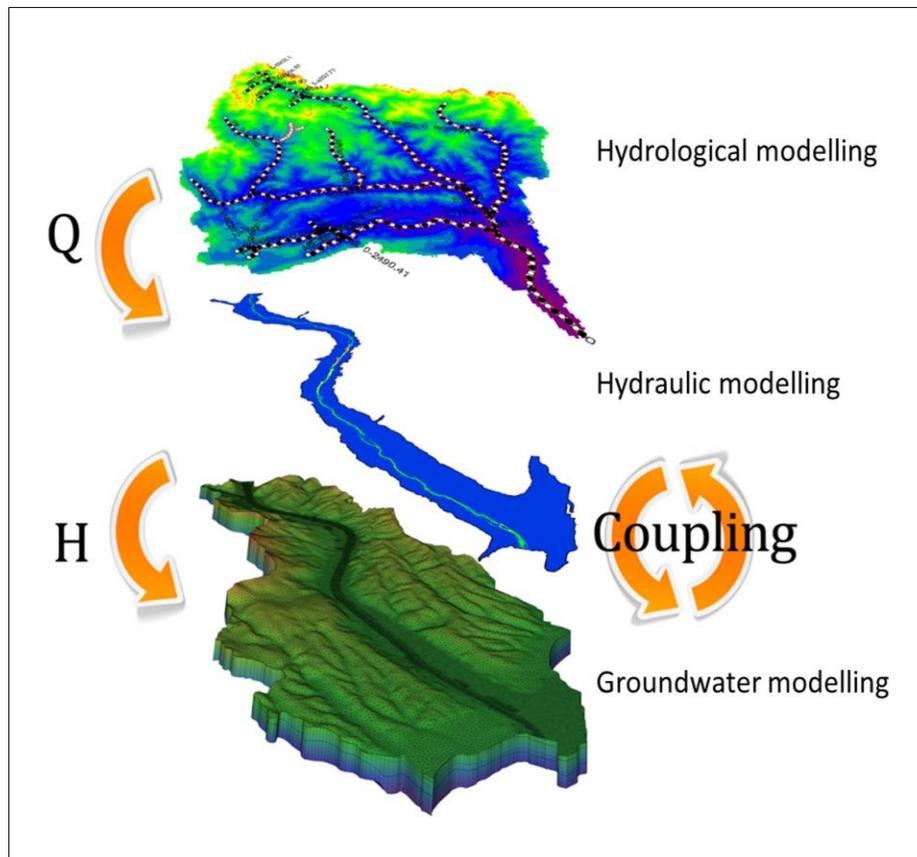


Figure 25: Modelling structure of AquaVar projects.

- A hydrological model was built to simulate the multiple hydrological processes existing in the catchment water system including rainfall-runoff, snow melting process, infiltration, evapotranspiration, groundwater, and exchange between surface and groundwater.
- A river hydraulic model was built to mainly focus on the surface water movement at the downstream part.
- A groundwater flow model was built to detail represent the water movement at the unconfined aquifer at lower Var valley.
- Coupling interface between hydraulic and groundwater models was developed in order to perform accurate simulation of river-aquifer exchanges in the low valley of Var catchment.

All these modelling components were developed independently and at the end combined together to form the core of EDSS that can be operated by the local water management authority to support decision making process. Linked with the real time monitoring system and weather forecast or meteorological estimated studies in Var region, the developed EDSS with validated models working integrated could have the capacity to produce reasonable simulation results to support the local managers.

3.2. Objectives and Challenges of this Study

The hydrogeological characteristics of Var catchment are involute due to its significant elevation variation and complicated geological layers distributed underground. There are many difficulties faced by the hydrogeological engineers to implement a series of field measurement in this area especially at the upstream parts. However, as results of the increase of social activities such as the urbanization of NICE city located at the outlet of the catchment, the natural impacts on the local society becomes more and more significant. Since 1990s, the local governments and research institutes recognized that it is necessary to have a clear understanding of the hydrogeological components of Var catchment. Until now a series of studies had been carried out to assess the hydraulic, hydrological and geological phenomenon of Var (Emily et al., 2010; Gugliemi, 1993; Guglielmi and Regnaud, 1997; Potot, 2011; Potot et al., 2012). But most of studies were more concentrated in the stationary hydrogeological or hydrochemical measurements at the low Var valley. The detail information over whole catchment or of unconfined aquifers located at the downstream part is still not available. The knowledge gap of the physical characteristics existed in the Var catchment strongly affects the hydrological assessment of catchment and needs to be filled by the research.

In this study which could be considered as one third of the Var project is mainly focused on the hydrological modelling assessment of Var River Basin. Considering the research gap and information limitation from previous studies, the study objectives are purposed as follow:

- The data collection and assessment should be emphasized in the hydrological analysis to improve the understanding of both hydrogeological and meteorological conditions of Var catchment.
- One hydrological model should be set up to represent the multiple hydrological integrated working in the catchment water system. The validated model should have the capacity to be applied for running in real time, estimating the future scenarios and producing information (e.g. boundary conditions) for the other two parts of modelling assessments in AquaVar project.

However, to achieve those two main tasks, many challenges faced by the hydrological modelers during the modelling and assessment:

- Start from the model selection, among numerous hydrological models available in the market, the model applied in the hydrological assessment of AquaVar project should satisfied following criteria:
 - The model should have the modelling characteristics of deterministic distributed, which has the capacity to physically represent the distributed hydrological processes in catchment water system.
 - The model simulation should cover both the long time period and short events with reasonable calculation time interval and running time.

- The validated model should be able to apply for real time simulation and estimation of future scenarios.
- The model output should be in the standard format which could be simply transferred to other hydraulic and groundwater models applied in the integrated modelling system of AquaVar project.
- To set up the deterministic distributed model, most of the model inputs should be in the distributed format, hence, how to transfer the stationary measurements to distributed format is a big challenge and require a series of test about the interpolation methods. Due to the serious data missing in this region, for some parameters requested by the modelling simulation, the modeler should find the reasonable assumption to deal with the missing parts.
- Moreover, as results of the hypothesis applied in the modelling set up, it may cause the increase of modelling uncertainty at the same time. Therefore the uncertainty analysis should be implemented during the whole assessment period from data analysis until the discussion of modelling simulation.

3.3. Model Selected for AquaVar Hydrological Assessment (MIKE SHE)

Comparing the criteria and the advantages/disadvantages discussed before, the structure of deterministic distributed hydrological model is a combination of distributed characteristics and physical interpolation the hydrological processes, hence it is expected to provide significant advantages over existing hydrological models for a wide range of application. Furthermore, due to the calculation in the model through grid scale, thus it may help to overcome the data problem at large catchment with limited data collection (Vo, 2015).

Several tools are today available and could be used for supporting integrated hydrological assessment in the interested catchment. The typical of this kind of model is MIKE SHE developed and extended by DHI.

3.3.1 MIKE SHE philosophy

In 1970s, in Europe, compared to the previous modelling studies, a new generation hydrological models aimed to provide more scientific information for optimizing water resources management and estimating impacts of increase of social activities such as urbanization, land use changes and infrastructural developments on natural environment were requested to be designed with physical distributed structure. At that moment, the Europe Hydrological System –Système Hydrologique Européen (SHE) was born to satisfy the new requirement asked by the water resources managers. After getting success in simulating the hydrological phenomenon in Europe, SHE was considered as the starting points for many deterministic distributed hydrological models like SHETRAN, SHESED and MIKE SHE (Ewen et al., 2000) SHE was originally produced by the cooperation among three European water agencies including British Institute of Hydrology, UK, Danish Hydraulic Institute (DHI), Denmark and SOGREAH, French under the financial support from European Commission (Abbott et al., 1986).

The SHE model was built fundamentally on the blueprint proposed by Freeze and Harlan in 1969 for modelling hydrological cycle (Abbott et al., 1986). It divided the runoff process into many sub-processes individually simulated through different corresponding equations. The formulas applied in the model calculation were deterministic which have the capacity to accurately represent the physical phenomenon of the catchment (Freeze and Harlan, 1969). The algorithm was developed independently at three partners under the form of software model, the Institute of Hydrology, UK was in charge of produce the simulation including snow melting, interception during the rainfall process, evapotranspiration. Both of the surface water movement named with overland flow in the model and the stream water movement named with channel flow was implemented by SOGREAH, France. Moreover, DHI was responsible for the soil water flow through unsaturated and saturated zones in the catchment and integrated combined multiple functions together to produce the final simulation results (Abbott et al., 1986).

After a series of validation tests of the model quality, the first version of SHE was became operational in 1982. Since that time, the SHE model has been continued developing and extended by DHI with new mane of MIKE SHE. Recently, the MIKE SHE model is considered as a high performance modelling system for representing the water cycle in the catchment. It contains as full suite of pre-and post-process tools plus a flexible mix of advanced and simple solution techniques for each hydrological processes existed in the watershed. The main hydrological

processes such as the evapotranspiration, rainfall-runoff process, overland flow and soil flow including unsaturated and saturated flow could be accurately caught in the MIKE SHE simulation and represented with different level of spatial distribution and complexity depended on the purpose of the modelling assessment, availability of the field measurements and modeler's decisions (Butts et al., 2004; Graham and Butts, 2005). One added value of MIKE SHE compared to other hydrological software is it has the user friendly interface allows the user to intuitively build the model description based on the user's previous modelling study like the conceptual model of the watershed. The input data required by MIKE SHE modelling set up is specified in a variety of formats independent of the model domain and grid including most of common GIS formats. Moreover, during the running time, the spatial data is mapped with numerical grids which make the changes of spatial discretization become feasible (Graham and Butts, 2005).

In addition, with the development of MIKE series models, recently, the MIKE SHE model has the capacity to couple with other MIKE series models such as MIKE 11 and MIKE URBAN to achieve more complicated tasks. For instance, the channel flow simulated in MIKE SHE is implemented by coupling with MIKE 11 which described the stream flow with 1D Saint-Venant equation and linked with overland function in MIKE SHE by grid located near the H-points calculated in the channels. Then the surface water stages are then calculated in MIKE SHE by simple comparison between water level at H-point and the elevation of closest grid. The MIKE 11 could continue to route water downstream as 1D flow meanwhile the water is also available to rest of MIKE SHE for other hydrological processes such as evaporation or infiltration. With this coupling process, it makes the MIKE SHD be able to apply to simulate large catchment with big water bodies like lakes, reservoirs and flooded area. It is also possible to couple the MIKE SHE with the software named MIKE URBAN to represent the surface/subsurface hydrological process and sewer system in the urban area (DHI, 2012).

3.3.2 MIKE SHE architecture

As we explained before, for most of the deterministic distributed hydrological application, significant amount of data requirement and long execution time could be two main obstacles limited the application range. Obviously, by simplifying the hydrological processes in the model simulation could effectively reduce the complicity of the model structure and data requirement. But the impacts of representing only main processes in the model simulation on the results accuracy should be assessed and discussed carefully among hydrological modelers. In 2005, Graham and Butts (2012) had a discussion about this topic of considering one or two main hydrological processes dominate the water behavior. They suggested that a complete physics based flow description for all process in one model is rarely necessary. Over-parameterized description may occur for simple applications (Vo, 2015). Therefore, the model applied to represent the catchment behavior should have flexibility to let the modeler select suitable simulation methods which may not only limited with fully deterministic approaches but also including a part of stochastic approach.

In the MIKE SHE model, the simulation approaches are integrated organized including several solution techniques to translate different processes in nature. Therefore it gives the space for the modelers to optimize the function of each component when the model were selected to be applied for representing the hydrology system in large river basin or the catchment which has complicated hydrogeological conditions. The modelling structure mainly consisted with 8 main

functions including “Rain and Snow”, “Evapotranspiration”, “Snow Melt”, “Overland Flow”, “Channel Flow”, “Unsaturated Zone Flow”, “Groundwater Flow” and “Sewer Flow” to represent the multiple hydrological process in a catchment (Figure 26).

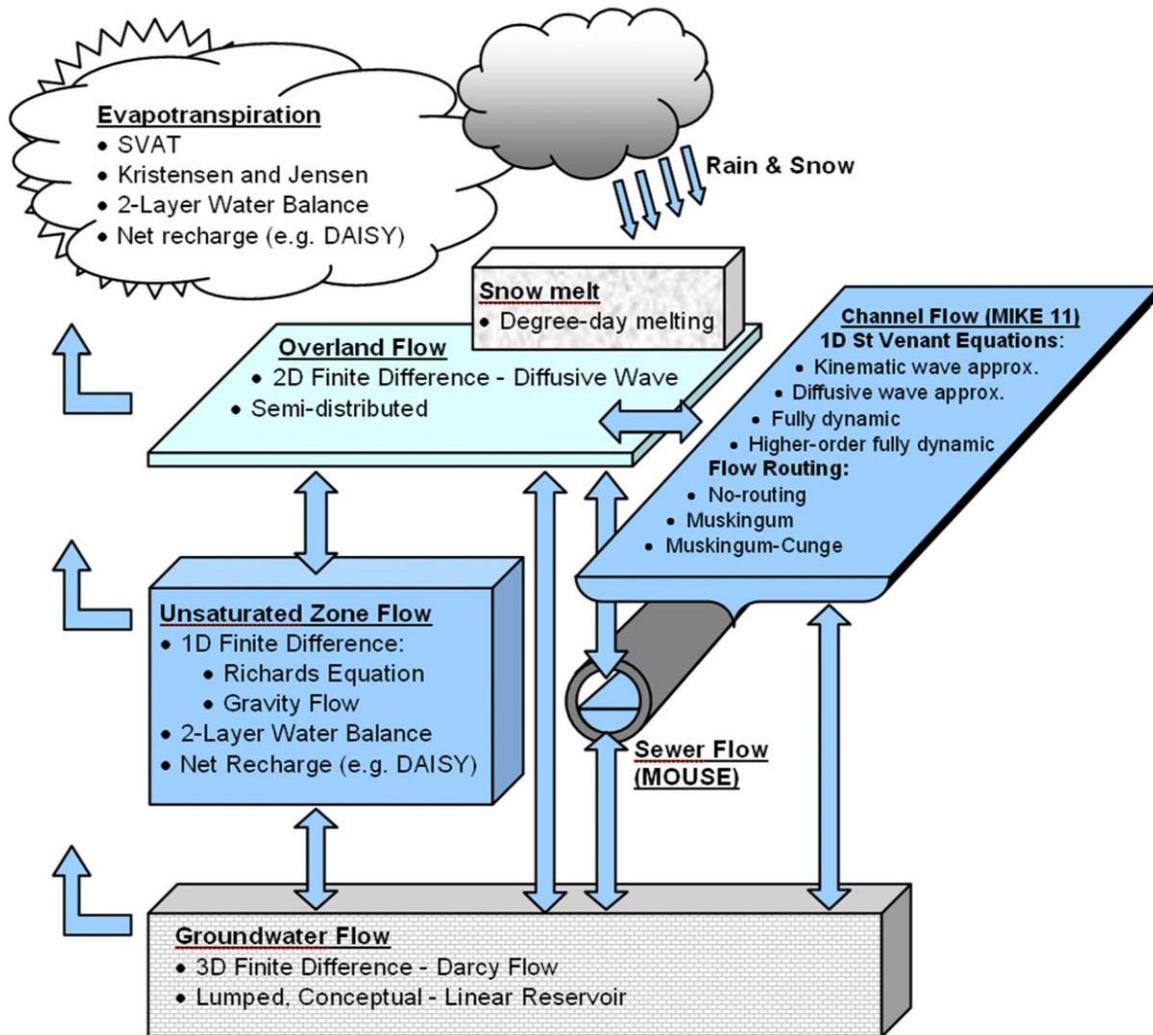


Figure 26: Schematic view of the process in MIKE SHE (DHI 2014).

Rain and Snow

The rainfall or the precipitation is the key factor in most of the hydrological systems which often be considered as the starting point and the main inputs of the hydrological processes especially for the rainfall-runoff representation. The quality of the rainfall data has significant impacts on the simulation accuracy. In MIKE SHE model, temporally, the precipitation rate could be described in two different ways including constant value and time series depended on the data availability and modelling objectives. Moreover, spatially, MIKE SHE allows the precipitation to be represented with three different formats: “Uniform”, “Station Based” and “Full Distributed”. The uniform rainfall applied in the MIKE SHE simulation is commonly used for simulating the hydrological phenomenon in small catchment or in case of significant shortage of survey data. It

assumed the study area has homogeneous rainfall situation at certain simulation time. For the “Station Based” rainfall applied in the MIKE SHE simulation, it is more suitable for simulating the medium size catchment or large catchment with the relatively higher density of gauging stations. The “Station Based” rainfall in MIKE SHE divides the study catchment into several sub-catchments based on the available gauging stations and assumes in each sub-catchment the rainfall is “Uniform”. There are several ways to define the area of sub-catchments, and one of the most famous and common one is through Thiessen Polygons method. However, there is still no clear conclusion of the discussion about the criteria of suitable density of gauging station in one catchment. The third ways of rainfall represented in the MIKE SHE is now considered as the best way to describe the meteorological condition of catchment which is “Full Distributed”. It is expected to be more closed to the reality and have significant improvement on the simulation results. The main obstacle for applying this kind of rainfall input is due to the measurements of rainfall in the catchment often implemented at few locations. Consequently, this rainfall input could not be obtained directly from the data collection of the study. It is generally got via several interpolation methods. In addition, for the “Full Distributed” rainfall, MIKE SHE also provides a tool to correct the rainfall variation based on the elevation via “Precipitation Lapse Rate”.

Evapotranspiration

When calculating the water balance in catchment hydrological system, the evapotranspiration is an important component. In MIKE SHE model, the simulation of evapotranspiration uses not only the meteorological but also vegetative information to estimate the total evapotranspiration and net rainfall based on many components such as canopy interception from rainfall, evaporation from canopy surface, evaporation from soil surface, uptake water by plant and its transpiration. There are three main functions available in MIKE SHE to calculate the actual evapotranspiration (AET) during the simulation:

- Soil Vegetation Atmosphere Transfer (SVAT)

The SVAT function is developed based on an assumption of system consisted with two layers (soil and canopy) and their resistance network link ([Shuttleworth and Wallace, 1985](#)). It includes a single, semi-transparent canopy layer located above the soil layer and calculates the AET directly from standard meteorological and vegetation data. One pointed need to be highlighted here is this process is not dependent on Reference evapotranspiration ([Graham and Butts, 2005](#)).

- Kristensen and Jensen Method

The Kristensen and Jensen Method is the primary ET model in MIKE SHE which based on empirically derived equations conceived by [Kristensen and Jensen \(1975\)](#) at the Royal Veterinary and Agricultural University (KVL) in Denmark. The model uses the following equations to solve the relationship among Reference Evapotranspiration, Root Depth, Leaf Area Index (LAI) and Soil moisture status. The precipitation is assumed not occur as snow due to the consideration of temperature above 0°C. The data requirement of implementing this function in MIKE SHE is including a time series of Reference ET, LAI and root depth, and other empirical parameters. The Reference ET is the rate of ET from reference surface with an unlimited amount of water. It could be independent of everything but climate and calculated from meteorological data. Here the

FAO Penman-Monteith method is recommended for defining the Reference ET value in case of on ET information directly available from the gauging stations.

ET from Snow

$$ET_{snow} = ET_{wetsnow} + ET_{drysnow} \quad \text{Equation 1}$$

with

$$ET_{wetsnow} = ET_{ref} * \Delta t$$

$$ET_{drysnow} = ET_{ref} * S_f * \Delta t$$

where ET_{snow} (L) is the evapotranspiration from the snow cover area in the catchment which sum the ET from both wet and dry snow storage. The calculation is divided into two steps: firstly the ET will take the water from wet snow storage if it exists based on the ET_{ref} (LT^{-1}) the Reference Evapotranspiration. In case of insufficient wet snow storage exists in the study area, the ET will take the water from dry snow as sublimation depends on ET_{ref} and S_f (-) which is the sublimation reduction factor defined in the Snow Melt function in MIKE SHE. If there is not enough snow storage at the calculation time step, ET_{snow} will reduce the snow storage to zero.

Evaporation from Canopy

$$E_{can} = \min(I_{max}, ET_{ref} * \Delta t) \quad \text{Equation 2}$$

with

$$I_{max} = C_{int} * LAI$$

where E_{can} (LT^{-1}) is the canopy evaporation calculated based on the comparison between I_{max} (L) which is the interception storage capacity and amount of ET_{ref} during the calculation time interval Δt . To get value of I_{max} , both C_{int} (L) interception coefficient and LAI (-) is required in the model simulation.

Plant Transpiration

$$ET_{at} = f_1(LAI) * f_2(\theta) * RDF * ET_{ref} \quad \text{Equation 3}$$

with

$$f_1(LAI) = C_2 + C_1 * LAI$$

$$f_2 = 1 - \left(\frac{\theta_{FC} - \theta}{\theta_{FC} - \theta_W} \right)^{\frac{C_3}{E_p}}$$

where ET_{at} (LT^{-1}) is the transpiration from vegetation calculated with two functions considered impacts of LAI and soil moisture content. The RDF (-) is a function of root distribution. C_1, C_2

and C_3 are empirical parameters applied in the calculation. θ_{FC} (-) is the volumetric moisture content at field capacity. And θ_W (-) is the volumetric moisture content at wilting point. The parameter of θ (-) is the actual volumetric moisture content at the simulation time step.

Soil Evaporation

$$E_s = ET_{ref} * f_3(\theta) + [ET_{ref} - E_{at} - ET_{ref} * f_3(\theta)] * f_4(\theta) * [1 - f_1(LAI)] \quad \text{Equation 4}$$

where soil evaporation E_s (LT^{-1}) estimated from the upper part of unsaturated zone consisting with a basic amount of evaporation $ET_{ref} f_3(\theta)$ plus additional evaporation from excess soil water when soil saturation reaches field capacity.

In addition, the evapotranspiration is extracted from saturated zone only when the roots of vegetable are in contact with water table (DHI, 2014). Moreover, to implement the Kristensen and Jensen method in MIKE SHE simulation, it requires when using Richards equation and gravity flow methods in the Unsaturated Zone Flow calculation (Graham and Butts, 2005).

- Two Layer Water Balance Method

To reduce the complicity of simulating the transpiration process in unsaturated flow, in MIKE SHE model, Two Layer Water Balance Method is proposed to achieve this task. This method is based on a formulation conceived by Yan and Smith (1994) which simply divided the unsaturated zone into two parts and designed to calculate the actual evapotranspiration and amount of water recharges the saturated zone (DHI 2014). The calculation of AET followed Two Layer Water Balance Method is similar as Kristensen and Jensen Method. It explicitly calculates from various storages in MIKE SHE:

$$ET_{actual} = ET_{snow} + ET_{canopy} + ET_{ponded} + ET_{UZ} + ET_{SZ} \quad \text{Equation 5}$$

where the ET_{actual} (LT^{-1}) is calculation by the sum of ET from snow cover, canopy, ponded water bodies, unsaturated zone and saturated zone with the same data requirement as Kristensen and Jensen calculation. However, compared to Kristensen and Jensen method, there is no flow dynamics taken into account in the Two Layer Water Balance simulation.

The simplification by implementing Two Layer Water Balance method is commonly applied to represent the hydrological processes in swamps or wetland areas with relatively shallow groundwater table. It also could be accepted to the simulation of with deeper and drier unsaturated zone. But in this case, the model results should be calibrated carefully.

Snow Melt

In order to consider the impacts of snow melting and freezing process on stream flow in the catchment, the MIKE SHE model support the modelers to representing the snow melting process with a modified degree-day method. The snow melting function in MIKE SHE has the capacity to consider the melting process affected due to different sources like air temperature, radiation or energy:

$$M_{total} = M_T + M_R + M_E \quad \text{Equation 6}$$

- Air temperature melting

$$M_T = C_T * (T_{air} - T_0) \quad \text{Equation 7}$$

where the rate of melting M_T (LT^{-1}) due to the air temperature is depended on the degree-day factor C_T (unit in mm/day/C) and the difference between air temperature T_{air} at the calculation cell and the threshold melting temperature T_0 which in most of the cases defined as $0^\circ C$.

- Radiation melting

$$M_R = -C_{rad} * R_{sw} \quad \text{Equation 8}$$

where the radiation melting rate M_R (LT^{-1}) is controlled by the radiation melting factor C_{rad} (unit: mm/kJ/m²) and the amount of incoming solar radiation (R_{sw} (unit: kJ/m²/hour)

- Energy melting

$$M_E = C_E * P * (T_{air} - T_0) \quad \text{Equation 9}$$

where the rate of melting due to energy in liquid rain M_E (LT^{-1}) is calculated by energy melting coefficient C_E (unit: mm/mm rain/C) and the difference between air temperature and threshold melting temperature.

Moreover, for three different method calculated the amount of snow melting caused by different reasons, the empirical coefficients of C_T , C_R could be described with time varying and spatially distributed format allows the modelers calibrated the model over winter season as the snow properties change. For the parameter of C_E , it is a constant value for the entire model.

Overland Flow

The surface runoff could be produced by ponded water flow downhill towards the river system. This ponded water could be formed from remaining rainfall after considering the losses due to infiltration or evapotranspiration, river flow flooded over the banks and water exchange between surface and underground. Considering the water movement on catchment surface, the overflow function in MIKE SHE mainly requires topography and flow resistance as well as the losses by evapotranspiration, infiltration or other hydrological process along the flow path as the two main inputs in the calculation through Finite Different Method solving 2D St.Venant equations:

The mass conservation equation:

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x} (uh) + \frac{\partial}{\partial y} (vh) = i \quad \text{Equation 10}$$

And the momentum equation:

$$\begin{cases} S_{fx} = S_{0x} - \frac{\partial h}{\partial x} - \frac{u}{g} \frac{\partial u}{\partial x} - \frac{1}{g} \frac{\partial u}{\partial t} - \frac{qu}{gh} \\ S_{fy} = S_{0y} - \frac{\partial h}{\partial y} - \frac{v}{g} \frac{\partial v}{\partial y} - \frac{1}{g} \frac{\partial v}{\partial t} - \frac{qv}{gh} \end{cases} \quad \text{Equation 11}$$

where h is the flow depth (L). And u and v are the flow velocities in x- and y-direction. i is the net input into overland flow. S_f is the friction slope in x- and y-direction, and S_0 is the slope of ground surface.

However, to get the dynamic solution of the 2D St.venant equations is numerically challenging. In MIKE SHE calculation, it applied the simplification which neglected the momentum losses due to local and convective acceleration and lateral inflows perpendicular to the flow direction (DHI 2014). Then the complicity of the equations are significantly reduced, which well known as the diffusive wave approximation:

$$\begin{cases} S_{fx} = S_{0x} - \frac{\partial h}{\partial x} = -\frac{\partial z_g}{\partial x} - \frac{\partial h}{\partial x} = -\frac{\partial z}{\partial x} \\ S_{fy} = S_{0y} - \frac{\partial h}{\partial y} = -\frac{\partial z_g}{\partial y} - \frac{\partial h}{\partial y} = -\frac{\partial z}{\partial y} \end{cases} \quad (z = z_g + h) \quad \text{Equation 12}$$

The application of diffusive wave approximation allows the flow depth have significant variation between neighbouring calculation grids and backwater conditions to be simulated. However, in cases of simulating the water movement with low velocities and shallow water depth, it could lead to some numerical problems.

In MIKE SHE model the Strickler/Manning law is applied to describe the relationship between water depth and velocity, the final simplifying equations with Strickler coefficients K in both x- and y-direction are showed as follow:

$$\begin{cases} uh = K_x \left(-\frac{\partial z}{\partial x}\right)^{1/2} h^{5/3} \\ vh = K_y \left(-\frac{\partial z}{\partial y}\right)^{1/2} h^{5/3} \end{cases} \quad \text{Equation 13}$$

Besides the topography and Manning number required by the calculation, in the overland flow function of MIKE SHE, there are two extra parameters also asked by the modelling set up:

1. The detention storage – parameter control the amount of water flow over the ground surface. It means with the value defined by detention storage, the overland flow only occurs when the ponded water depth exceed this threshold.
2. The initial water depth – the amount of water already existed at the starting time of your simulation.

In addition, a function of semi-distributed overland flow which implemented with an empirical relationship among flow depth, surface elevation and surface roughness is also available in MIKE SHE model to describe the over land flow (Crawford and Linsley, 1966).

Channel Flow (Coupling with MIKE 11)

In theory, the MIKE SHE overland function has the capacity to accurately represent the channel flow as 2D surface flow when the topography input within fine resolution. However, in reality firstly, the high resolution topography data is often not available at least for the large catchment. Secondly, the simulation with high resolution input required longer running time. Therefore, in MIKE SHE model, the channel flow is simulated by coupling with MIKE 11 which assumed the channel flow has only one direction and applied implicit, finite different scheme for solving the 1D St.Venant equation representing the unsteady flow in the rivers and estuaries. With the coupling with MIKE 11, it support the MIKE SHE to have more accurate channel flow simulation and meanwhile the simulation of hydraulic structure such as weirs and gates impacts also become feasible.

The MIKE SHE/11 coupling is implemented via river links (Figure 27) located at the edges that separate adjacent grid cells. The river link network is created by MIKE SHE set up program, based on the coupling reaches. The entire river system is always including in the hydraulic model, but MIKE SHE will only exchange water with the coupling reaches (Vo, 2015). Besides, since these river links are defined on the edges between grid cells, details of MIKE 11 river geometry could be partly represent with MIKE SHE depending on the MIKE SHE resolution. Obviously, more refined MIKE SHE grid, the more accurately the river network can be reproduced.

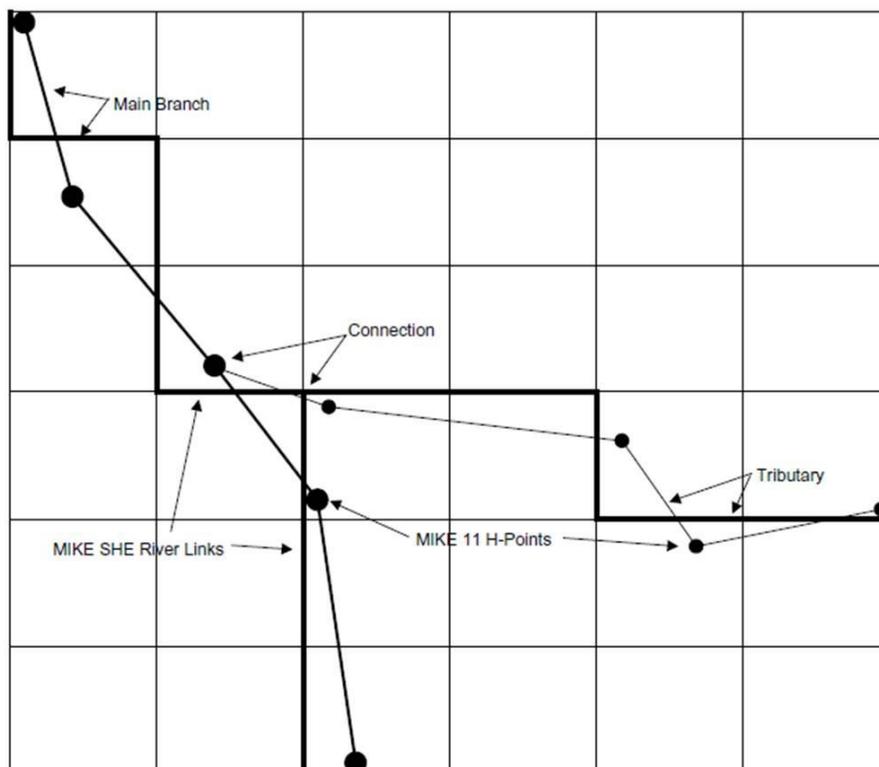


Figure 27: MIKE 11 Branches and H-points in a MIKE SHE Grid with River Links (DHI 2014).

The water exchanged between could also controlled by the function applied in the MIKE SHE/11 coupling process. When the flooding is not allowed, the MIKE 11 river water level at H-points are interpolated to the MIKE SHE river links, but only the exchange flow from overland and saturated zone in MIKE SHE will be considered in the calculation. When the flooding is allowed, via the Flood codes defined in the coupling process in MIKE SHE, the water level of MIKE 11 river is interpolated to specified MIKE SHE grid cells to determine if ponded water exists on the cell surface. If there is water existed, the unsaturated or saturated exchange flows are calculated with the ponded water level above the cell. The last case is the overbank spilling, which allowed the water from river channel to spill onto the MIKE SHE model as overland flow (Figure 28).

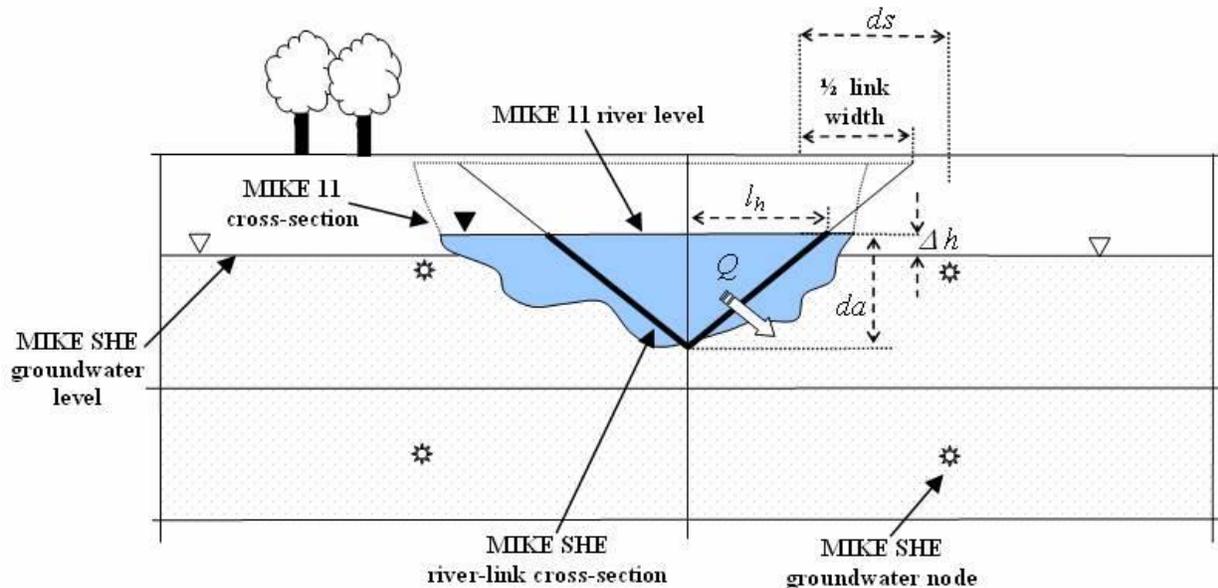


Figure 28: A typical simplified MIKE SHE river link cross-section compared to the equivalent MIKE 11 cross-section (DHI, 2014).

However, the coupling between MIKE SHE and MIKE 11 implemented via link reaches also has some limitations. For example, each MIKE SHE link could only be associated with one coupling reach. It may lead to problems in case of detailed drainage or river network with branches less than on half a cell width apart or when the length of MIKE 11 branch smaller than the MIKE SHE cell size. Moreover, in case of MIKE 11 cross section wider than the MIKE SHE cell size, then the river link cross section is reduced to the cell width. Therefore, it is necessary to active the Flood code option or Direct Overbank Spilling options to represent the water in the flood plain.

Unsaturated Zone Flow

The flow through unsaturated zone is one of the central processes in MIKE SHE and most modelling applications. Naturally, the unsaturated zone could be considered as a top shallow layer at the top soil which is heterogeneous and characterized by cyclic fluctuations in the soil moisture as water transferred among different hydrological processes like rainfall, evapotranspiration or infiltration. The flow in unsaturated zone could be expressed with both vertical and horizontal ways. However, since gravity plays the major role during infiltration

process, the flow could be considered primarily vertical. Therefore, in the MIKE SHE model simulation, the unsaturated flow is calculated only vertically in 1D and ignored the lateral movement. This assumption could be accepted in most of the cases but also limited in several cases such as on very steep hill slopes or in small scale catchment where the intensity of lateral and vertical flow roughly same.

The hydrological process in the unsaturated zone could be generally described as the water from rainfall fulfilling the top soil moisture with a part of water extracted by evapotranspiration and another for recharging the groundwater table. In the MIKE SHE model, there are three options available to represent the vertical water movement through the unsaturated zone in the catchment.

- Richards Equation

The full Richards equation which named after L.A. Richards who first used it in 1931, requires a tabular or functional relationship for both moisture-retention curve and effective conductivity, is considered as the default option in the MIKE SHE unsaturated zone model.

$$C \frac{\partial \Psi}{\partial t} = \frac{\partial}{\partial z} \left(K(\theta) \frac{\partial \Psi}{\partial z} \right) + \frac{\partial K(\theta)}{\partial z} - S \quad \text{Equation 14}$$

where, Ψ is the pressure head (L). θ is the volumetric soil moisture (-). $K(\theta)$ is the unsaturated hydraulic conductivity (LT^{-1}). z is the gravitational component (L). S and T are the root extraction (LT^{-1}) and time component (T^{-1}). C is the soil capacity (-).

The numerical solution in MIKE SHE for full Richards Equation is applied fully implicit formulation in which the space derivatives in the equation above described by their finite different analogues at time level $n+1$. And the values of $C(\theta)$ and $K(\theta)$ are referred to at time level $n+1/2$.

For an interior node, the implicit scheme yields the following discrete formulation of the vertical flow:

$$q_{J+1/2}^{n+1} = -K_{J+1/2}^{n+1/2} \left(\frac{\Psi_{J+1}^{n+1} - \Psi_J^{n+1}}{\Delta Z_{J+1}} + 1 \right) \quad \text{Equation 15}$$

where the subscript J and n are referred to the spatial increment and time increment (Figure 29). Then the discrete from previous equation could give:

$$C_J^{n+1} \frac{\Psi_J^{n+1} - \Psi_J^n}{\Delta t} = \left[K_{J+1/2}^{n+1/2} \left(\frac{\Psi_{J+1}^{n+1} - \Psi_J^{n+1}}{\Delta Z_{J+1}} \right) - K_{J-1/2}^{n+1/2} \left(\frac{\Psi_J^{n+1} - \Psi_{J-1}^{n+1}}{\Delta Z} \right) \right] \frac{1}{1/2(\Delta Z_{J+1} + \Delta Z_J)} - S_J^{n+1} \quad \text{Equation 16}$$

With soil property K described as the arithmetic mean at centred space:

$$\begin{cases} K_{J+1/2}^{n+1/2} = \frac{K_{J+1}^{n+1/2} + K_J^{n+1/2}}{2} \\ K_{J-1/2}^{n+1/2} = \frac{K_J^{n+1/2} + K_{J-1}^{n+1/2}}{2} \end{cases} \quad \text{Equation 17}$$

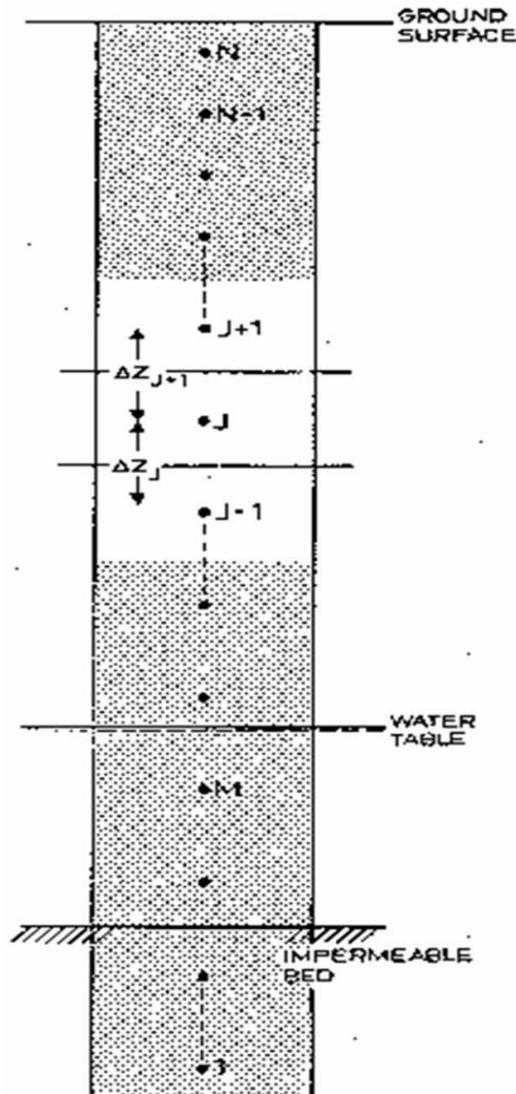


Figure 29: Vertical Discretization in the Unsaturated Zone (DHI 2014).

In addition, this solution techniques explained above has been found to eliminate stability and convergence problems arising from the non-linearity of the soil properties.

- Gravity Flow

In practice, the simulation through Richards Equation requires longer running time. In MIKE SHE model, the function of Gravity Flow could be applied to solve that issue. Based on the assumption that the gravity flow is the primary flow direction in the unsaturated zone, the impacts of pressure head term to vertical flow is ignored in this function:

$$\frac{\partial \theta}{\partial t} = \frac{\partial q}{\partial z} - S(z) \quad \text{Equation 18}$$

The equation applied in Gravity Flow function in MIKE SHE is solved explicitly from the top of soil column downward. From the ground surface, the water depth on the overland is hypothesized as the available water amount for infiltration. Then the infiltration is controlled by the information of conductivity-saturation relationship input into the model by the hydrological modelers.

Compared to the full Richards equation, the simulation based on gravity flow runs much faster and more computationally stable. It is widely applied for coarse soil which has small capillary pressure or for specially objective more focused on evapotranspiration and infiltration process in the study area as the dynamics in the unsaturated zone is neglected.

- Two layer Water Balance

As we mentioned before in the evapotranspiration section, the two layer water balance function in MIKE SHE is an alternative to the more complex unsaturated flow process coupled to the Kristensen and Jensen model for describing evapotranspiration (DHI, 2014). And main purpose of this function is to calculate actual evapotranspiration and the amount of water that recharges the saturated zone. Hence, it divided the unsaturated zone into two parts, upper zone and lower zone (Figure 30). The upper layer could be defined by the model from the ground surface to the ET extinction depth input by the modeler.

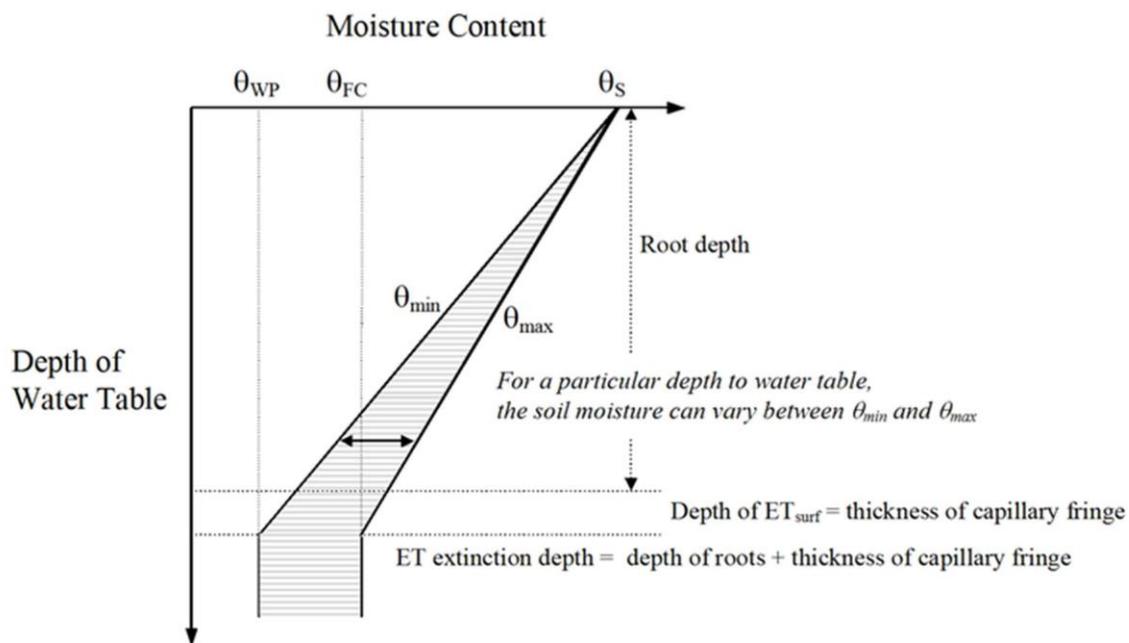


Figure 30: Allowable range for soil moisture in the upper ET layer as a function of the depth to the water table (DHI, 2014).

During the simulation process, the thickness of the upper unsaturated zone at different time step is changed whenever the root depth or water table changed. When the water table is at the ground surface, then the thickness of the upper zone is zero. If the water table is calculated below the ET extinction depth, the lower zone is added in the calculation from the bottom of the upper zone to

the water table. And when the water table is above the ET extinction depth, the thickness of the lower zone is zero.

In addition, due to the storage of the unsaturated zone is ignored, the two layer water balance function in MIKE SHE does not take into account the infiltration process with the assumption of all infiltrated water recharging immediately to saturated zone.

In summary, DHI releases comments as:

- The full Richards equation method is the most computationally intensive but also the most accurate when the unsaturated flow is dynamic.
- The gravity flow method could provide a suitable solution for assessing the time varying recharge to the groundwater table based on actual precipitation and evapotranspiration and no dynamic existed.
- The two layer water balance method is more accepted when the water table is shallow and groundwater recharge is primarily affected by the evapotranspiration.

Moreover, in the MIKE SHE model the flow through macropores which defined as a secondary, additional continuous pore domain in the unsaturated zone could also be represented by either simple bypass flow or full macropore flow.

In the simple bypass flow function, it assumed the infiltration water could be divided into two parts, with the one through soil matrix and another routed directly to the groundwater table so called bypass flow. The bypass flow is simulated as a fraction of the next rainfall at each calculation time step for unsaturated zone. The actual bypass fraction is a function of a user-specified maximum fraction and the actual water content of the unsaturated zone (DHI, 2014).

However, in the full macropore flow method, it simulates the macropore flow initiated when the capillary head in the micropore domain is higher than a threshold matrix pressure head; corresponding to the minimum pore size that is considered as belonging to the macropore domain. The water flow in this case is assumed to be laminar and not influenced by capillarity, corresponding to gravitational flow.

Due to the close contact between unsaturated and saturated zone, the interaction between those components in MIKE SHE is solved by an iterative mass balance procedure. It ensures a realistic description of water table fluctuations in situation with shallow soils. This coupling process is not solved by a single matrix with an implicit flux coupling. A great advantage of this kind of coupling method is that, as results of they are possible to run with different time steps, it helps to optimize computational time at each other's.

Groundwater Flow (Saturated Zone Flow)

The groundwater process is one of the most significant hydrological processes in most of the catchment water system all over the world. It could be the main resources recharge the stream flow during the dry season. Furthermore, the groundwater process could have numerous

interactions among other hydrological processes through different ways. To integrated consider this process in the hydrological process is significant necessary and effective to reduce the moderm uncertainty. In MIKE SH, due to the complicity of the model function integrated in the modelling system, the groundwater process is represented by the simulation of saturated zone with the methods of either Finite Different Method or Linear Reservoir Method.

- Finite Different Method

In this method, the water flow in saturated zone is generally simulation through 3D Darcy equation:

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) - Q = S \frac{\partial h}{\partial t} \quad \text{Equation 19}$$

where K_{xx} , K_{yy} and K_{zz} are the hydraulic conductivity in x-, y- and z-direction (LT^{-1}). h is the hydraulic head (L) and Q presents the source/sink terms. S is the specific storage coefficient (-).

The equation is solved by an iterative implicit finite different technique so call Finite Different Method in MIKE SHE model set up. And MIKE SHE supports two kinds of solution/techniques including Successive Over-Relaxation (SOR) technique and Preconditioned Conjugate Gradient (PCG) technique. The data requirements of implementing the Finite Different Method is varied among the definition of saturated area (Lower/Upper level and Horizontal extent), hydraulic conductivity (in horizontal and vertical directions), specific yield, initial and boundary conditions and drainage. Despite the simulation with Finite Different Method in saturated zone of MIKE SHE could produce more accurate results, due to the large amount of data requirement, several parameters input in the model have to be estimated by some hypothesizes or under special conditions, the uncertainty of the model simulation and the difficulty for setting up the model could be strongly increased.

- Linear Reservoir Method

To simplify the computational process and its data requirements, the lumped conceptual approach so call Linear Reservoir Method is also possible in the MIKE SHE saturated zone simulation. It based on the relation between storage and time as follows:

$$S = kQ \quad \text{Equation 20}$$

where S is the storage in the reservoir (L), k is the time constant (T) and Q is the outflow from reservoir (LT^{-1}).

To calculate the groundwater flow, this method divided the study area into several sub-catchments as individual reservoirs (Figure 31). Within each sub-catchment, the saturated zone is represented by a series of interdependent, shallow interflow reservoirs, plus a number of separate, deep groundwater reservoirs that contribute to stream base flow.

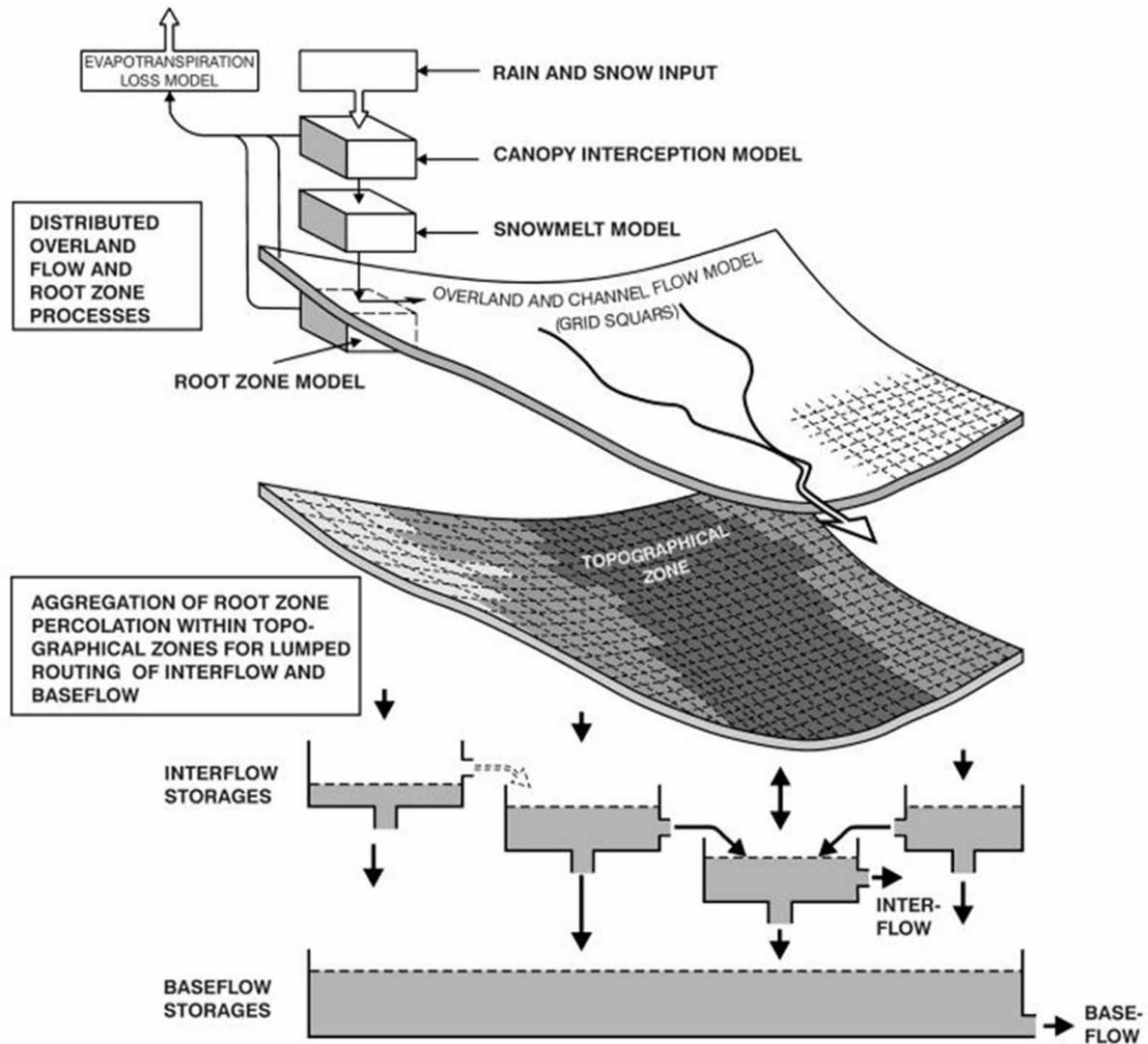


Figure 31: Model Structure for MIKE SHE with the linear reservoir module for the saturated zone (DHI, 2014).

Moreover, the flow exchanged between each sub-catchment (reservoirs) could be described as in Figure 32. Therefore, the input data is simplified to only the map information about division of the model area into sub-catchment, interflow and base flow reservoirs.

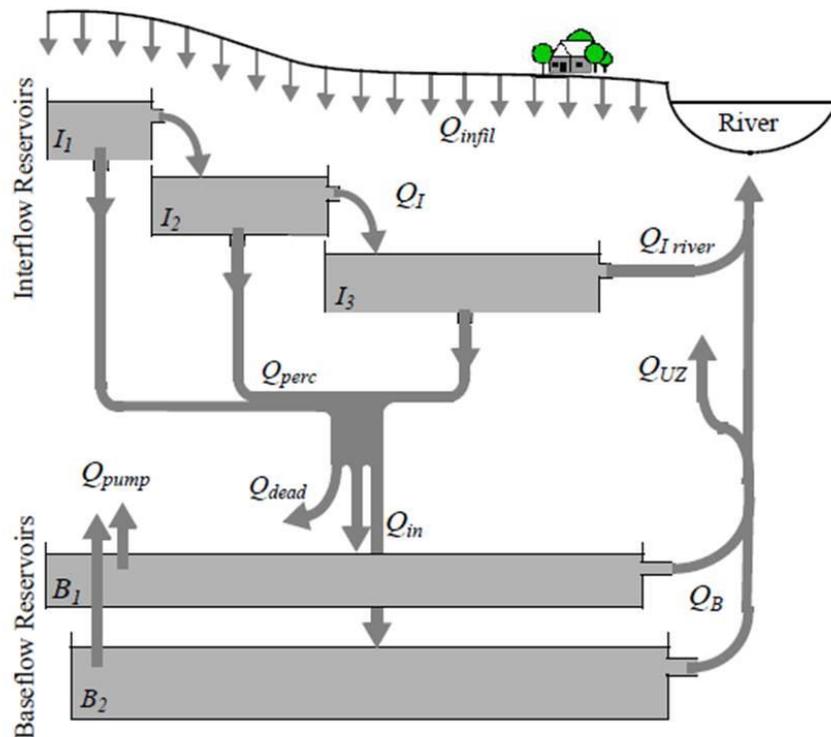


Figure 32: Schematic flow diagram for the Sub-catchment-based, linear reservoir flow module (DHI, 2014).

The Linear Reservoir Method in MIKE SHE saturated zone simulation is proposed to provide a reliable, efficient instrument in the following fields of application: assessment of water balance and simulation of runoff for ungauged catchment, prediction of hydrological effects on land use changes, flood prediction or long term simulation such as climate changes assessment.

3.3.3 Performances of MIKE SHE

In the design of AquaVar EDSS, the hydrological modelling assessment as the starting point of the modelling process plays significant role in the integrated modelling system. The model selected in this part should have excellent performance to produce detailed and accreted representation of the complicated catchment hydrological system. After a long discussion and comparison, the MIKE SHE model which has been widely applied in many countries around the world by organizations ranging from universities and research centers to consulting engineers companies (Refsgaard et al., 1997) was selected to complete our tasks.

As we introduced before, the MIKE SHE model is able to integrated simulation numerous hydrological processes interacted in a catchment system. It has been applied as the main hydro-informatics tool to answer the questions about water resources management and deal with the problems related to environmental and ecological components between surface and ground water. In this section, several examples of MIKE SHE applications classified into three categories including applied topography, catchment scale and different objectives were reviewed to prove its modelling flexibility.

Morphological diversity

The MIKE SHE as a deterministic distributed hydrological model has been applied in the simulation of various topographical types (McMichael et al., 2006; Sahoo et al., 2006; Thompson et al., 2004; Zhang et al., 2008). In 2004, Thompson et al. applied MIKE SHE coupling with MIKE 11 to simulate the hydrological system in Elmley Marshes Catchment in UK. With the remarkable results in flood simulation and representation of water exchange among surface, underground and channel, it demonstrated that through the coupling with MIKE 11, the MIKE SHE modelling system is able to represent the various hydrological components in a wetland environment. Sahoo et al. (2006) and Zhang et al. (2008) respectively applied the MIKE SHE model to simulate the stream flow process at catchment in USA and China. The impressive modelling results from their studies proved the capacity of MIKE SHE to describe the hydrological factor in mountain region. Besides, in 2008, McMichael et al, also succeed to apply MIKE SHE model in semi-arid area hydrological simulation. With various cases around the world, the MIKE SHE model has strong ability for represent the catchment hydrological characteristics with numerous terrains in the study area.

Catchment scale

Operating on a flexible mechanism, the simulation resolution in MIKE SHE (cell size) could be changed flexible to adapt with real situation (Vo, 2015). The algorithm does not limit the modelling scale of study area. Indeed, the MIKE SHE has been operated in wide range of scale from small size to great size (Andersen et al., 2001; Geflan, 2010; Hundecha et al., 2002; Ma et al., 2013; Sahoo et al., 2006; Zhang et al., 2008). There are various cases of MIKE SHE applying in small size catchment, such as we mentioned before, Sahoo et al., (2006) and Zhang et al., (2008) respectively applied the MIKE SHE model to simulate the stream flow process at catchment in USA and China. Both of those two catchments have the control area less than 100 km². In contrast, for the large scale catchment, with flexible computation resolution, MIKE SHE is expected as an effective solution for overcoming the uncertainty problems often occurred in large catchment. The succeed application could be found among the studies of Senegal River Basin (375,000km²) (Andersen et al., 2001), Kaidu Watershed (19,000km²) (Ma et al., 2013) and Seim River (7,460km²) (Gelfan, 2010). Moreover, due to the special characteristics of MIKE SHE which is deterministic distributed, it is also widely to be used for overcoming the data shortage issues which often happened in large scale catchment and study area located at developing countries (Hundecha et al., 2002; Ma et al., 2013).

Simulation Objectives

The model of MIKE SHE has also been widely applied to achieve various purposes. Such as:

- Snow melting simulation

Taking the advantage of integrated representing the interaction among different hydrological processes, the MIKE SHE could also be used for simulating individual process such as snow melting process. In 2013, the case study made by Ma et al. at northwest China selected the MIKE SHE model as the main hydro-informatics tool to assess the snow melting impacts on the catchment hydrological system. In conclusion, they declared that is it necessary to integrate as

much as possible the hydrological components into the model simulation for assessing the snow melting flow in the catchment system and MIKE SHE model has the capacity to achieve this task. Besides, [Gelfan \(2010\)](#) also succeed to use MIKE SHE for representing the extreme snow melting flood in Seim River, Russia which confirm the ability of snow melting function in the model.

- Flood analysis

In MIKE SHE model, the channel and flood plain are represented by coupling with MIKE 11 and overland function in the model. It has the opportunity to simulate the flood event especially the overbank flow from channel to the flood plain. Moreover, due to the overland calculation in MIKE SHE is implemented through cell by cell, it is also able to produce the 2D flood map in the simulation. The succeed application could be found in the study of [Sen and Niedzielski \(2010\)](#) applied MIKE SHE for evaluating the flood phenomenon at the second largest river of Poland. Also, [Nielsen \(2006\)](#) utilized MIKE SHE model to deal with the flood plain inundation and urban drainage assessment in South East Asia.

- Assessment of land use changes

As we mentioned before, in EDSS, the modelling selected in the system should be sensitive to response the changes of any physical parameters such as land use. [Oogathoo \(2006\)](#) made a series of comparison among different hydrological models then selected MIKE SHE to evaluate the impacts of design scenarios with changing land use percentages on catchment hydrological system at Canagagigue Creek Catchment, Canada. Consequently, the simulation of MIKE SHE well performed in represent the stream flow variation related to the land use changes. Similar study could also be found in study of [Wijesekara et al. \(2014\)](#) in Elbow River, Canada.

- Groundwater analysis

By accounting mostly hydrological components and especially possessing a good algorithm for ground water modelling; MIKE SHE has been highlighted as one of the best modelling choices to simulate the ground water movement especially the exchange between stream and groundwater flow. One succeed study of MIKE SHE application for assessing various groundwater management plans could be found in the study of [Demetriou and Punthakey \(1998\)](#) in Australia. In their study, to solve the problems related to rising of groundwater table and salinization, the MIKE SHE model was selected as the main modelling tool to produce integrated view of the catchment situation. Moreover, due to the efficient coupling process between MIKE SHE and MIKE 11, the surface and underground exchange flow could be represent in detail with MIKE SHE simulation. One succeed study could be found in the study of [Liu et al. \(2007\)](#), who used MIKE SHE to assess the relation between surface and ground water in Tarim Basin, China. Besides those two, many studies of MIKE SHE application in groundwater assessment declared that this modelling tool could be considered as an efficient way to integrated analyze the groundwater dynamics and their impacts on other hydrological processes or the whole catchment environmental system. Moreover, the model also has the capacity to dealing with the pollution problems happened in the aquifers or other ecological risks at the interesting underground areas. Such as the study of [Thorsen et al. \(2001\)](#), they selected the MIKE SHE to simulate the nitrate

leaching to aquifer at catchment scale in Karup catchment, Denmark. In addition, with the characteristics of deterministic model, MIKE SHE could also be used for determining the soil properties like [Christiaens and Feyen \(2001\)](#) used MIKE SHE to describe the soil properties at Ohebach catchment, Germany.

- Evapotranspiration analysis

The evapotranspiration process is one of the main hydrological process having impacts on many main hydrological processes from rainfall-runoff to soil water movement. There are numerous succeed cases of MIKE SHE simulating the evapotranspiration process in catchment hydrological cycle. One example could be found in the study of [Vázquez and Feyen \(2003\)](#), who assess the impacts of potential evapotranspiration on hydrological system at a medium size watershed. Similar modelling process succeed in large catchment could be found in the study of [Vu et al. \(2008\)](#), in Vietnam.

- Estimation of climate change impacts

Climate change is expected to affect most of hydrological factors (e.g. precipitation, temperature, evapotranspiration, etc.) in catchment environmental system. To evaluate the impacts of climate change on the stream flow requires the selected modelling tool has the ability to simulate the hydrological components as much as possible. Moreover, the selected model satisfying the above requirement is also expected to have acceptable prediction accuracy. Therefore, the MIKE SHE is widely applied for achieve the tasks related to climate changes assessment. [Mernild et al. \(2008\)](#) applied the MIKE SHE in estimation of varied tendency of intra- and inter- annual discharge from snow and glaciated Zackenberg River drainage basin (512 km², around 20% area covered by glacier) in northeast Greenland. Comparison between present situation and the model simulation of future scenarios (2071-2100), indicates the increasing trend of snow melting and its impacts of the stream flow. Another study of similar topic could be found by [Bosson et al. \(2012\)](#), who applied the MIKE SHE to simulate the terrestrial hydrology associated with various climate conditions over Forsmark catchment, Sweden. Moreover, among different hydro-informatics modeling tool working in the climate change assessment, [Vansteenkiste et al. \(2013\)](#) made a comparison between MIKE SHE WetSpa with a case study of climate change impacts on medium size catchment hydrological system. The modelling results showed that the decrease of low flow simulated by WetSpa was around two times higher than MIKE SHE simulation as results of the ground water component neglected in WetSpa model. On one hand, the authors indicated the importance of counting the groundwater impacts in the climate change model. On another hand, they confirm the good performance of MIKE SHE in climate change estimation.

3.4. Characteristics of Var Catchment

The Var catchment is located at southeast part of France with around 2800km² control area. It is the largest catchment at French Mediterranean Region also well known as the famous vacation resort named with Côte d'Azur often known in English as the French Riviera. The catchment includes two departments Alpes-Maritimes (06) and Alpes-de-Haute-Provence (04) with many cities and villages inside such as Saint-Martin-Vésubie, Carros, Saint-Laurent-du-Var and the fifth biggest city in France, NICE.

Since beginning of 19th century, human activities have significantly increased in Var catchment and started to modify the regional topography especially at the area of Var downstream part named with Lower Var Valley where the NICE city is located. Moreover, due to the growth of local population (Figure 33) and the increase of tourists, many cities in Var catchment has to extend their urban area, the need of land has become a rigid demand.

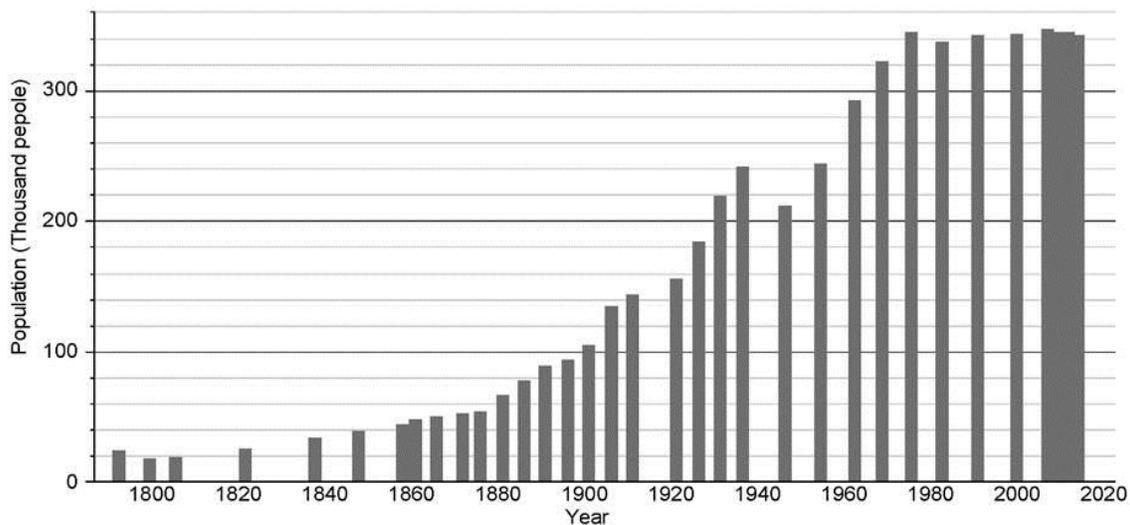


Figure 33: Demographic evolution of NICE since 19th century (National Institute of Statistics and Economic Studies of France).

Recently, including the drinking water supply for nearly 300,000 residents of NICE, 100,000 inhabitants at other cities and villages in Var catchment plus around 400,000 tourists coming every year (INSEE, 2008) and other agriculture and industrial uses, all the social activities are supported by the water resources taken from stream flow and groundwater in Var catchment (Du et al., 2016; Potot et al., 2012). Therefore, the fluctuation of catchment hydrological factors has significant impacts on the social development. To optimization the water resources management plan and to reduce the damages caused by natural disasters, it is necessary to have an integrated view of the complicated hydrological processes in the whole catchment scale.

3.4.1 Geological characteristics of Var Catchment

The Var catchment is characterized by a conspicuous variation of elevation from 0 m (sea level) at the outlet of the catchment up to over 3000m at the summits of the Southern Alps Mountain (Figure 34). The black lines presented in the figure divided the Var River Basin into 5 sub-

catchments named Estéron, UpVar, Tinée, Vésubie, and LowVar. The Var River starts at the spring originated from the south of mountain pass of Cayolle and flows through a distance nearly 114km to reach the outlet between NICE and Saint-Laurent du- Var at Mediterranean sea. The elevation variation in Var River is from 1790m down to the sea level, which forms a steep streamline slope of 1.57% in average.

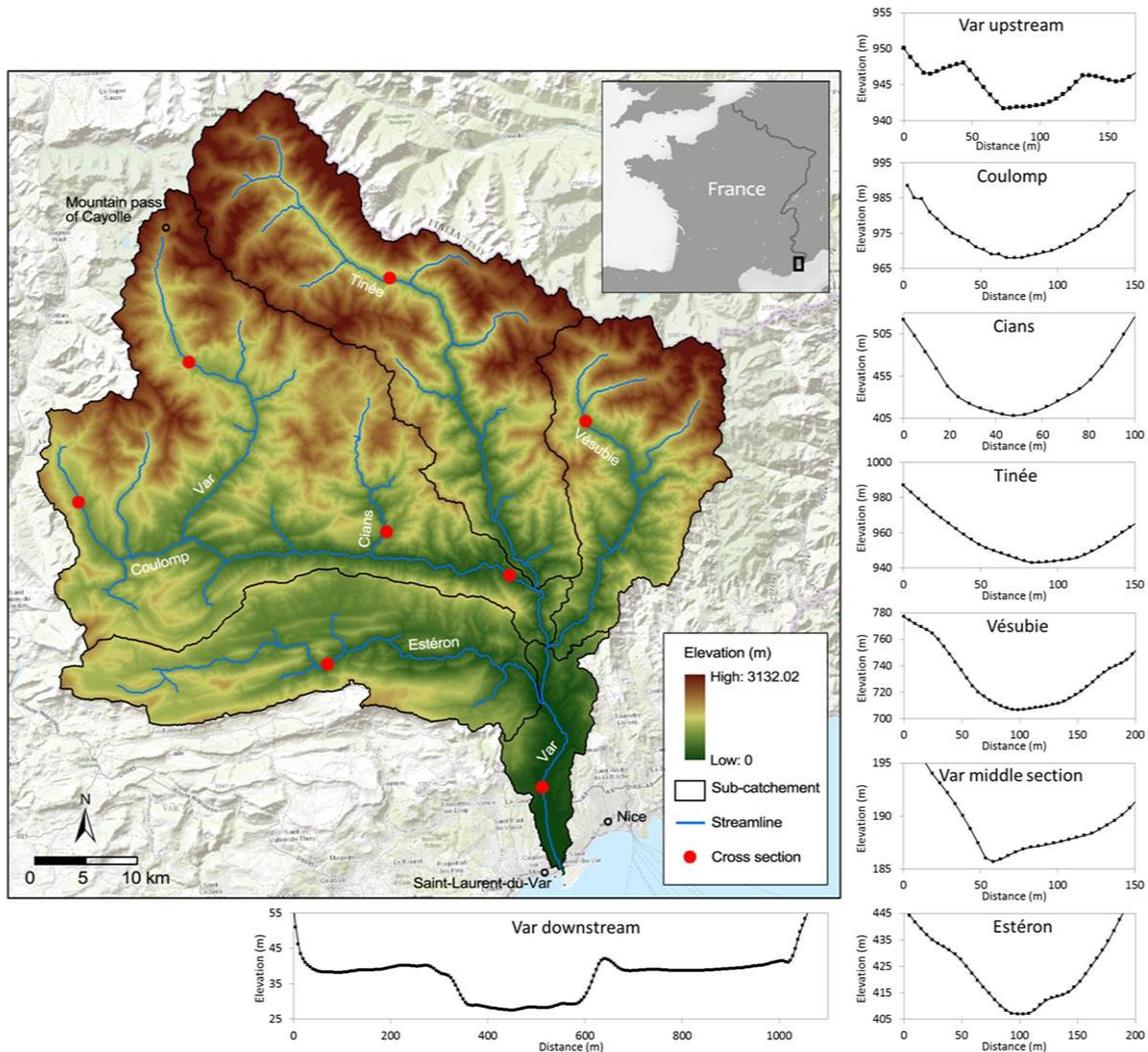


Figure 34: Geography of Var catchment and the locations of numerous profiles (Source: 5m × 5M DEM from Métropole NICE Côte D’azur).

The Var River as the longest river in the catchment receives water resources mainly from 5 tributaries: Coulomp (20km), Cians (25km), Tinée (75km), Vésubie (48km) and Estéron (67km). All the streams flows in Var catchment could be characterized as typical mountain stream with “V” shaped cross sections formed by natural erosion effect.

The Var catchment is also well known with its steep surface slope (in average 26.46°) which mainly contributed by the upper and middle parts sub-catchments such as Tinée sub basin located at the upper part and Vésubie sub basin in the middle (Table 5). Comparison among all the sub basins, the Low Var sub-catchment located at the downstream parts showed gentler and more flat

ground surface (average slope 19.90°), especially the last 27 km of the Var river started from the junction between Var and Vésubie ended at the river mouth to the Mediterranean sea (Figure 35). Different to the narrow mountain streams with the width in range of 10 to 50 m, the channel width in the Low Var has grown up to 100–300 m with more than 1 km flood plain extension. The large flood plain area in Low Var Valley gives the opportunity to the local cities such as NICE to satisfy its need of urban development. But, considering more than 2/3 parts of the catchment having steep surface slope, the rainfall concentration time in Var catchment is relatively high (less than 1 day). Consequently the cities located at the downstream often suffered flood disasters with high intensity rainfall occurring in mountain area.

Table 5: Summary of sub-catchments' geographical information in Var catchment (Source: 25m × 25m DEM from Metropole NICE Côte D'azur).

Sub-catchment	Area (km ²)	Elevation Range (m)	Maximum Slope (°)	Average Slope (°)	Slope Standard Deviation (-)
UpVar	1082.77	117.62 - 2886.20	85.49	26.98	11.71
Tinée	741.96	180.41 - 3027.22	82.33	30.39	11.50
Vésubie	392.36	132.43 - 3132.07	79.98	11.30	
Estéron	446.73	180.41 - 3027.22	84.72	23.80	11.09
LowVar	150.76	0 - 1539.53	82.32	19.90	12.79

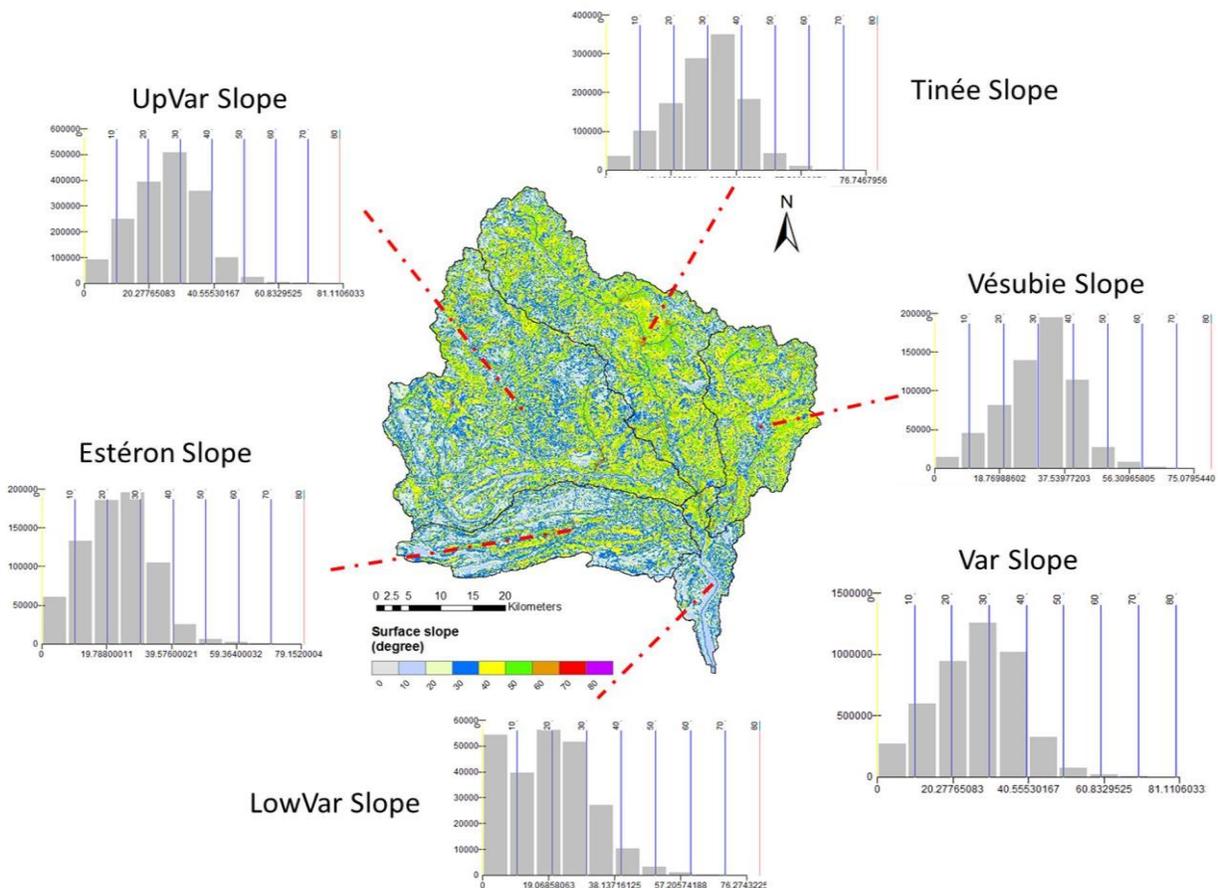


Figure 35: Slope distribution in Var catchment (Source: 25m × 25m DEM from Metropole NICE Côte D'azur).

In Var catchment, existing types of land use could be summarized into 5 main categories: forest, pasture, open area with less vegetation, artificial area, and water bodies (Figure 36) (Table 6). The top three land use types in Var catchment are Forest (47.80%), Pasture (31.61%) and Open Space with less vegetation (16.88%). There are some villages located in the upper and middle parts of the catchment such as Saint-Martin-Vésubie. But compared to the urban area contributed by NICE city in the LowVar catchment, the impacts of artificial area in other sub-catchment are negligible.

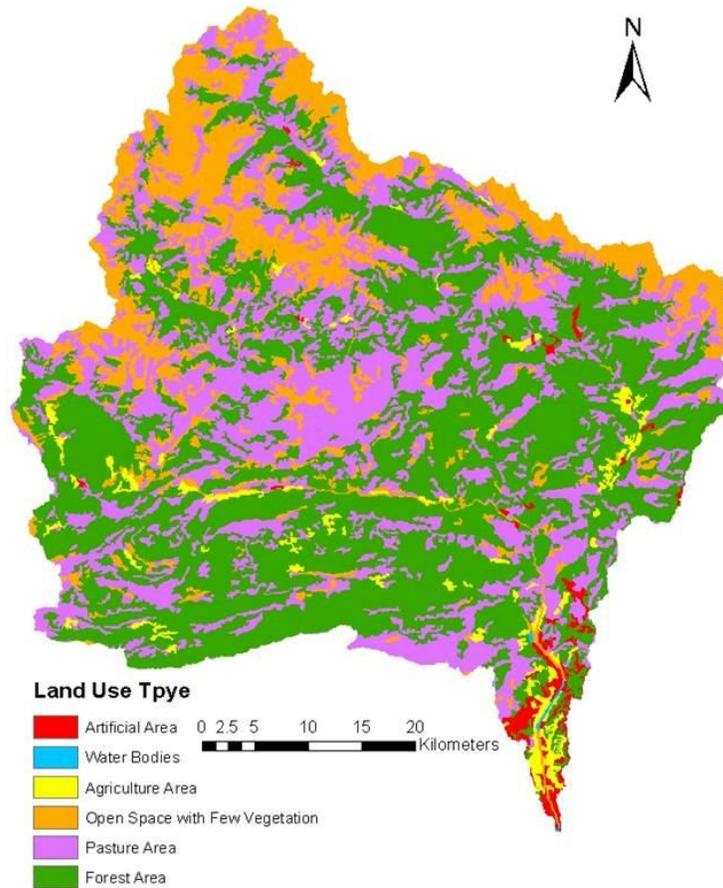


Figure 36: Land use distribution in Var catchment (Source: 100m × 100m land use map from European Environment Agency).

Table 6: Land use information of different sub-catchments and Var catchment (Source: 100m × 100m land use map from European Environment Agency).

Catchment	Forest (km ²)	Pasture (km ²)	Agriculture (km ²)	Open Space (km ²)	Artificial Area (km ²)	Water Bodies (km ²)
UpVar	472.35	385.9	18.96	204.06	1.44	0
Tinée	311.69	221.34	4.26	202.39	2.07	0.29
Vésubie	208.09	118.22	10.13	51.64	4.55	0
Estéron	301.13	123.94	11.52	10.07	0	0
LowVar	53.30	41.02	21.83	7.48	27.68	1.78
Var	1346.56	890.42	66.70	475.64	35.74	2.07

The geological characteristics of Var catchment shows strong heterogeneity consisting in (1) Magmatic and metamorphic rocks located at north-eastern edge of the basin; (2) Continental sediments consist mainly as clays and fine micas in the north-western part; (3) Marine sediments consist in marl-limestone and sandstones in central and western part; (4) Miocene molasses, marls and limestones are found at the south part; (5) and at the mouth of the catchment, about 700m thick conglomerates containing the pebbles from rocks outcropping in the whole basin (Figure 37) (Potot et al., 2012).

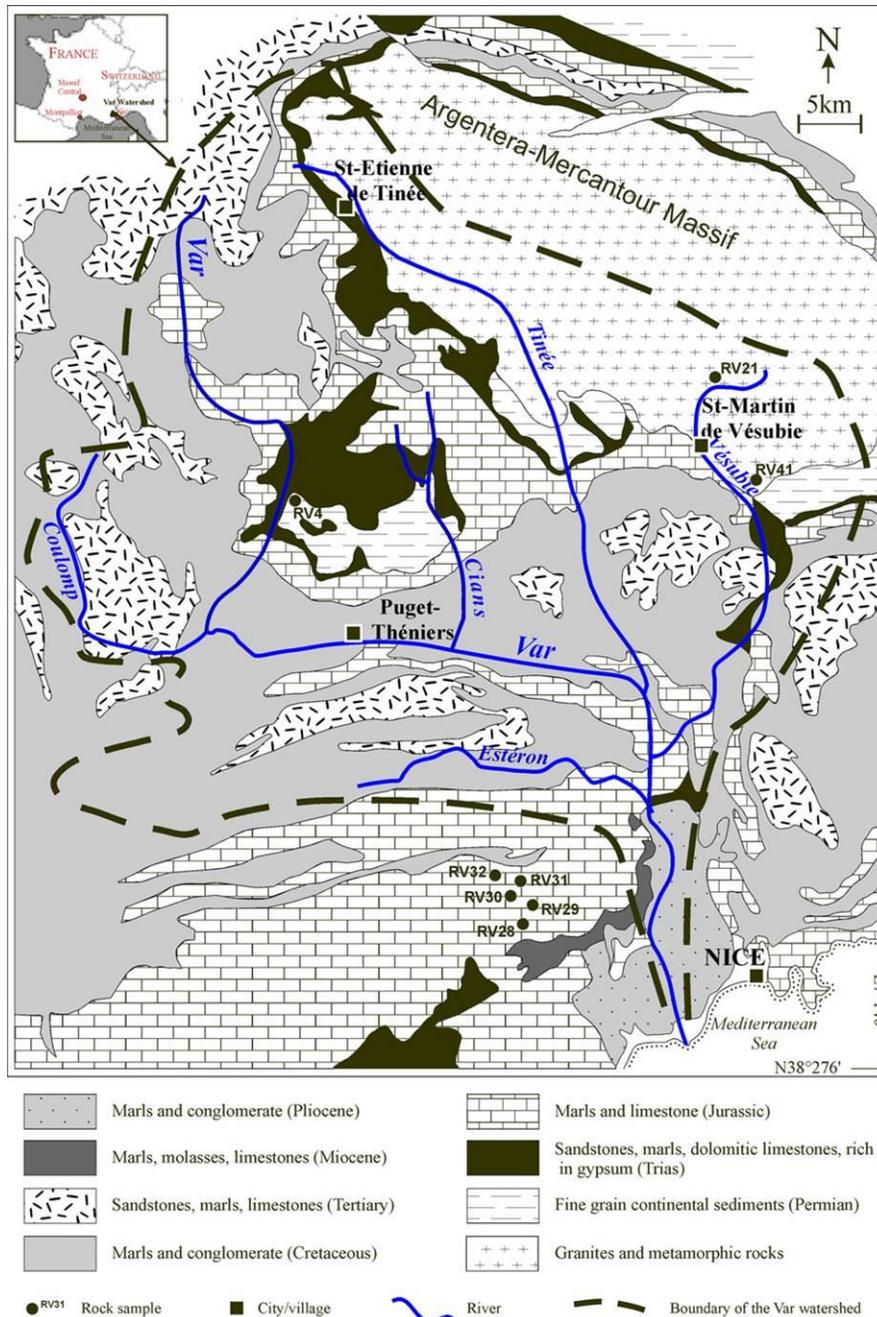


Figure 37: Simplified geological map of catchment area of the Var River and location of some analyzed rocks samples (Potot et al., 2012).

At lower part of Var catchment, due to the urbanization process, the morphology of the river has been reshaped and the river bed is strictly narrowed by artificial embankments made of rubbles and concrete blocks. It causes significant increase of flow velocity at those places, thus erosions are gradually happened and observed in many places along the river.

Before 1984, the sand and gravels from alluvial sediment of Var catchment were commonly used as main material source for concrete industry. However, due to the strong connection between river and its aquifer, with the revelation of river bed erosion, groundwater depletion has been reported (Souriguère, 2003). Since 1967, the most severe shortage of groundwater occurred in lower Var valley, the groundwater table was decreased by 8 m below its static level. In order to maintain the groundwater level, started at 1971, some artificial weirs were built on the river bed to reduce the erosion process. From 1986, a ministerial decree had been approved to forbid the extraction of sediment either in the valley or in the river bed and 11 weirs had been constructed in different sections of the river (Figure 38).

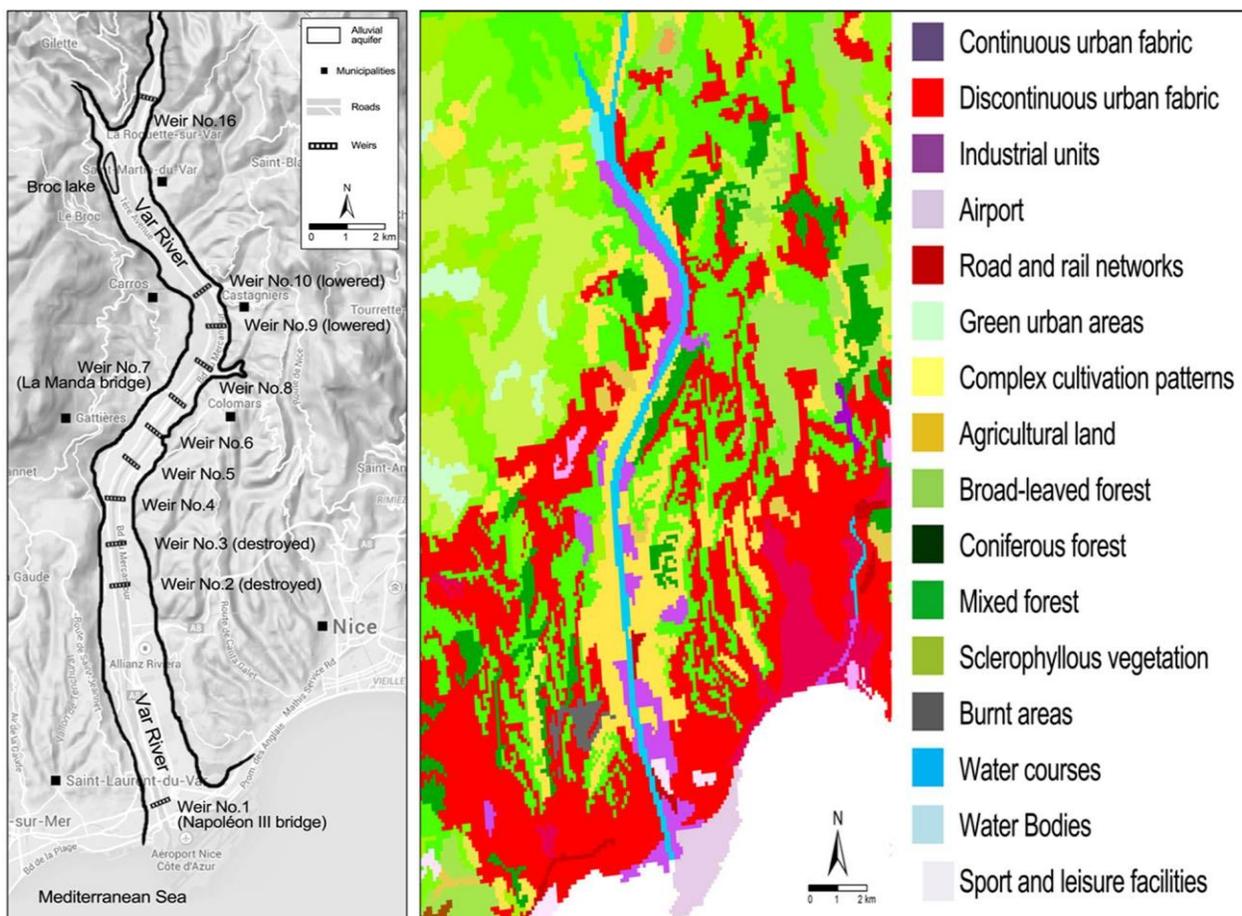


Figure 38: Weirs and land use distribution in low Var valley.

The construction on lower Var valley flood plain has never been stopped since 1960s. Several significant morphology changes could be found from 1970s when municipality of Carros started to create an industrial zone on the right bank of Lower Var Valley, which made around 200 hectares area of flood plain become high imperviousness land. Also, at same period, the

extension of Saint-Laurent-du-Var replaced around 50 hectares flood plain area by industrial and commercial zone. Recently, the estuary of the valley is highly urbanized with administrative centre of department Alpes-Maritimes (06), national interest market, airport (third largest in France) and a commercial centre (Cap 3000).

3.4.2 Meteorological characteristics of Var Catchment

In AquaVar project, all meteorological information is supported by the national meteorology service in France – Météo-France. Since the first meteorological measurement was set up in Var catchment in 1928, until now, there are 81 stations built in the catchment to collect the meteorological information such as precipitation. However, due to some reasons such as destruction of natural disasters or budget limitations, recently, only 16 stations in total still exist in the Var catchment and producing the real time precipitation information with daily or hourly time interval (Table 7).

Table 7: Rainfall gauging stations distributed in Var catchment (Source: Météo-France).

Stations	Number	Basin	Daily Records	Hourly Records	Elevation
ENTREVAUX	4076001	UpVar	✓	✗	475 m
MEAILLES	4115001	UpVar	✓	✓	1090 m
ASCROS	6005001	Estéron	✓	✓	1173 m
ASPREMONT	6006001	LowVar	✓	✗	380 m
BEUIL-OBS	6016001	UpVar	✓	✗	1460 m
CARROS	6033002	LowVar	✓	✓	78 m
COURSEGOULES	6050002	Estéron	✓	✓	998 m
LANTOSQUE	6074005	Vésubie	✓	✓	550 m
PEIRA CAVA	6077006	Vésubie	✓	✗	1443 m
LE MAS	6081001	Estéron	✓	✗	1525 m
NICE	6088001	LowVar	✓	✓	2 m
PEONE	6094002	UpVar	✓	✓	1784 m
RIMPLAS	6102001	Tinée	✓	✓	1130 m
ST ETIENNE DE TINEE	6120004	Tinée	✓	✓	1150 m
ST MARTIN D'ENTRAUNES	6125001	UpVar	✓	✓	1642 m
ST-MARTIN-DE-VESUBIE	6127001	Vésubie	✓	✗	994 m

The elevation variation of meteorological stations in Var catchment is in the range from 2 m above the sea level (NICE airport) up to 1784 m (mountain area) which covered 75.18% of total area. The density of installation at middle and lower part of Var catchment is much higher than the mountainous area, due to the agglomeration of the population in those places. For the summits of mountains and the area whose elevation beyond the range (24.82%), there is no meteorological information available (Figure 39).

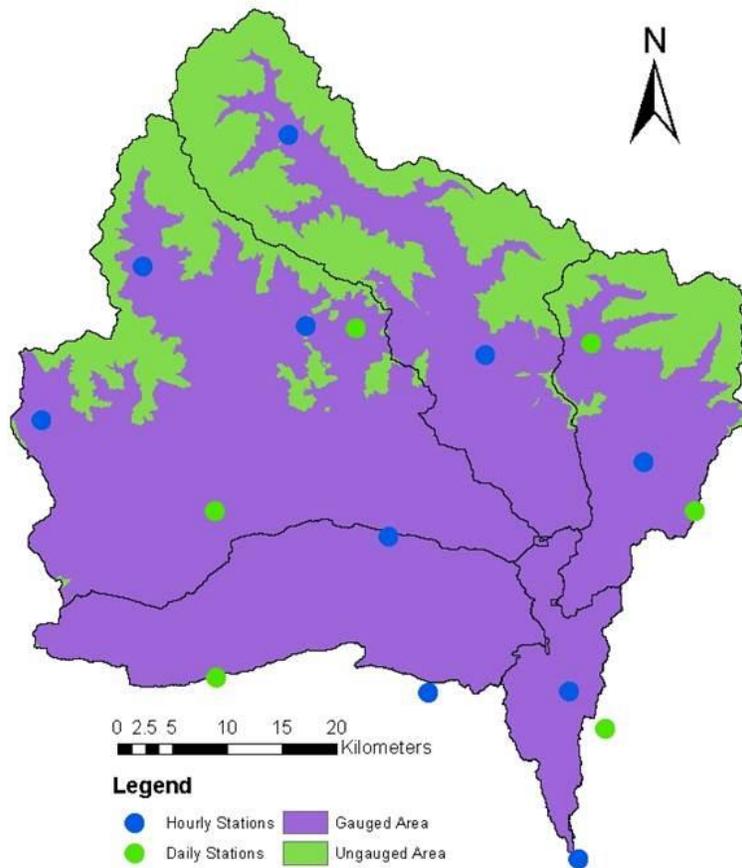


Figure 39: Distribution of rainfall gauging stations and their control area in Var catchment (Sources: Météo-France).

The meteorological characteristic of Var catchment could be identified with typical Mediterranean climate with rainy winters and dry summers. The annual precipitation in Var catchment could achieve nearly 1154 mm/year with 96 mm/month in average. However, the rainfall temporal distribution in Var catchment shows significantly inhomogeneous phenomenon (Figure 40). The total rainfall amount in the driest period from July to September takes less than 15% of annual rainfall. In contrast, during the rainy season, the Var catchment may receive more than 16% of annual total rainfall in only one month (e.g. November). The rainfall difference between driest and rainiest months could be more than 80%.

Moreover, based on the average monthly rainfall in Var catchment (red line in the figure), the rainy period of Var catchment could be divided into two main parts, named with spring rainy season (from April to May) and winter rainy season (from October to January). Obviously, compared to the spring rainy season, either the total amount or the intensity of rainfall is significantly higher in winter time. It could be considered as the main cause of flash flood disaster occurring at the downstream part of the catchment.

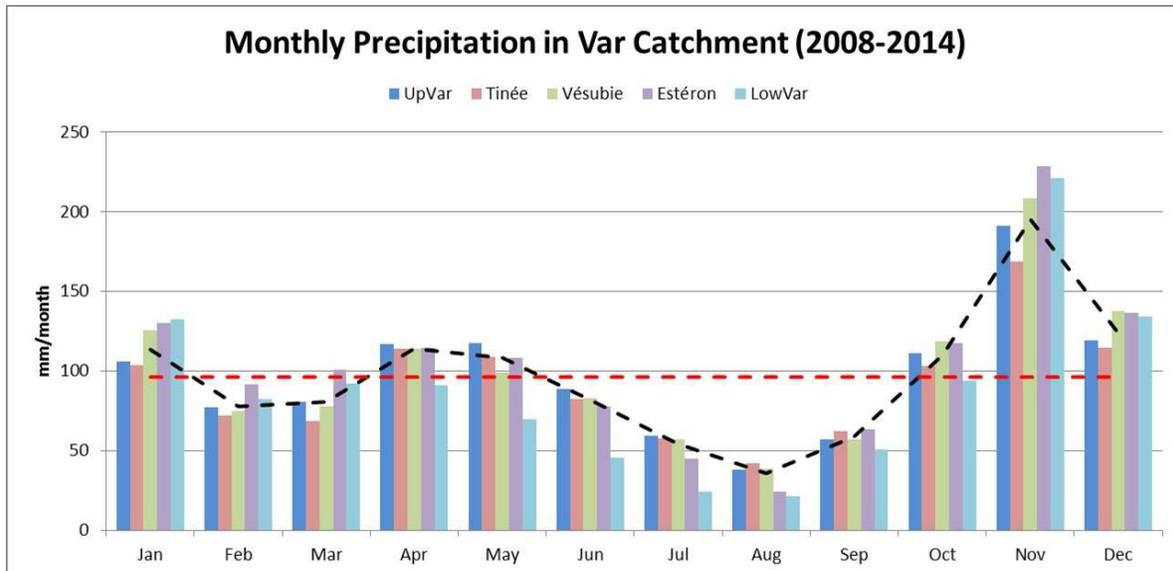


Figure 40: Monthly Precipitation of different sub-catchments in Var Catchment (2008-2014).

Due to the strong elevation variation in Var catchment, especially at the upper and middle part of the catchment, its meteorological characteristics could be integrated affected by both the Mediterranean Sea and its mountainous terrain. In order to identify the influence of altitude and distances to sea, four stations were selected to make the comparison among their monthly rainfall distribution. The selected stations were distributed in four sub-catchments in Var with different elevation in range of 2m to 1784m above the sea level (Table 8).

Table 8: Selected stations for assessment of rainfall spatial distribution.

Stations	Number	Elevation (m)	Distance to sea (km)	Total Rainfall (mm) (2008-2014)	Control catchment
PEONE	6094002	1784	48.56	1178.47	UpVar
ST-MARTIN-DE-VESUBIE	6127001	994	46.92	1327.66	Vésubie
COURSEGOULES	6050002	998	14.97	1462.43	Estéron
NICE	6088001	2	0.33	941.33	LowVar

In Figure 41, it is clearly indicated that the rainfall temporal distribution in all test stations represents the impacts of Mediterranean climate with rainy winter and dry summer. Comparison between station NICE located at the coastal area and station COURSEGOULES located in the middle part of Var catchment, with obvious increases of both elevation (2m to 998m) and distance to the sea (0.33km to 14.97km), there is no significant changes in the rainfall temporal distribution. Both two stations recorded the monthly rainfall peak at same time (April and November). However, for the rainfall amount, station COURSEGOULES in the middle part of Var catchment with higher elevation and farther to the sea could receive much more rainfall than in the coastal area (COURSEGOULES: 107.95mm and 190.00mm; NICE: 65.06mm and 161.88mm, respectively in April and November) Further comparison has been implemented between stations COURSEGOULES and station ST-MARTIN-DE-VESUBIE which has similar elevation (994m) but much farther to the sea (46.92km). In the winter rainy period, except the decrease of monthly rainfall amount, there is no temporal changes (peak still at November). However, in the spring rainy period, the rainfall peak recorded at the station ST-MARTIN-DE-

VESUBIE which is located farther to the sea has been delayed in one month (April to May) with higher rainfall amount (107.25mm). At the end, the last assessment was between station ST-MARTIN-DE-VESUBIE and PEONE with similar distance to the sea but different elevations. We could notice that with certain distance to the sea (46.92km and 48.56km respectively), with higher elevation (PEONE, 1784m) the monthly rainfall showed a decreased tend in every month.

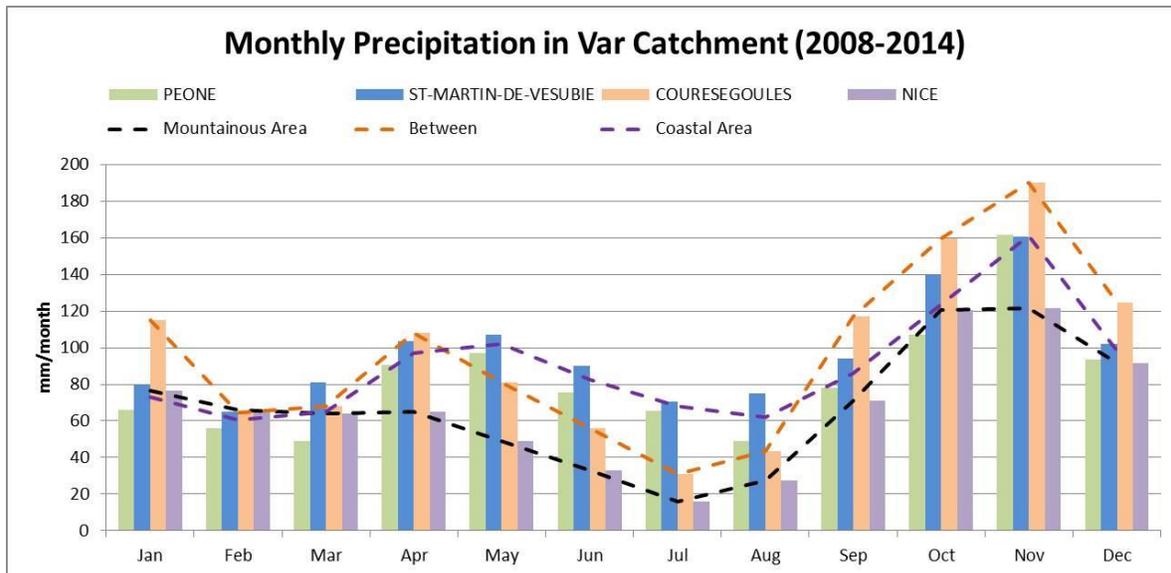


Figure 41: Elevation and sea impacts on rainfall temporal distribution in Var Catchment (2008-2014).

Based on the location of the stations, if we classified the test stations into three groups: “Mountainous Area” (including PEONE and ST-MARTIN-DE-VESUBIE), “In Between” (COURSEGOULES) and “Coastal Area” (NICE), we could estimate that in Var catchment both the sea climate and the catchment terrain has impacts on its meteorological characteristics. Assessment of rainy period, in winter time, the main impact factor could be the Mediterranean climate which caused the high intensity rainfall extending over the whole catchment area in November. During this period, the terrain influence could be mainly presented by its impact on rainfall amount. With the increase of surface elevation, the catchment area may receive more rainfall during the rainfall event. But there should be one threshold value existing with certain distance to the sea. When the distance between the catchment area and the sea reach a certain value (e.g. 20km), the impacts of elevation variation on the rainfall amount may turn to the opposite direction. Moreover, in the spring rainy period, we could consider the impacts of the Mediterranean climate were slightly decreased. At this moment, the terrain influence may effect on both amount and temporal distribution of rainfall. Firstly, with the increase of elevation, the peak of monthly rainfall has been delayed in one month from April to May. Secondly, the same as in winter period the threshold value of distance to the sea should still exist to control the impacts of elevation variation on amount of rainfall. Comparison with in winter tile, this threshold value was expected to be slightly increased (e.g. 45km) which support the increase of elevation has positive impacts on rainfall amount at larger area in Var. In addition, for the dry period, the terrain variation showed similar impacts as in spring rainy period.

In conclusion, the Var catchment, both the regional (Mediterranean climate) and local (terrain impacts) factors has affected its precipitation distribution. Compared to the spring period, in

summer and winter time, we assumed the regional impacts play more significant role on Var precipitation characteristics, and the elevation impacts in that period were mainly focused on the amount of the rainfall with low threshold value of distance to the sea. For the spring rainy period, the regional impacts have been reduced and the impacts of local factor become more important. With the increased threshold values of distance to the sea, the terrain impacts (elevation and distance to the sea) may represent in both temporal and quantity aspects of rainfall.

Due to the data limitation, six precipitation gauging station distributed in Var catchment were selected to detect the changing trend of annual rainfall (Figure 42). The control area of the selected stations could covered most part of the catchment with elevation variation from 2m (NICE) up to 1174m (PEONE). The annual rainfall distribution in last 30 years showed similar situation as the monthly rainfall distribution that the within certain distance to the sea, the area has elevation could receive more rainfall. The highest annual average precipitation was observed at station ST-MARTIN-DE-VESUBIE with 1173.98mm/year in last 30 years and second at station COURSEGOULES with 1157.25mm/year. The lowest annual average rainfall was recorded at the station NICE located at the coastal area of Var.

Comparison between different part of the catchment, most of the rainfall in Var catchment were recorded at the upstream area (PEONE and ST-MARTIN-DE-VESUBIE) with higher annual average rainfall (1062.90mm/year and 1157.25mm/year) and larger number of year with rainfall over 1000mm (23 and 27 over 30 years). Combining the steep slope distributed at the same region, it could lead to the flash flood disaster at the middle and downstream part of the catchment.

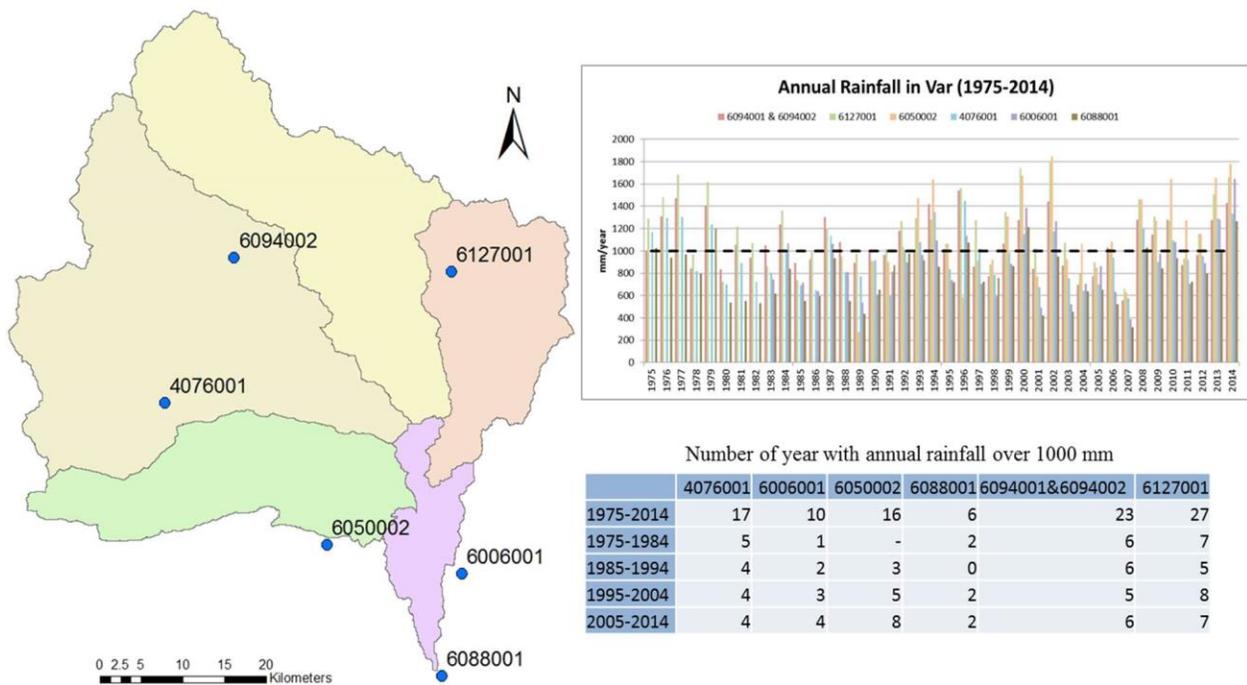


Figure 42: Annual precipitation in different stations distributed in Var catchment.

Moreover, to assess the rainfall intensity in Var catchment, the results were showed in Table 9. During last 30 year, the high intensity daily rainfall (above 100mm/day) was more often occurred

at Vésubie (ST-MARTIN-DE-VESUBIE) and Estéron (COURSEGOULES). Considering the missing data and uncertainty of measurements, there is no clear sign of increasing high intensity (above 100mm/day) rainfall frequency at Var catchment in last three decades. However, at the stations located at mountainous area, recently, the rainfall with intensity in rang of 20mm/day to 500mm/day become more often than before. Therefore, the possibility of the flood risks at the downstream cities could be expected to have a slightly increase trend in the future.

Table 9: Number of days in different stations in Var catchment with daily rainfall intensity in three categories.

1975-2014						
	4076001	6006001	6050002	6088001	6094001 & 6094002	6127001
>100 mm/day	6	8	25	5	14	26
>50 mm/day	78	74	109	71	68	111
>20 mm/day	482	361	305	405	534	552
1975-1984						
	4076001	6006001	6050002	6088001	6094001 & 6094002	6127001
>100 mm/day	0	0	-	0	1	6
>50 mm/day	22	6	-	20	16	32
>20 mm/day	129	27	-	108	130	149
1985-1994						
	4076001	6006001	6050002	6088001	6094001 & 6094002	6127001
>100 mm/day	1	1	3	2	3	5
>50 mm/day	18	21	24	14	22	20
>20 mm/day	117	102	61	94	133	120
1995-2004						
	4076001	6006001	6050002	6088001	6094001 & 6094002	6127001
>100 mm/day	3	4	12	2	6	11
>50 mm/day	17	24	36	20	18	28
>20 mm/day	113	104	117	91	124	143
2005-2014						
	4076001	6006001	6050002	6088001	6094001 & 6094002	6127001
>100 mm/day	2	3	10	1	4	4
>50 mm/day	21	23	49	17	12	31
>20 mm/day	123	128	127	112	147	140

With the data support from Météo-France, there are 13 station distributed in Var catchment with no missing records of daily air temperature from 2008 to 2014 available in this project. Their elevation variation is same as the precipitation measurement with the range from 2m up to 1784m. However, compared to the rainfall measurement, there is a smaller number of stations existing in the Var catchment to monitor the daily air temperature. Thus, the ungauged area of air temperature has significant increased especially at the UpVar sub-catchment (Figure 43).

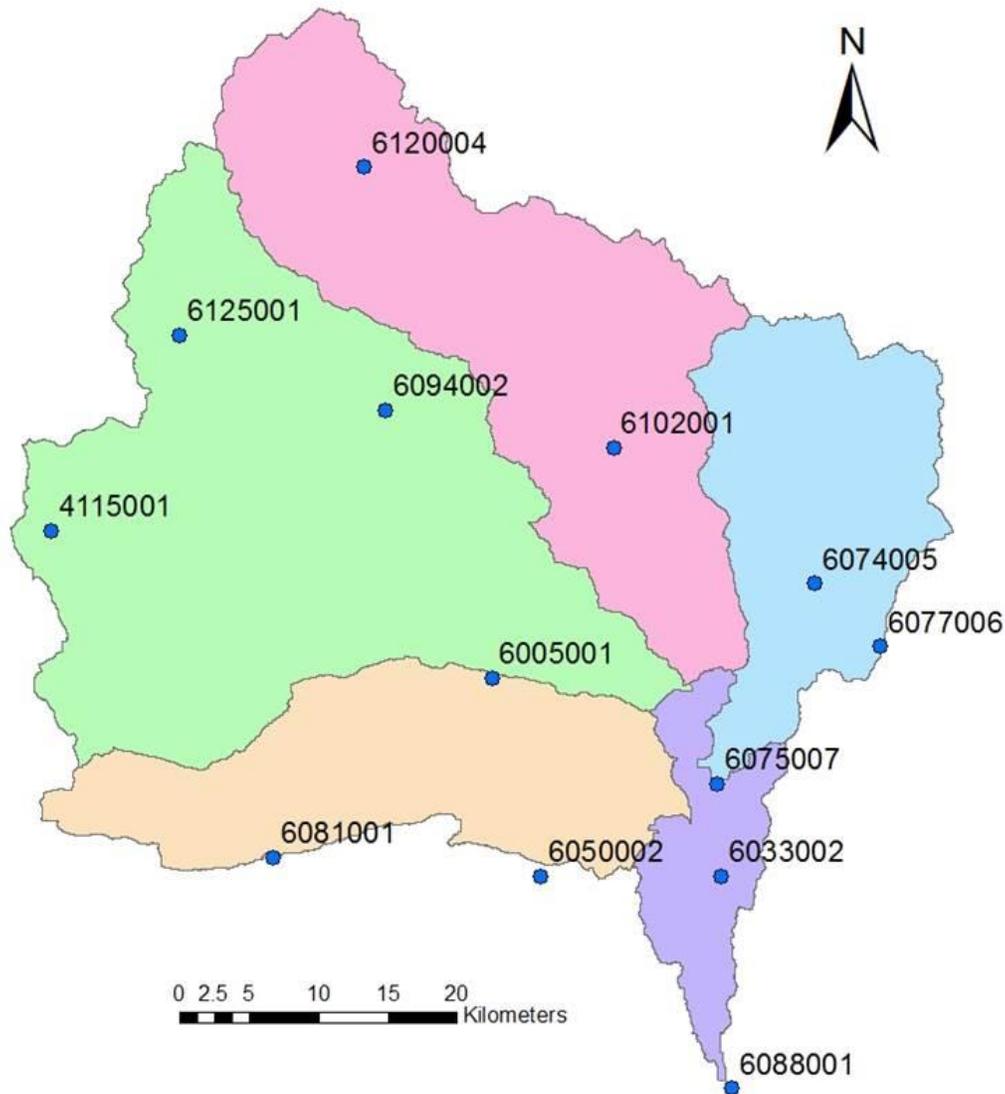


Figure 43: Daily temperature records distributed in Var catchment (2008-2014).

The air temperature is considered as one of most important driving factors in the catchment hydrological system. It is expected to play significant role in several hydrological process such as evaporation and snow melting/freezing process. In Var catchment, as results of Mediterranean climate impacts, in most part of the Var catchment (especially at downstream and middle area), the annual air temperature is always above $^{\circ}\text{C}$ (Figure 44). The catchment annual monthly air temperature is equal to 10.7°C . The monthly temperature fluctuation is in the range from 2.7°C (February) to 19.8°C (August) which could be linked with the snow melting/freezing process in Var. Moreover, considering the variation of air temperature and rainfall temporal distribution, in the summer time, when the catchment has relatively higher air temperature, with less precipitation landed on the ground surface, the amount of water from catchment surface through infiltration process to recharge the groundwater flow could be significantly reduced. Therefore, at this moment, the exchange process in direction of stream flow to groundwater flow is expected in Var catchment especially at the lower Var valley.

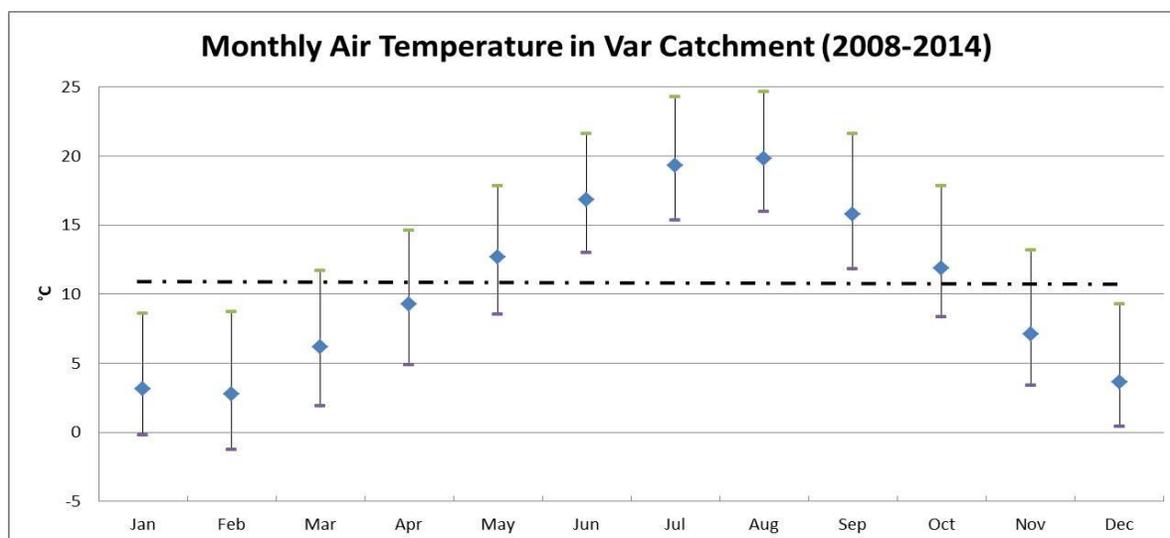


Figure 44: Monthly airt temperature in Var catchment (2008-2014).

The elevation variation has obvious impacts on air temperature in Var catchment. At upper part of the catchment with higher surface elevation, daily air temperature has the possibility to reach nearly -10°C and less at the winter time and produce the snow cover storage at summits of mountains. In Table 10 and Figure 45, it clearly showed that with the increase of surface elevation, the measured air temperature has been obviously reduced. Comparison between the coastal station NICE and the mountainous station PENONE, the difference of annual monthly air temperature could reach nearly 10°C . Moreover, among 13 stations in Var catchment, the average Temperature Lapse Rate is $-0.611^{\circ}\text{C}/100\text{m}$, slightly higher than the globe value ($-0.649^{\circ}\text{C}/100\text{m}$). Considering the ungauged area in the catchment with elevation higher than 1784m, the value of Temperature Lapse Rate in Var catchment could be estimated closed to the globe value. In addition, we also noticed that from 2008 to 2014, there are 465 days recorded at the mountainous station with measured air temperature lower than 0°C . In contrast, at costal area, the possibility to have daily air temperature lower than 0°C is considerably lower.

Table 10: Daily temperature recorded in Var catchment (2008-2014).

Stations	Number	Elevation (m)	Min ($^{\circ}\text{C}$)	Max ($^{\circ}\text{C}$)	Mean ($^{\circ}\text{C}$)	days ($T < 0^{\circ}\text{C}$)
PEONE	6094002	1784	-11.6	22.2	6.9	465
ST MARTIN D'ENTRAUNES	6125001	1642	-9.9	23.4	8.1	346
LE MAS	6081001	1525	-9.5	24.3	8.1	364
PEIRA CACA	6077006	1443	-9.1	24.0	8.7	276
ASCROS	6005001	1173	-6.7	25.0	10.1	142
ST ETIENNE DE TINEE	6120004	1150	-8.5	23.6	9.3	245
RIMPLAS	6102001	1130	-6.3	26.1	10.8	114
MEAILLES	4115001	1090	-6.6	25.9	10.9	132
COURESGOULES	6050002	998	-5.9	26.3	11.1	74
LEVENS	6075007	691	-3.9	26.8	12.1	41
LANTOSQUE	6074005	550	-4.2	26.7	12.1	45
CARROS	6033002	78	-1.2	30.2	15.3	1
NICE	6088001	2	1.3	28.9	16.2	0

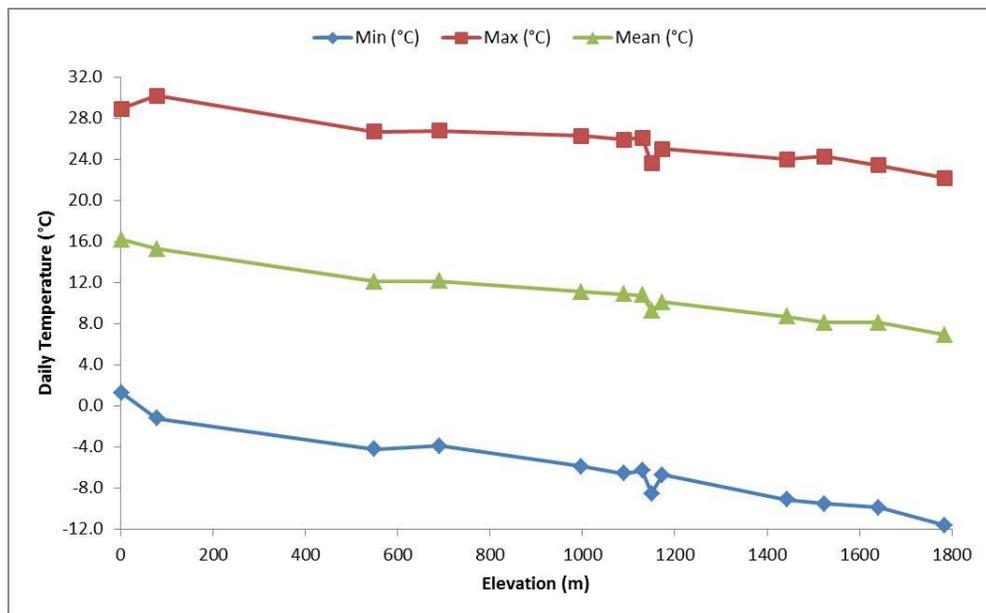


Figure 45: Relationship between daily temperature and elevation in Var catchment (2008-2014).

3.4.3 Hydrological characteristics of Var Catchment

In AquaVar project, there are 10 stations able to produce stream flow discharge in both daily and hourly time interval (Figure 46). The station distribution could cover all the sub-catchments in Var catchment and benefit the modelers to calibrate their hydrological models in different spatial scales.

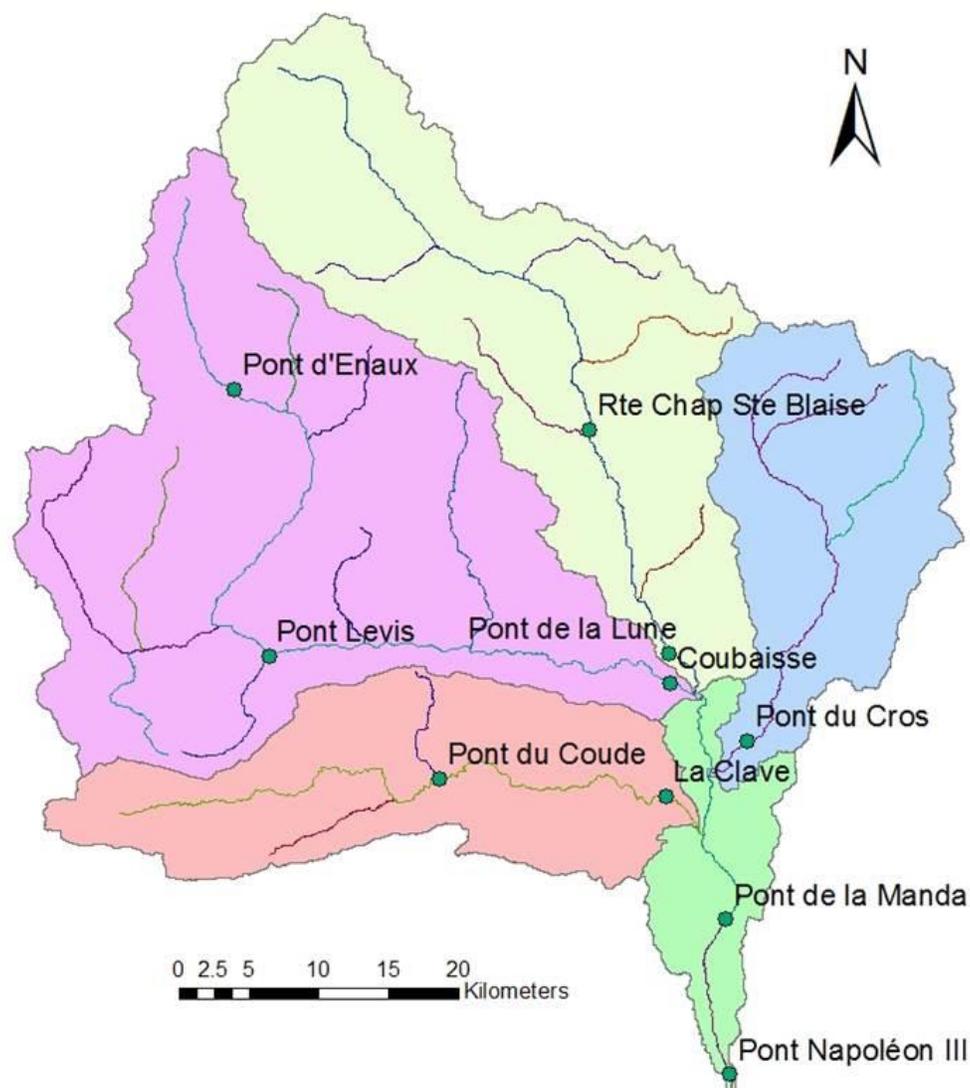


Figure 46: Discharge measurements available in Var catchment (Source: www.vigicrues.gouv.fr).

Assessing the stream flow discharge monitored at Napoléon III Bridge at the outlet of Var catchment (Figure 47), its annual stream runoff is around $51.0\text{m}^3/\text{s}$ (missing period from 2001 to 2005). If we simply considered the value of $60\text{m}^3/\text{s}$ as a criteria to identify wet year, from 1985 to 2014, the year of 1994 ($84.8\text{m}^3/\text{year}$), 1996 ($76.4\text{m}^3/\text{year}$), 2013 ($67.9\text{m}^3/\text{year}$) and 2014 ($78.4\text{m}^3/\text{year}$) could be highlighted in wet year category. And the years have annual stream runoff lower than $40\text{m}^3/\text{s}$ could be concluded into dryer year. Furthermore, with the monthly discharge calculated at Napoléon III Bridge, in November 1994, its monthly discharge ($276.4\text{m}^3/\text{s}$) was obviously higher than other months. The main contribution could be traced to the serious flood disaster happened at beginning of this month with estimated peak flow around $3680\text{m}^3/\text{s}$. Moreover, assessing the monthly runoff during one year, the highest discharge was observed in May which is slightly different to our expectation based on higher monthly rainfall and flood disaster frequently be recorded in November. Consequently, beside the rainfall, the water resources received by Var River in May could have other sources such as snow melted from mountainous area.

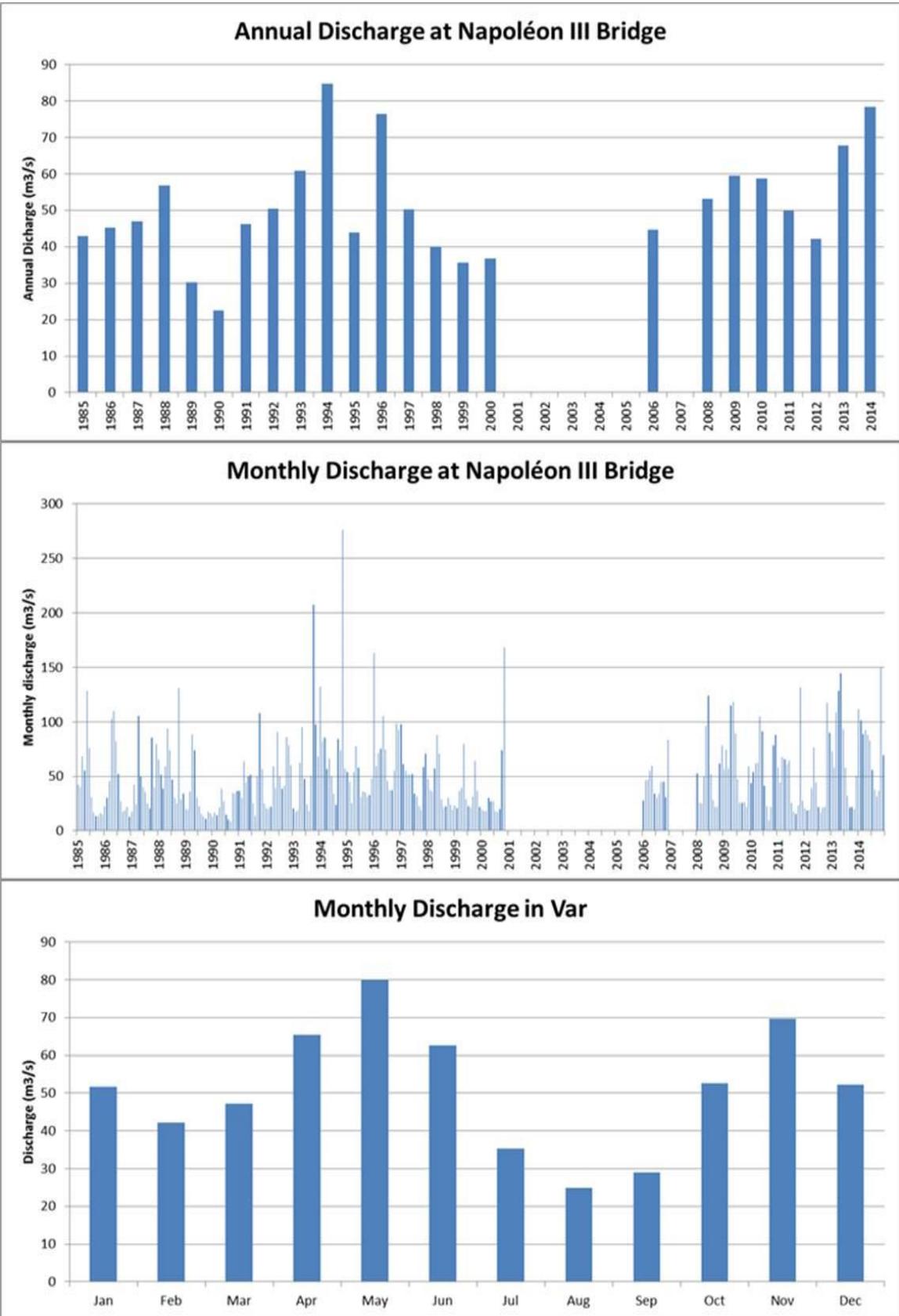


Figure 47: Annual and monthly discharge at outlet of Var catchment (Napoléon III Bridge).

The figure of monthly discharge at different sub-catchments clearly represented the characteristic of mountainous streams with high temporal variation of their stream flow runoff (Figure 48). It is interesting to notice that during the dryer period, besides the UpVar who has largest control area producing highest surface flow, the second stream flow producer in Var catchment is not the second biggest sub-catchment Tinée, but the Vésubie sub-catchment. One of the main reasons of that could be pointed to the difference between flow paths existing in those two sub-catchments during the intense rainfall period.

For instance, both the Tinée and Vésubie sub-catchment could be characterized as mountainous catchment with steep surface slope and bigger area covered by rocks. Even though the control area of Tinée is obviously larger than Vésubie, due to steeper slope in Tinée, its surface flow was expected to move much faster than in Vésubie. Moreover, the surface slope may have impacts on the top soil depth. With steeper slope in Tinée, compared to Vésubie, its top soil depth may significantly reduce. Consequently, after the precipitation process, less water could be stored in high slope area and released after. Compared to Tinée, the higher monthly discharge of Vésubie in the dry period could be a good example to explain this assessment.

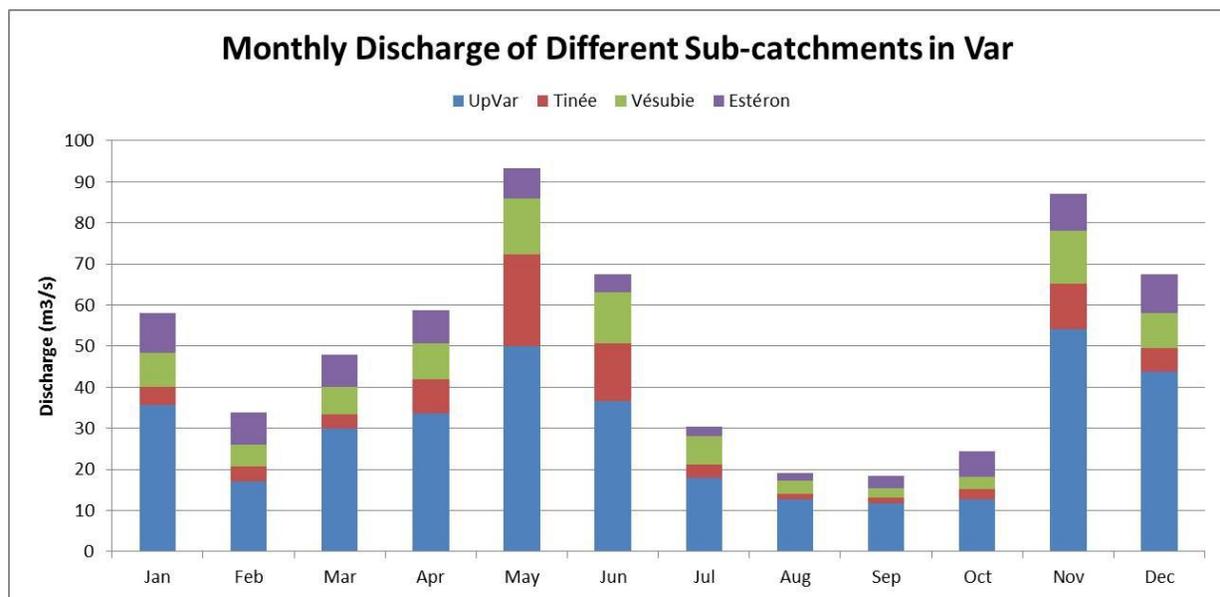


Figure 48: Monthly discharge of different sub-catchments in Var catchment.

In comparison among the surface flow from four upper sub-catchments, it is reasonable to have highest surface discharge from UpVar with the largest sub-catchment area. As we observed from rainfall assessment of Var catchment, the amount of precipitation in November is obviously higher than in May. In general, with more rainfall received in the catchment, higher surface runoff is expected at its outlet. However, it is not the case in Var.

In UpVar, the monthly discharge in May and November is almost same ($49.8\text{m}^3/\text{s}$ and $54.1\text{m}^3/\text{s}$ respectively). And in Tinée, which is the second largest sub-catchment in Var catchment, the monthly discharge showed opposite situation. Its monthly discharge in May ($22.4\text{m}^3/\text{s}$) is nearly twice more than in November ($11.2\text{m}^3/\text{s}$). The explanation could be traced to the impacts of snow melting and frozen process at mountainous area in this sub-catchment. With higher elevation, the

air temperature has more dramatic fluctuation. In winter time, even though there is big amount of rainfall landed in Tinée, due to the lower air temperature in its mountainous area, a part of precipitation would be frozen as the snow cover stored on the ground and not produce the surface flow. Then in spring time, when the air temperature started to grow up, the snow cover would be melted to produce extra surface flow combined the rainfall-runoff process to have higher stream flow. Similar process could also be found in the upper part of Vésubie.

The second assessment was concentrated on the LowVar sub-catchment (Figure 49) with the comparison between discharges measured from two stations located at La Manda Bridge and Napoléon III Bridge. It is interesting to notice that in general especially in the rainy period, the discharge recorded at La Manda Bridge is often higher than the discharge recorded at more downstream part of Var River (Napoléon III Bridge). As we mentioned that in this so call lower Var valley, the connection between the stream flow and aquifer plays significant role in the local hydrological system. With this observation data, we could simply estimate the variation of exchange directions between surface and underground water. From upstream to downstream, with the decrease of surface flow rate during rainy period, we could consider in this region (between La Manda Bridge and Napoléon III Bridge), the main direction of water exchange could be in direction from stream flow to groundwater flow.

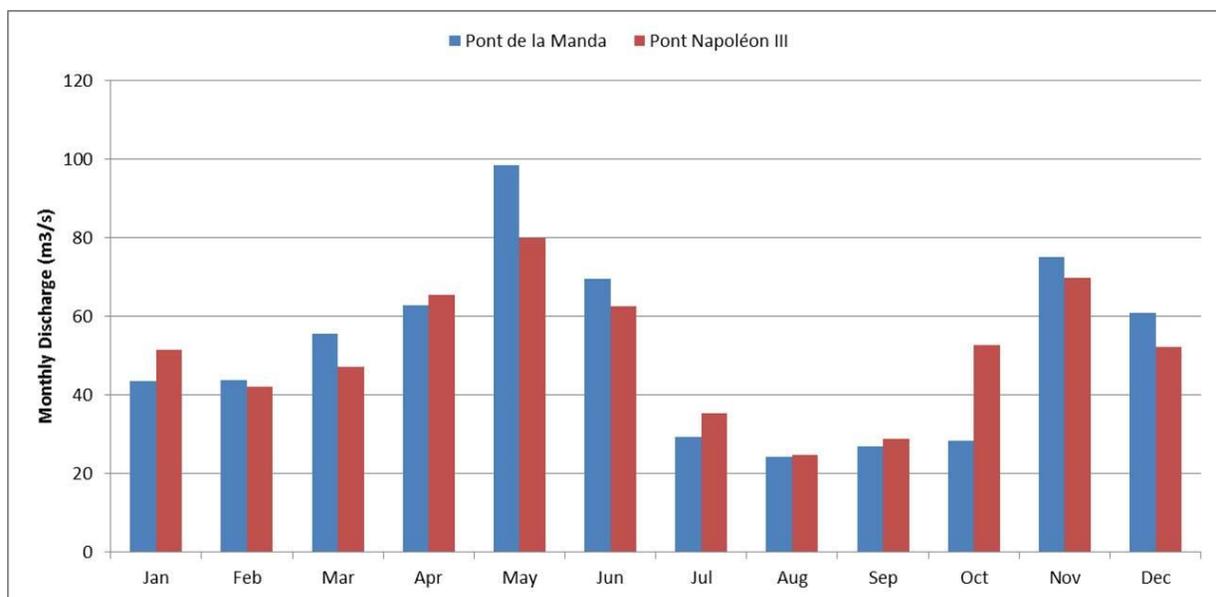


Figure 49: Comparison between the discharges recorded in two downstream stations in Var.

An additional point would be further discussed is the discharge variation at every beginning of the rainy period in Var catchment (e.g. monthly discharge in April and October). In every beginning of the rainy period, the discharge recorded at the upper part of Lower Var Valley is often lower than the downstream part. And comparison between discharge in April and October, the difference between upper and lower part discharge in October is obviously higher than in April. This phenomenon could be linked to the integrated impacts among meteorological, geological and hydrological characteristics in Var. For example, in April, when the air temperature started to be increased in Var catchment, the snow melting process at the mountainous area become more intense than before. The contribution of snow melting flow to the stream runoff is increased during this period. Different to the precipitation process with most part

of rainfall directly produces the surface flow, the snow melted water first infiltrated into the top soil to feed the underground layers in upper and middle parts of Var catchment, then flowed from upstream to downstream through the soil. Thus in this month, as most of the soil layers in Var catchment was fed by the snow melted water, there is less surface flow recorded at the downstream part. After April, in May, when most of the soil layers in Var catchment is closed to saturation, the precipitation plus the snow melting process may produce more surface runoff in Var. The water level in the downstream channel could be significantly increased and lead to the increase of hydraulic gradient between surface and groundwater in LowVar. Thus, more water at this time could be transferred from stream to underground, which causes the losses of surface flow along the lower Var River represented by the runoff difference between La Manda Bridge and Napoléon III Bridge.

The changes of groundwater level in lower Var are showed in Figure 50 clearly representing its temporal variation in different periods. At the upper part with relatively higher elevation, the groundwater level showed more dramatic fluctuation during one year. The difference of water level between rainy and dryer period could reach more than 4m. However, when the groundwater surface becomes more flat in middle part of valley, the groundwater level fluctuation becomes more stable with maximum difference reduced to less than 2m. The smooth water line has been changed at the lower part of the valley mainly due to the sea impacts. With the fluctuation of sea tide, the groundwater level recorded in coastal area showed an “unstable” situation with maximum difference slightly increased up to nearly 3m.

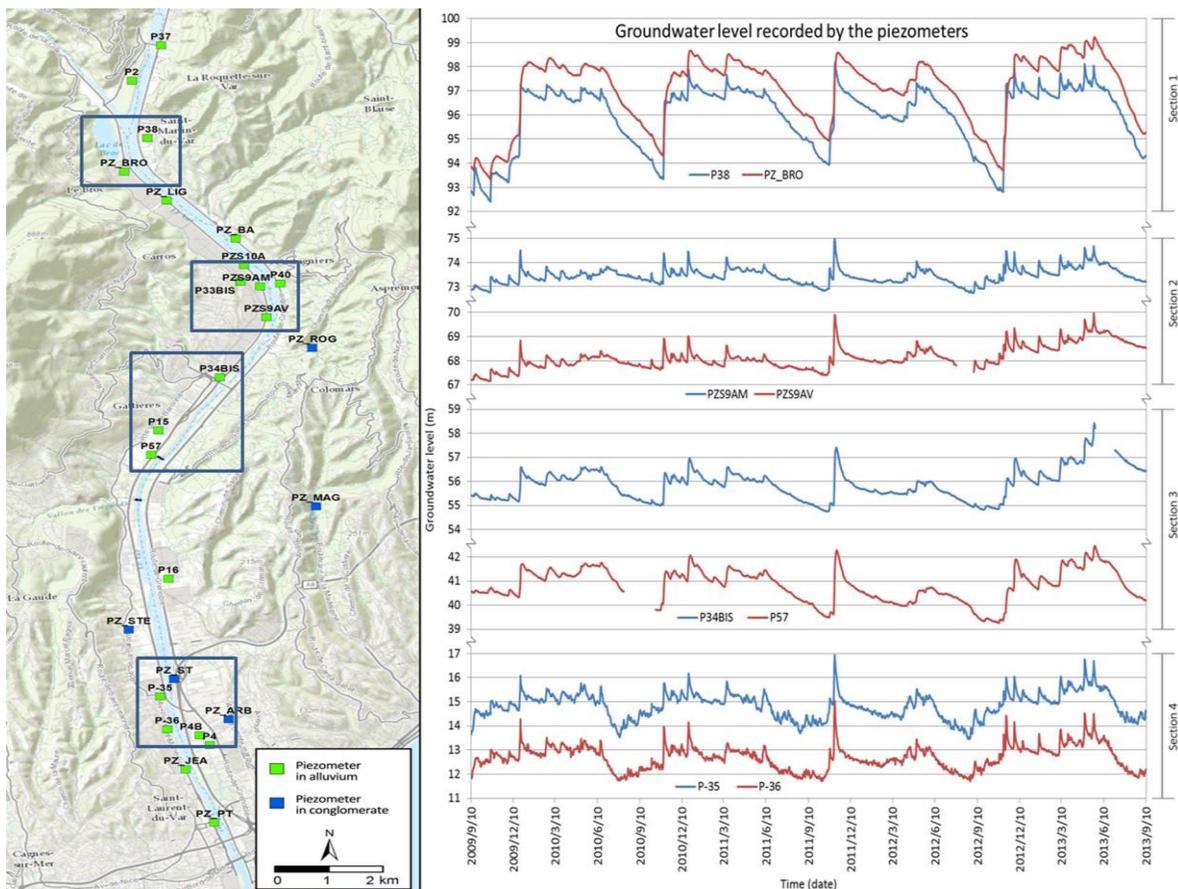


Figure 50: Groundwater level measured at lower Var valley (Source: <http://www.adès.eaufrance.fr/>).

3.5. Review of Historical Events (Flood and Drought)

As we mentioned before, the constructions on the lower Var flood plain never stopped since 1960s. Moreover, in recent years, the urbanization of downstream cities significantly changed the land use in the lower Var valley. Consequently, the damage of natural disasters has been obviously increased. Since, 1990s, the local institutes started to increase the field survey in the Var catchment, there are several serious flood disasters caused by extreme rainfall events observed in Var.

The flood occurred at 5th November 1994 is one of the most spectacular hydrological events recorded in the Var catchment (Guinot and Gourbesville, 2003). During this event, several dikes at the downstream parts of the basin are overlapped and a number of national and departmental roads were destroyed (Figure 51). Some small bridges were completely washed away and the flood entered international airport of NICE caused it to be closed for around 1 week. Fortunately; there were no lives lost, but the estimated damages of this hazard is around 23M€.



Figure 51: Damage of flood 1994 in lower Var valley (Source NICE Matin).

This hazard was mainly caused by the extreme rainfall event. The average rainfall from 2nd November to 5th November 1994 is around 200mm/day. Half of the precipitation was concentrated in 5th of November? which characterized by high rainfall intensities. Beside, before the extreme rainfall event came at 5th November 1994, there is another intense rainfall recorded at

3rd November 1994, which supposed to fully fill the unsaturated zone of the catchment. Therefore, when the high intensity rainfall occurred at 5th of November, with saturated soil layers in Var catchment, the infiltration process can be neglected. All the rainfall landed on the surface generate the surface runoff and due to the steep slope at mountainous area of Var catchment, the surface flow moved very fast and accumulated at the downstream leads to the serious flood at the flower Var flood plain.

There were few discharge records available at the upper stations during this event. The only detail information about the stream flow variation is estimated by the hydrologist after the event at outlet of the catchment (Figure 52). As results of the equipment at the gauging point was only able to record the discharge up to 600m³/s, all the red part in the hydrograph is estimated by the local managers who went to check the water marks after the event and calculated based on the rating curve applied at this gauging point before. Hence, there are high uncertainties in both the peak time and values.

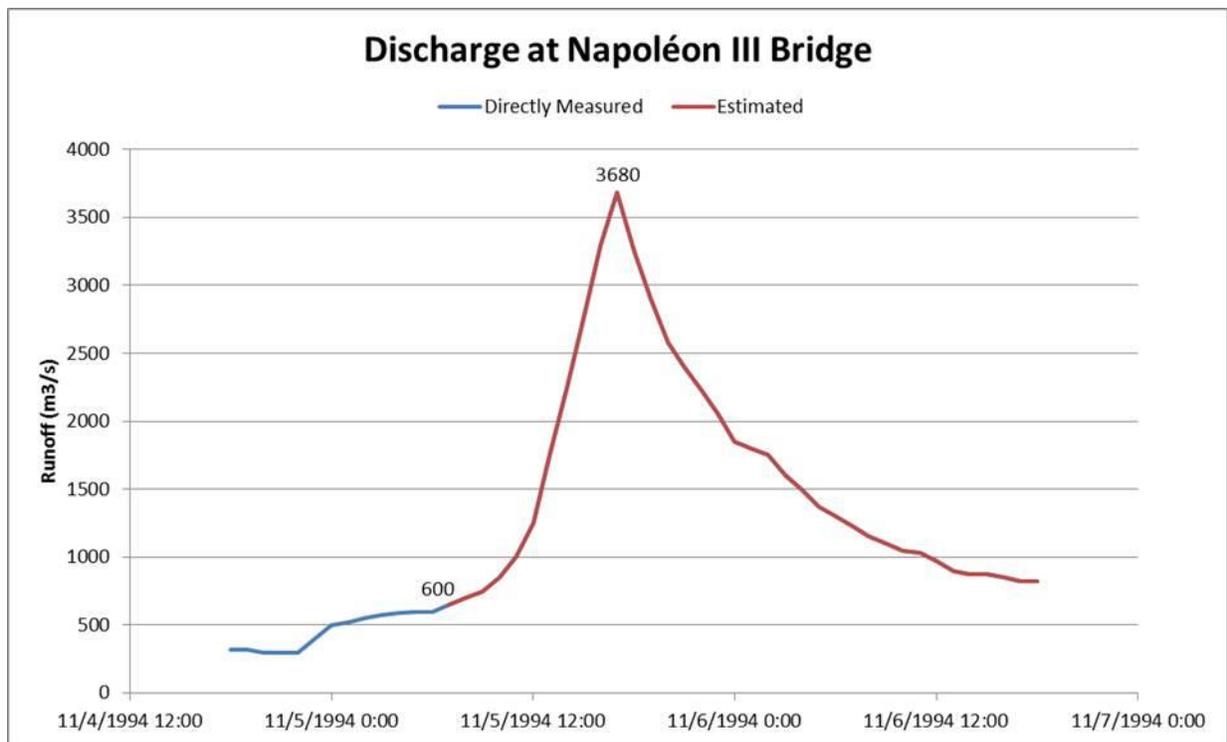


Figure 52: discharge of 1994 flood event at Napoléon III Bridge (Guinot and Gourbesville, 2003).

Another serious flood event was recorded at November 2011. Compared to flood 1994, more detail information was available during this 2011 event which helped us to have a clear view of the event's characteristics (Figure 53).

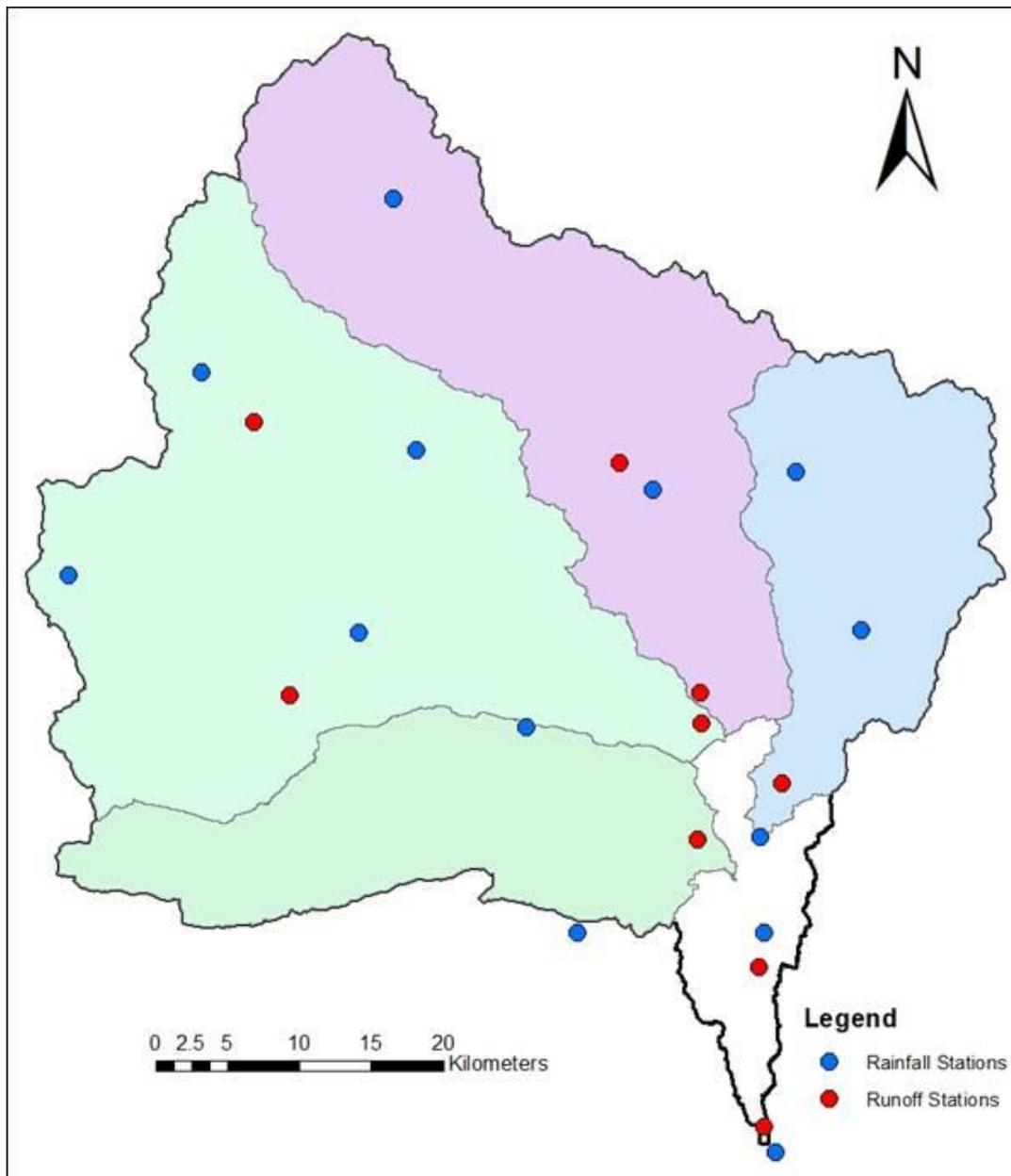


Figure 53: Available rainfall and runoff hourly measurements during flood event November 2011.

There are 13 rainfall stations in total available to produce hourly records during the event (from 1st November to 15th November, 2011). Only the upper part of Estéron sub-catchment was not well covered, which may bring some uncertainties of the rainfall interpolation assessment (Figure 54). Even though the highest rainfall intensity was recorded at station of COURSEGOULES with 21 mm/hour at 8:00am 5th November located at lower part of the catchment, the total rainfall amount was observed at station of St Martin D'Entraunes with 340.3mm during the event located at the upper part of the UpVar sub-catchment. With the interpolation assessment of total rainfall amount distribution in Var during the whole event, most of the precipitation was more concentrated at west part of the catchment insisted with the sub-catchments of UpVar and Estéron.

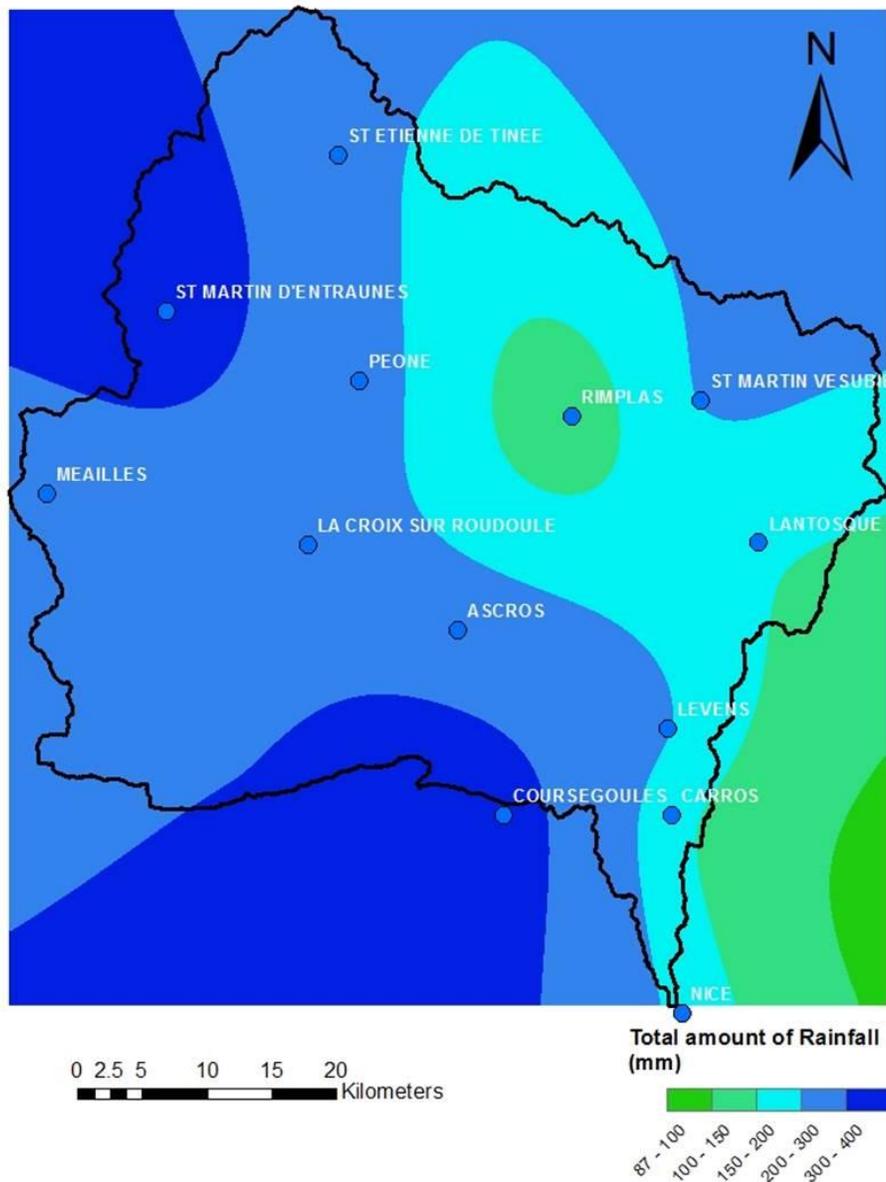


Figure 54: The distribution map of the total rainfall during the flood event November 2011 (Source: Météo-France).

In Figure 55, there are three peaks of discharge recorded at the outlet of the Var catchment, which could also be linked with precipitation peaks during this event. The time lag between the peak rainfall and peak discharge is less than 6 hours. Compared to the discharge, in general there are four peaks of rainfall during this flood event, but for the first peak recorded at 4th November 10:00am, there was no big discharge measured at catchment outlet. However, for the other three peaks occurred after, all of them could produce the considerable discharges at the downstream part. Hence, we could estimate that the rainfall in the period from beginning until the second rainfall peak occurred in Var, a part of the precipitation was infiltrated into the soil to saturate the soil layer in the catchment. Then, when the soil condition was almost saturated, following with the intense rainfall, a flash flood disaster occurred in Var.

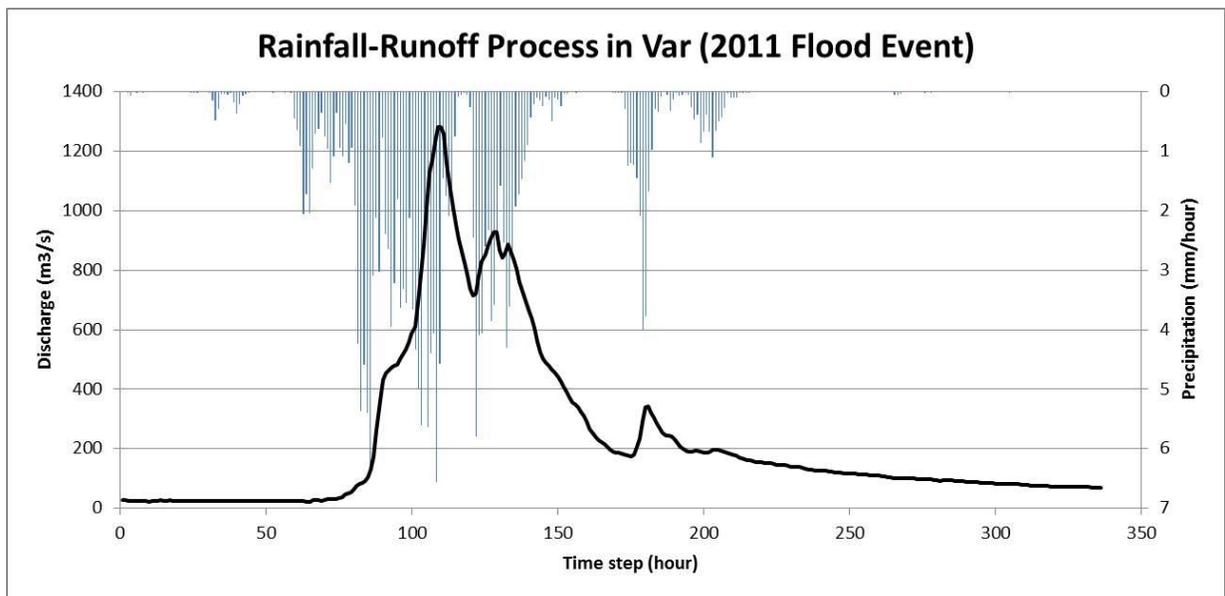
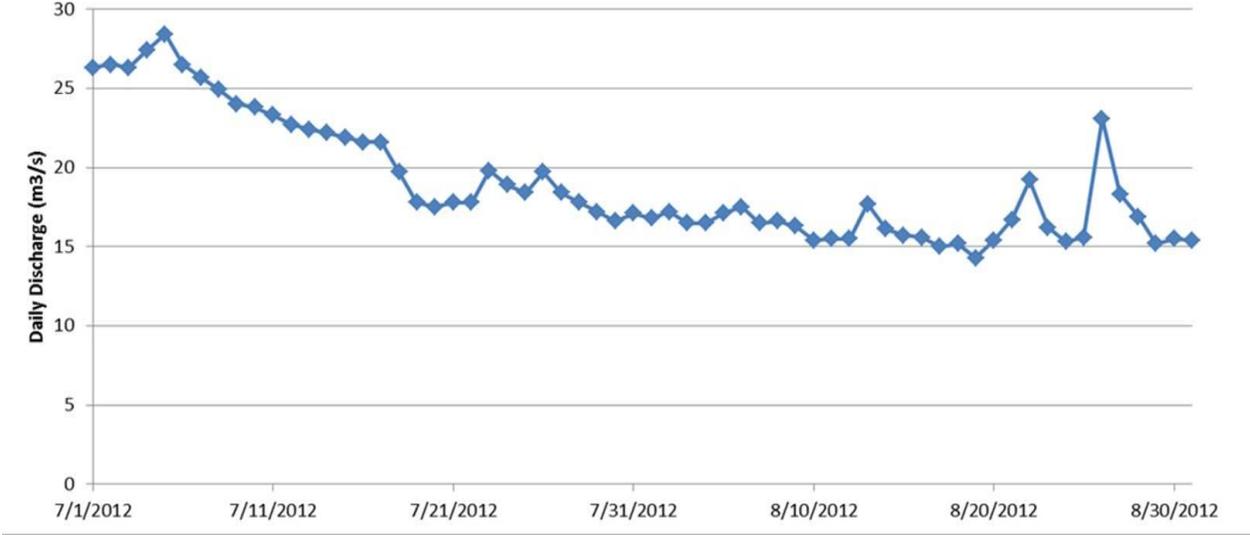


Figure 55: The rainfall-runoff process in Var during 2011 flood event (Start at 1st November 2011).

In the assessment of annual and monthly discharge, the year 2012 with average monthly discharge of $42.3\text{m}^3/\text{s}$, which is much lower than the average values from 1985 to 2014 ($51.0\text{m}^3/\text{s}$), could be considered as the dryer year in Var. Moreover, in the dryer period of this year, with few rainfall recharging the stream and soil, the surface flow showed with a series of lower discharges ($19.0\text{m}^3/\text{s}$ in average from July to August) (Figure 56). The lowest discharge observed during this period was just $14.3\text{m}^3/\text{s}$ at 19th August which could be considered as the minimum based flow in Var.

Daily Discharge during Drought Period in Var Catchment (2012)



Daily Discharge during Dry Year in Var Catchment (2012)

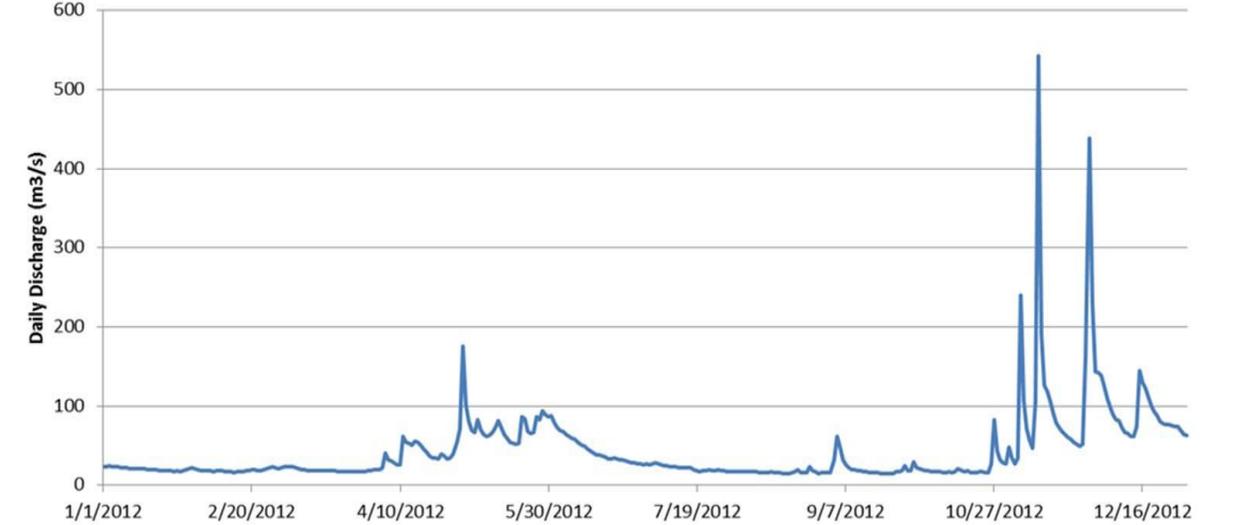


Figure 56: Daily discharge during drought period in 2012.

CHAPTER 4: MIKE SHE APPLICATION IN VAR CATCHMENT

In the design of AquaVar EDSS, the hydrological simulation is the starting point of the modelling assessments which in charge of representing the hydrological phenomenon of Var catchment and producing the inputs for the next step of modelling simulations (MIKE 21fm and FeFlow). After the assessment among meteorological, geological and hydrological characteristics of Var catchment, we could conclude that the environment system in this region is strongly affected by multi-hydrological processes interacted at different periods of the year. Therefore, two main conditions were necessarily added in the criteria of hydrological modelling assessment in this project:

On one hand, the hydrological modelling simulation should be able to accurately represent the interaction of multi-hydrological processes in detail. And on another hand, due to steep slope distributed at the upper and middle parts of catchment, the response time of rainfall-runoff process is relatively short in Var catchment. Consequently, it is reasonable to have the simulation with running time less than this concentration time to let the decision makers having enough time to make and implement their decisions or measures.

Among different kinds of hydrological models, the deterministic distributed hydrological model MIKE SHE is able to represent the complicated hydrological system and to produce detail of information at any places of the study area. However, the conflict between its required inputs and field data collection always limits its applications and requests a series of discussions. To overcome the obstacles caused by the ungauged inputs, following an efficient modelling strategy we described in the second chapter, the MIKE SHE modelling set up process was introduced here step by step.

In this chapter, it began with a discussion of function selections in MIKE SHE and an overview of their related data requirements. Then following the modelling strategy we concluded before, the first step was to define the reasonable simulation resolution in Var. Thus, it was assessed in the second section to find the balance between simulation accuracy and running time. Moreover, as we understood, the distributed data inputs play as the core of this kind of model, in third section of this chapter, many interpolation functions was tested in this project to identify the suitable interpolation method applied in French Mediterranean region. The whole process of modelling set up was described step by step in the following section with many hypotheses conceived for overcoming the issues caused by missing data in Var.

4.1. MIKE SHE Model for Var Simulation

As we introduced before, the deterministic distributed hydrological model MIKE SHE is able to integrated represent the complicated environmental system interacted by multi-hydrological processes including “Overland flow”, “Rivers and Lakes” (Channel Flow), “Unsaturated Flow”, “Evapotranspiration” and “Saturated Flow”.

In theory, to represent the hydrological system in one catchment, it is necessary to include all the functions in the simulation with deterministic computations. However, in real project, when more functions were added in the simulation, even though the hydrological phenomenon could be described more accurately, but not only the computation time will significantly increase, also the data requirement will become more strict. Therefore, an efficient modelling strategy should start with the functions selection based on both simulation objectives and filed data collection. Based on the discussion before, it is obviously better to added all the functions in the simulation to well describe the Var characteristics. Unfortunately, serious missing data in the filed data collection could not support us to realize this simulation.

The data available in this project and their resources were listed in Table 11. Supported by GIS department of local municipality (Métropole NICE Côte d’Azur), the topography information of Var was well collected in this project. However, as results of Var catchment crossing two departments in France (department 06 and department 04), two higher resolution Digital Terrain Models (DTMs) (1m × 1m and 5m × 5m resolution) of department 06 were collected directly from Métropole NICE Côte d’Azur and one DTM with 5m × 5m resolution of area located in department 04 was collected through the cooperation with GIS department in Alpes de Haute-Provence (Figure 57). Compared to the DEM, the DTM supposed to represent the land use without any buildings and vegetation which better to be used in the surface flow simulation. Both two 5m × 5m resolution data collected from two departments were measurement in 2009 and the higher resolution data only available in department 06 was recorded at 2013 expected to have better presentation of lower Var valley.

Table 11: Data collection of AquaVar hydrological modelling assessment.

Data Collection	Sources	Remarks
DTM (Department 06)	Métropole NICE Côte d’Azur	1m × 1m and 5m × 5m resolution
DTM (Part of Department 04)	Métropole NICE Côte d’Azur	5m × 5m resolution
Land use Information	European Agriculture Center	Recorded at 2006 (100m × 100m resolution)
Vegetation Information	European Agriculture Center	Recorded at 2006 (100m × 100m resolution)
Soil Map	European Soil Data Center	Recorded at 2009 (500m × 500m resolution maps of sand, clay and slit percentage)
Rainfall Records	Météo-France	16 stations in daily and 10 stations in hourly
Air Temperature	Météo-France	10 stations in daily
Reference Evapotranspiration	Météo-France	SAFRAN data (8000m × 8000m distribution map)
Runoff Records	Eaufrance	9 stations in daily and hourly
Snow cover	Project ALIRHYS	Records every 10 days

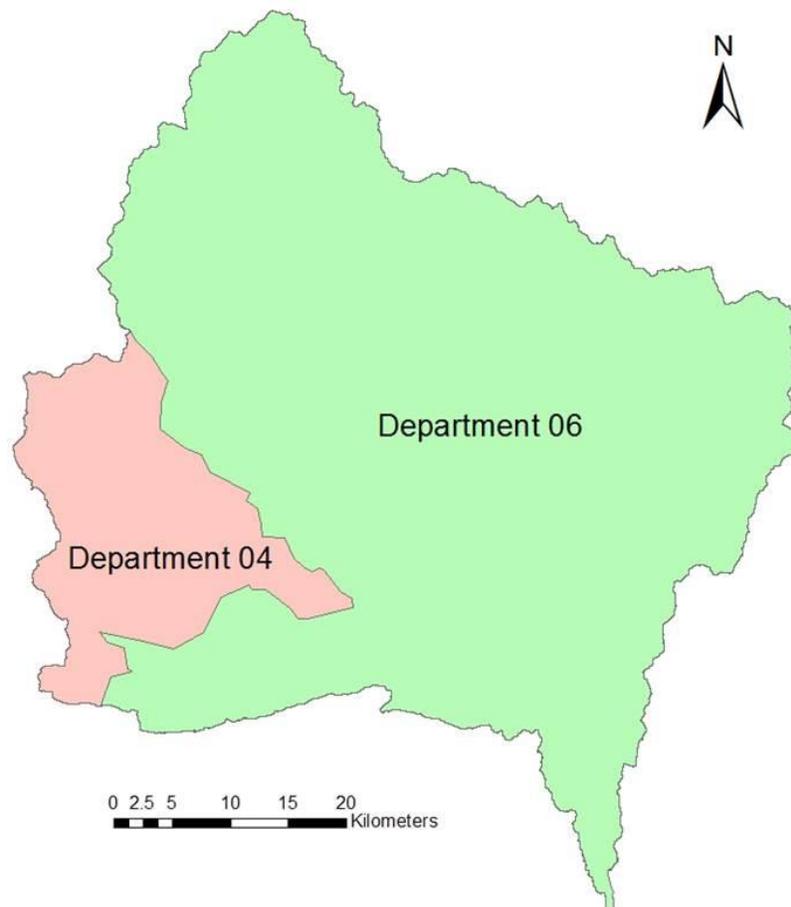


Figure 57: DTM collection from two departments in Var.

The land use and vegetation information were collected in raster data format ($100\text{m} \times 100\text{m}$ resolution) from European Agriculture Center who produced the land use information covered all the European countries. The data was recorded at 2006 with three levels of land use categories (Appendix 1). From the 3rd level of its classification, the vegetation information could also be extracted from this data base.

From the previous chapter, we could conclude that the water exchange between surface and underground in Var plays significant role in the catchment hydrological system. To represent the soil water movement, the soil parameters are necessarily required by setting up the MIKE SHE simulation in Var. Unfortunately, due to the more citizens were concentrated at the downstream cities, compared to the upper and middle parts of Var with less residents, the field survey was more interested at lower Var valley. Consequently, different to the DTM collection, there is very few soil information available in Var from the local institutes. The soil information applied in this AquaVar hydrological modelling assessment was collected mainly from European Soil Center.

In April, 2016, the European Soil Center published their new soil distribution map covered most of the European countries. The data was produced based on the satellite images with $500\text{m} \times 500\text{m}$ resolution contained the percentages of sand, clay and silt (Figure 58).

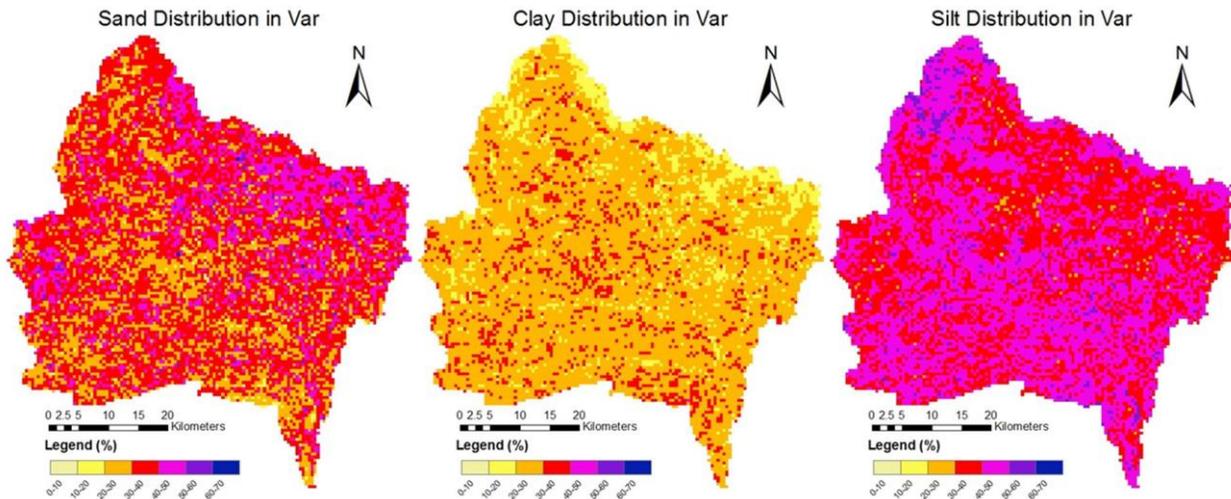


Figure 58: Soil information collected from European Soil Centre.

As we mentioned before, the meteorological data applied in this project was supported by Météo-France. All the rainfall and air temperature were recorded at gauging stations distributed in Var. Moreover, one distributed database so called SAFRAN data produced by Météo-France was also available in this project. The SAFRAN data could produce daily meteorological information including rainfall, air temperature and evapotranspiration with $8000\text{m} \times 8000\text{m}$ resolution maps (Figure 59).

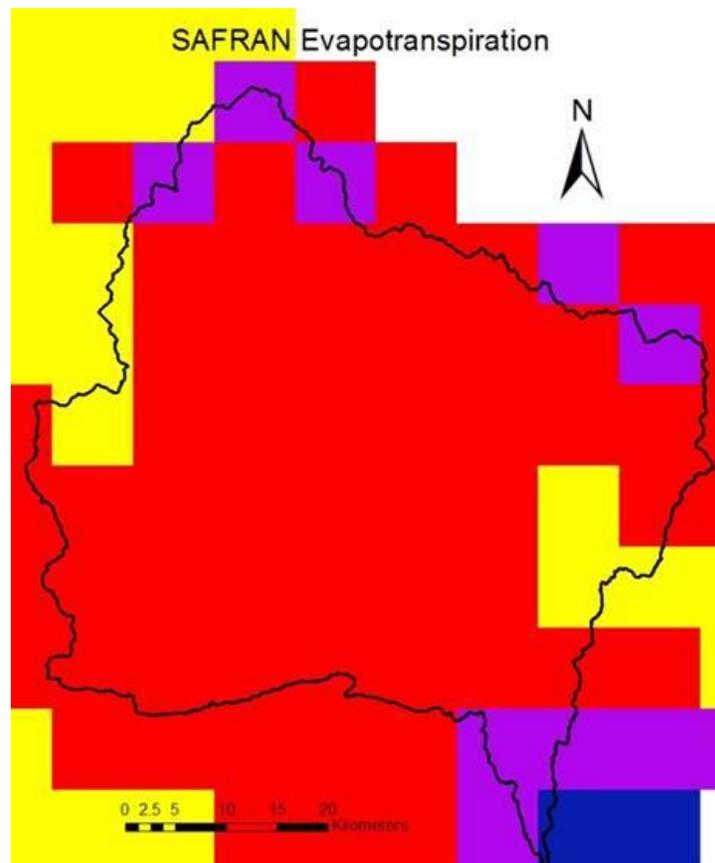


Figure 59: SAFRAN database in AquaVar project ($8000\text{m} \times 8000\text{m}$ resolution).

The snow melting and freezing process highly affected the flood in both spring and winter time in Var. The information of snow cover was collected from one project named ALIRHYS cooperated between France and Italy (Figure 60). The snow cover maps from this project were produced by satellite images with 10 days' time interval from 2000 to 2014.

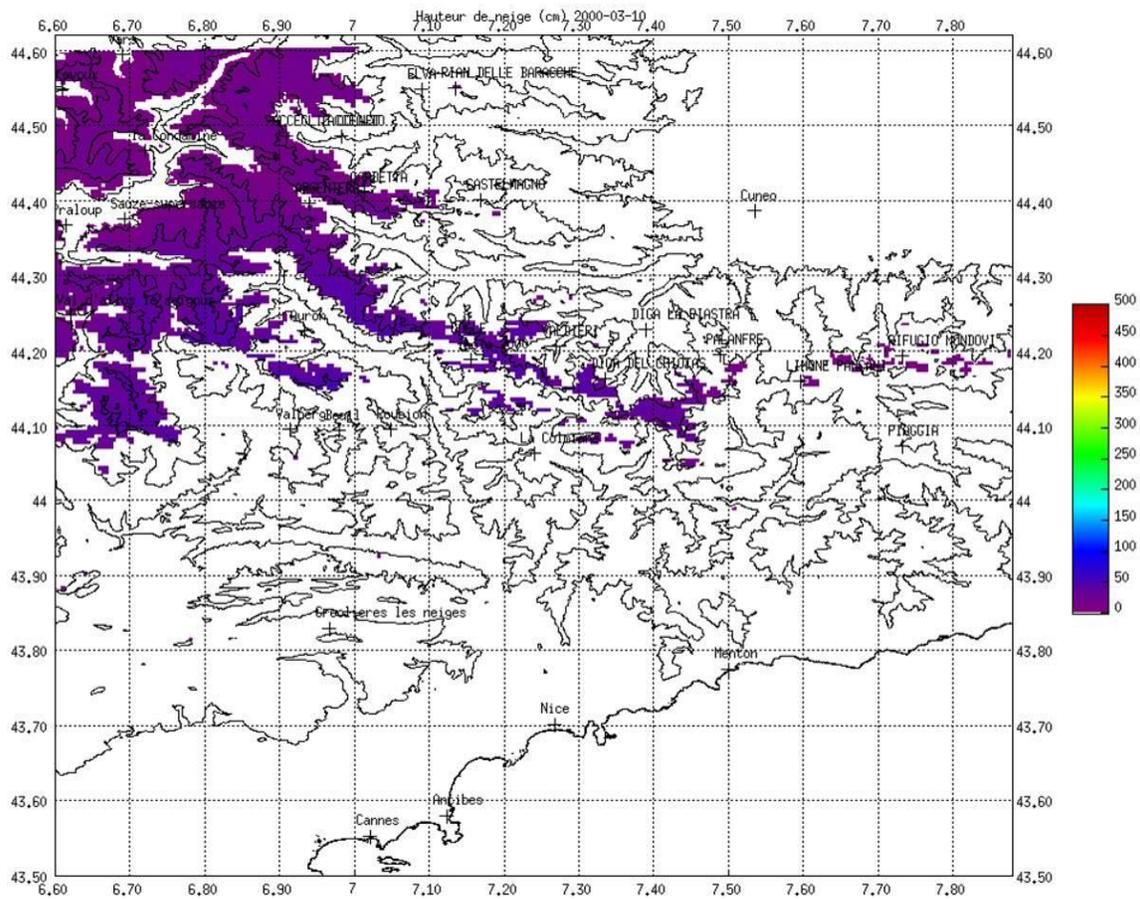


Figure 60: Snow cover information of Var catchment (Source: ALIRHYS project).

Moreover, we would like to highlight that only the topographical (DTM) and meteorological (Rainfall, Air temperature, Evapotranspiration and Snow cover) were collected from cooperation institutes or project, all the other information was downloaded from online databases which are free to all the public users.

Linking to the data available in this project, the functions selections of MIKE SHE model in Var catchment were showed in Figure 61. To simulate multi-hydrological processes in Var catchment, all the functions related to Water Movement (WM) were active in its model structure. With higher resolution DTM available in this project, the “Finite Different” method in the function of “Overland Flow (OL)” was selected to have more accurate simulation of surface water movement. However, as we mentioned before, the flow movement in MIKE SHE is calculated by 2D St.Venant equations with diffusive wave approximation, thus, the channel flow “Rivers and Lakes (OC)” is implemented by coupling with MIKE 11.

The soil data collection in AquaVar has big uncertainty mainly because of the soil type were not directly produced by the database (only material percentages were available). Therefore, detail information of the soil parameters such as the relationship between the hydraulic conductivity and soil moisture was not available in this modelling assessment. Besides, the depth of the soil asked by the MIKE SHE model to define the lower boundary in “Saturated Flow (SZ)” simulation was not available in this hydrological modelling assessment. To reduce the data requirements and simplify the modelling structure for reducing the uncertainty caused by data inputs, the “2 Layer UZ” method was selected in the “Unsaturated Flow (UZ)” function.

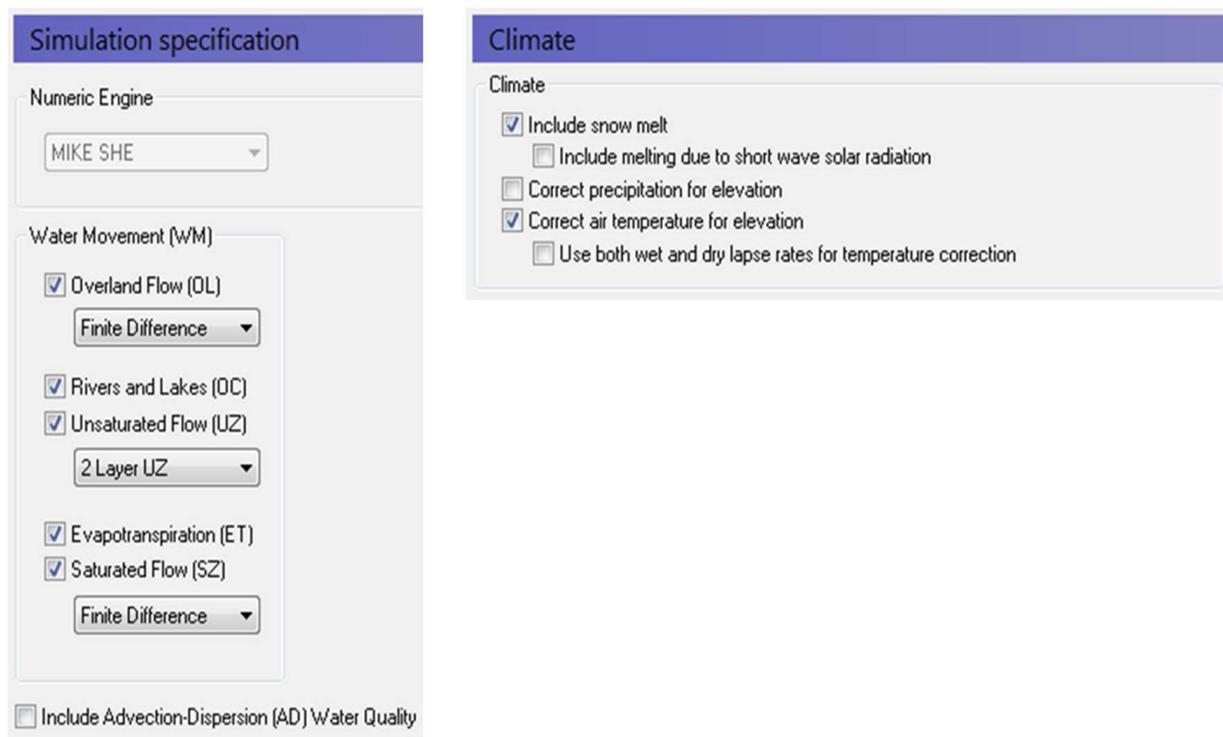


Figure 61: Function selection of MIKE SHE application in Var.

In the climate function, the snow melting simulation in MIKE SHE was selected to represent the influences of snow cover changes. However, even though we already understood that in this region the snow melting process is not only affected by the variation of air temperature but also influenced by the sun shine including intensity and duration, due to the data limitation only air temperature was available in Var, the function of “Include melting due to short wave solar radiation” was not selected in this model simulation.

Moreover, even though the SAFRAN database could produce the distributed air temperature cover the whole Var catchment, due to its coarse resolution (8000m × 8000m), this data was not selected to present the temperature variation in Var. Instead of fully distributed air temperature map, the “Station based” function is MIKE SHE was selected to represent the air temperature based on different gauging stations (Figure 62). Furthermore, the function of “Correct air temperature for elevation” was selected to describe the temperature changes caused by elevation variation with global average of -0.649C/100m.

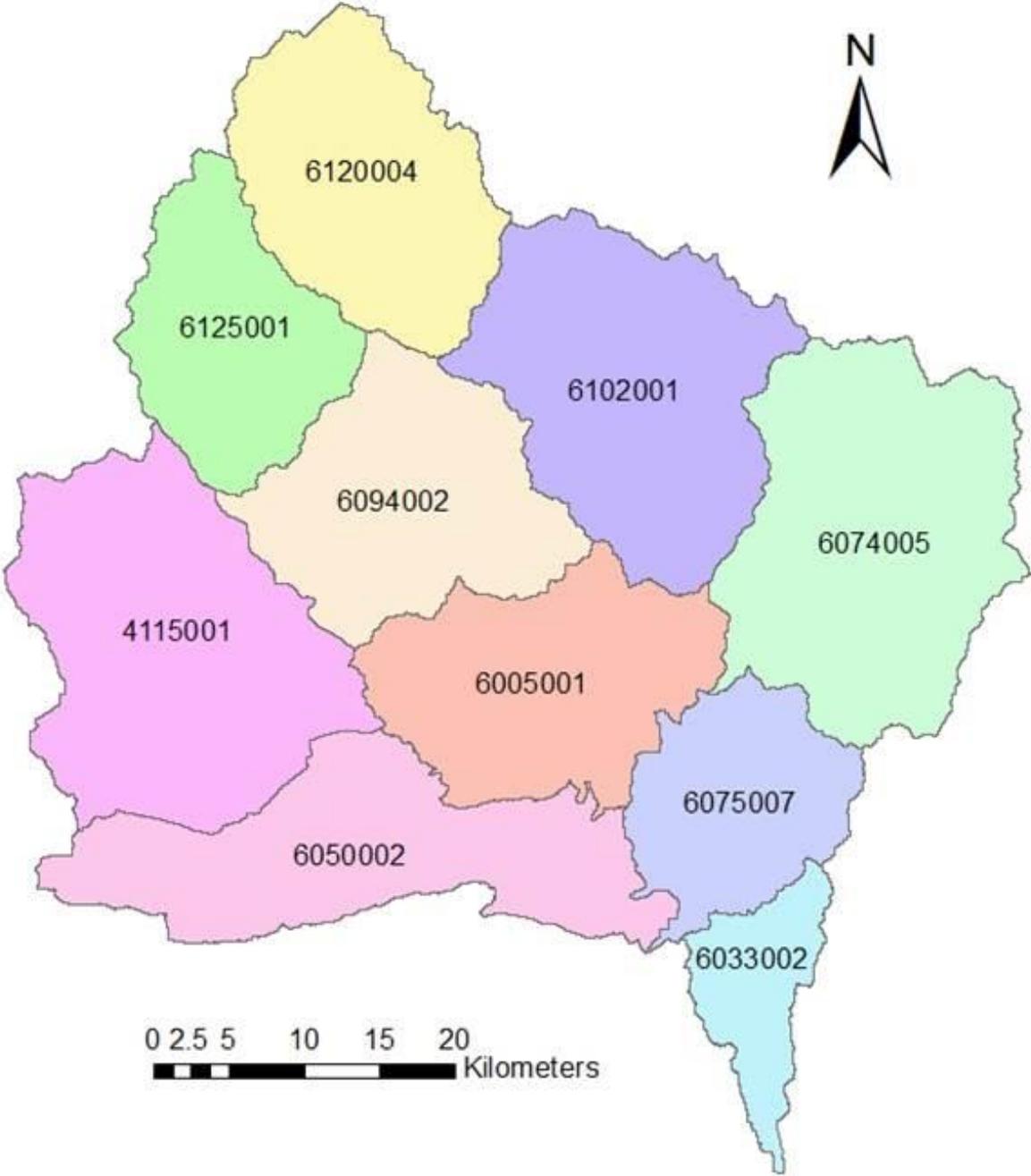


Figure 62: Station based air temperature distribution in Var.

4.2. Assessment of Simulation Resolution

The deterministic distributed hydrological model MIKE SHE is calculating the water movement through computational cells. In theory, the model with higher resolution could better represent the real phenomenon, but the computation time also be exponentially increased (Figure 63). There should be one optimized value of model resolution existed to balance the conflict between model accuracy and running time which we could general named as “Suitable simulation resolution”. Depends on the catchment characteristics and modelling objectives, the suitable simulation resolution in different cases could be slightly fluctuated. It is necessary to define this suitable model resolution before setting up the model simulation.

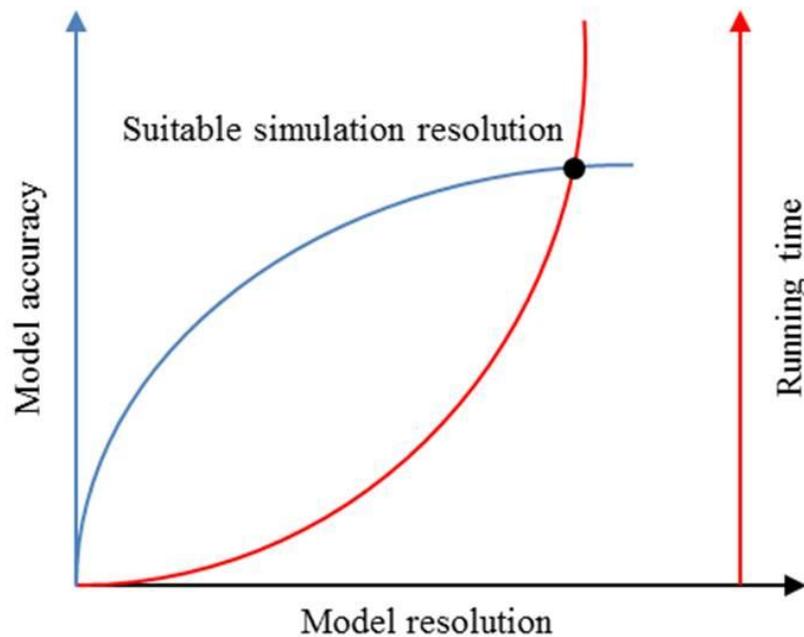


Figure 63: Relationships among model resolution, accuracy and running time.

In deterministic distributed model simulation, most of the physical factors were asked to be input with distributed format. However, very often, the distributed data collected from different producers has different resolutions. Therefore, the simulation resolution defined in the model needs to integrated consider the simulation objectives and the roles of different data inputs in the model calculation. In most of the cases, the model should be set up with certain resolution as same as the input data which involved in the premier hydrological process simulation defined by the modelers.

For this MIKE SHE application in Var catchment, firstly, in a catchment system consisted with multi-hydrological processes, the surface flow movement was considered as the most significant hydrological process which strongly affected the water distribution. Then, as we discussed before, to represent this process in the hydrological model simulation, as least two inputs should be taken into account in the simulation: topography and precipitation. Compared to the distributed precipitation, the resolution of the topography would have higher impacts on the model calculation due to one of the main input factors applied in the calculation formulas is the slope between each cell. Thus, the resolution of topography input applied in the model is often directly

identified as the model simulation resolution. And the suitable simulation resolution was pointed to the optimized resolution of topography accuracy and model running time.

In general, the topography information with high resolution is supposed to produce more detail and accurate presentation of the real elevation variation at the study area. However, in the discussion among deterministic distributed hydrological models, the “high resolution” is not the absolute high resolution such as data with 1m or less than 1m cell size, but the relative high resolution integrated considered the area and other geological characteristics of the catchment. For example, to represent the hydrological system at a medium size catchment mainly covered by flat terrain, the topography input applied in the simulation with a coarse resolution (e.g. 300m × 300m) could also be acceptable. But when people want to create a deterministic distributed simulation at a mountainous catchment with significant elevation variation, the higher resolution topography should be collected in the project.

The topography inputs in deterministic distributed hydrological model are frequently represented with DEM. The DEM could be further reclassified into two categories consisted with DTM and DSM (Digital Surface Model). The main difference between DTM and DSM is the DTM represents the terrain of the study area without any vegetation and artificial structures such as buildings. In this project, as we introduced in the previous section, the DTM data collected from Métropole Nice Côte d'Azur with 1m and 5m resolutions were available to be applied in the model simulation. The 1m resolution DTM measured at 2013 was expected to have more accurate information about the river channels at lower Var valley. But, due to the missing area in the data existed at the place belonged to department 04, the 5m resolution DTM without any missing areas was selected as the main topography reference in this resolution assessment.

The premier objective of model simulation is to produce accurate result. Thus compared to the having reasonable running time, this task should be first satisfied. In this AquaVar project, based on the 5m resolution DTM, four topography maps could be produced by resampling the information through GIS tools to assess the minimum data resolution of DTM accepted in this catchment. To evaluate the quality of those five DTMs, instead of assessing the elevation difference, we suggested that the evaluation criteria could more focus on their descriptions of surface slope. This is mainly because of in the computation equations applied at the MIKE SHE simulation, the surface slope is one of the driving factors involved in the calculation (Table 12).

Table 12: Assessment among DTMs with 5 resolutions in Var.

Data Resolution	A (km ²)	TDL (km)	MAX_S (°)	MIN_S(°)	AVG_S(°)	STD (°)
5 m×5 m	2814.58	2045.91	85.49	0	27.60	11.95
25 m × 25 m	2814.67	2021.51	80.79	0	26.74	11.23
75 m × 75 m	2816.49	1954.82	70.97	0	24.39	10.18
150 m × 150 m	2817.38	1896.98	58.38	0	21.55	9.36
300 m × 300 m	2819.70	1788.09	44.86	0.03	18.08	8.21

N.B.: A: Area (km²); TDL: Total Drainage Length (km); MAX_S: Maximum Slope (°); MIN_S: Minimum Slope (°); AVG_S: Average Slope (°); STD: Standard Deviation (°).

From the DTM assessment, we could conclude that the DTM resolution variation has obvious impacts in two aspects including surface slope and catchment drainage network. Comparison

between 5m and 300m resolution DTMs, in the coarse resolution data, the total drainage length had been reduced from 2045.91km to 1788.09km. And all of the surface slope factors had nearly 50% changes. It was clear that the 300m resolution DTM was not able to accurately represent Var topography characteristics. Moreover, when we analyzed the improvement of DTM quality from coarse resolution (300m) to high resolution (5m) in the table, the resolution increased from 300m to 150m has biggest improvements of 108.89km extension of total drainage length and 13.52° and 3.47° increases of maximum and average surface slope. Then, in the comparison among 300m, 150m and 75m resolution DTMs, it showed the improvements on all the assessing factors changed from 150m to 75m resolution had slightly decreased. The difference of total drainage length between those two data sets was only 57.84km and the improvements of both maximum and average surface slope was 12.59° and 2.84° respectively. Furthermore, after 75m resolution, kept increasing the DTM resolution until back to the original 5m resolution, the improvements of all the physical factors were continuously reduced. The differences among the higher resolutions (75m, 25m and 5m) were expected more concentrated at the mountainous area especially the summits or the cliffs in Var. The relationship between data accuracy and resolution was clearly followed the curve draw in Figure 63.

As we introduced before, in MIKE SHE model, the overland flow or called surface water movement is calculated with diffusive wave approximation of the St. Venant equations ignoring the impacts of momentum losses and the channel flow or called stream flow is simulated by coupling with MIKE 11 solving the fully dynamic 1D St. Venant equations. Therefore, the topography information including ground surface and river network was represented separately in the MIKE SHE simulation and both of them has their own criteria of resolution definition. In the overland flow simulation of MIKE SHE, the surface slope is the premier driving factor for identifying the suitable simulation resolution. But in MIKE 11, detail representation of branches and their channel shapes could be considered as the most important input material of setting up the model. From DTM resolution assessment, we noticed that the improvements of DTM quality in higher resolution range (from 75m to 5m) were not as significant as in lower resolution range (300m to 75m). Besides, their affected areas were presented at different places in Var. The improvement from coarse resolution to high resolution (e.g. 300m to 75m) were distributed cover whole the Var catchment. But the within the higher resolution assessment (e.g. 75m to 5m) only the summits in Var catchment were described more accurately which may not have significant impacts on the model accuracy as the affected area was relatedly smaller. Therefore, we could expected that for the Var catchment (nearly 2800km^2) with higher elevation variation (0m – 3800m), the DTM with resolution in range between 150m and 75m could be able to represent the topography characteristics in the MIKE SHE overland flow simulation of Var.

For the river network described in MIKE 11 model, unfortunately, in this catchment, there was few field data related to the mountainous streams and their cross sections. Considered the narrow cross section of the mountainous streams in Var, the information of both the river network and channel cross sections were better first extracted from higher resolution DTM (5m) through GIS software (Figure 64).

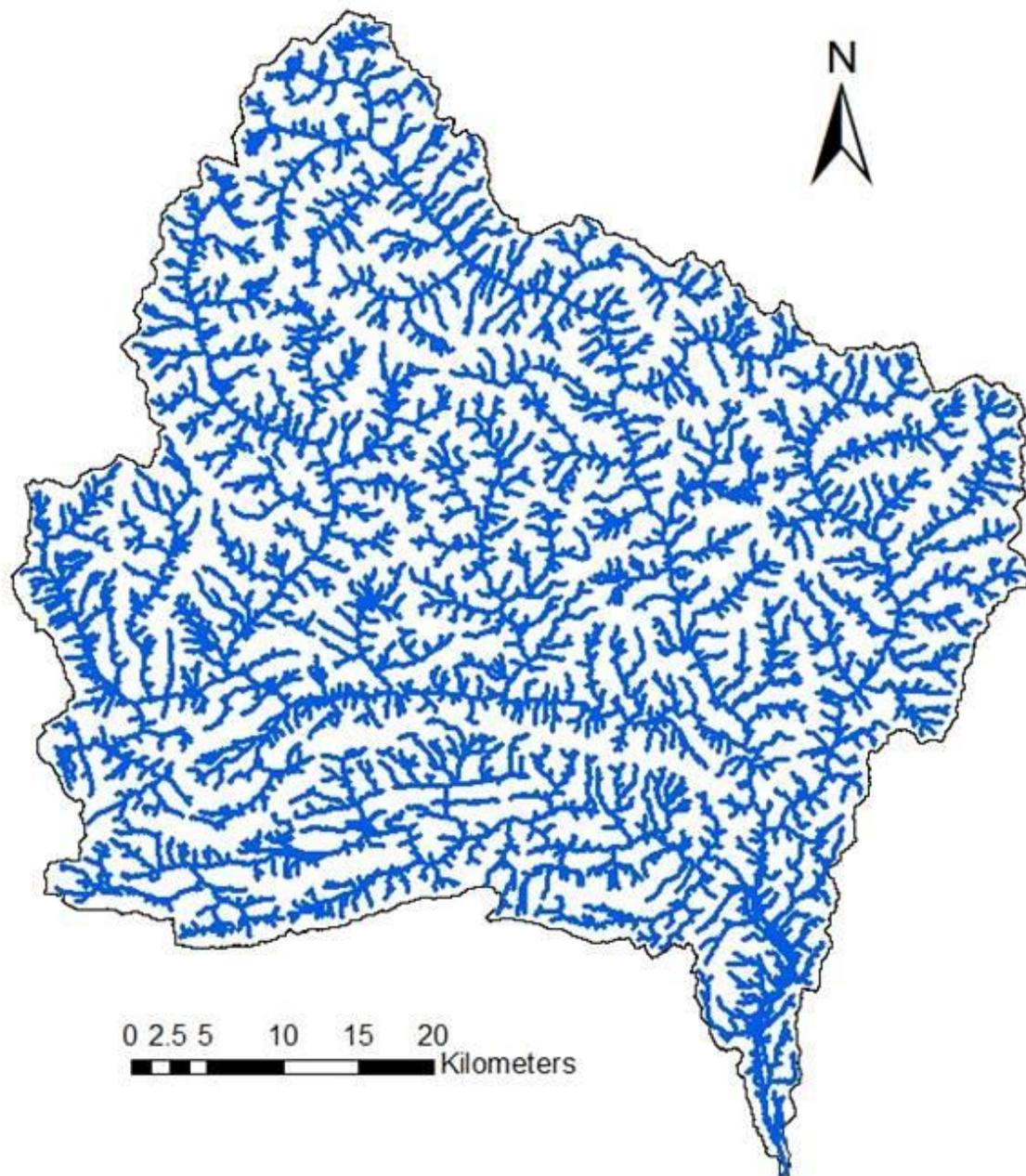


Figure 64: Drainage line of Var catchment (automatically extracted from 5 m resolution DTM).

The drainage lines extracted from 5m resolution DTM were the potential water paths calculated only depends on the elevation difference between each cell. In this case, the river network in Var was over-estimated. It is necessary to retreat this drainage network with some field survey or photography image of the interesting area by deleting the “unreal” branches from the drainage network automatically extracted from DTM. Supported by Métropole Nice Côte d'Azur, the photography image of department recorded at 2009 was applied as the main reference to achieve this task (Figure 65).

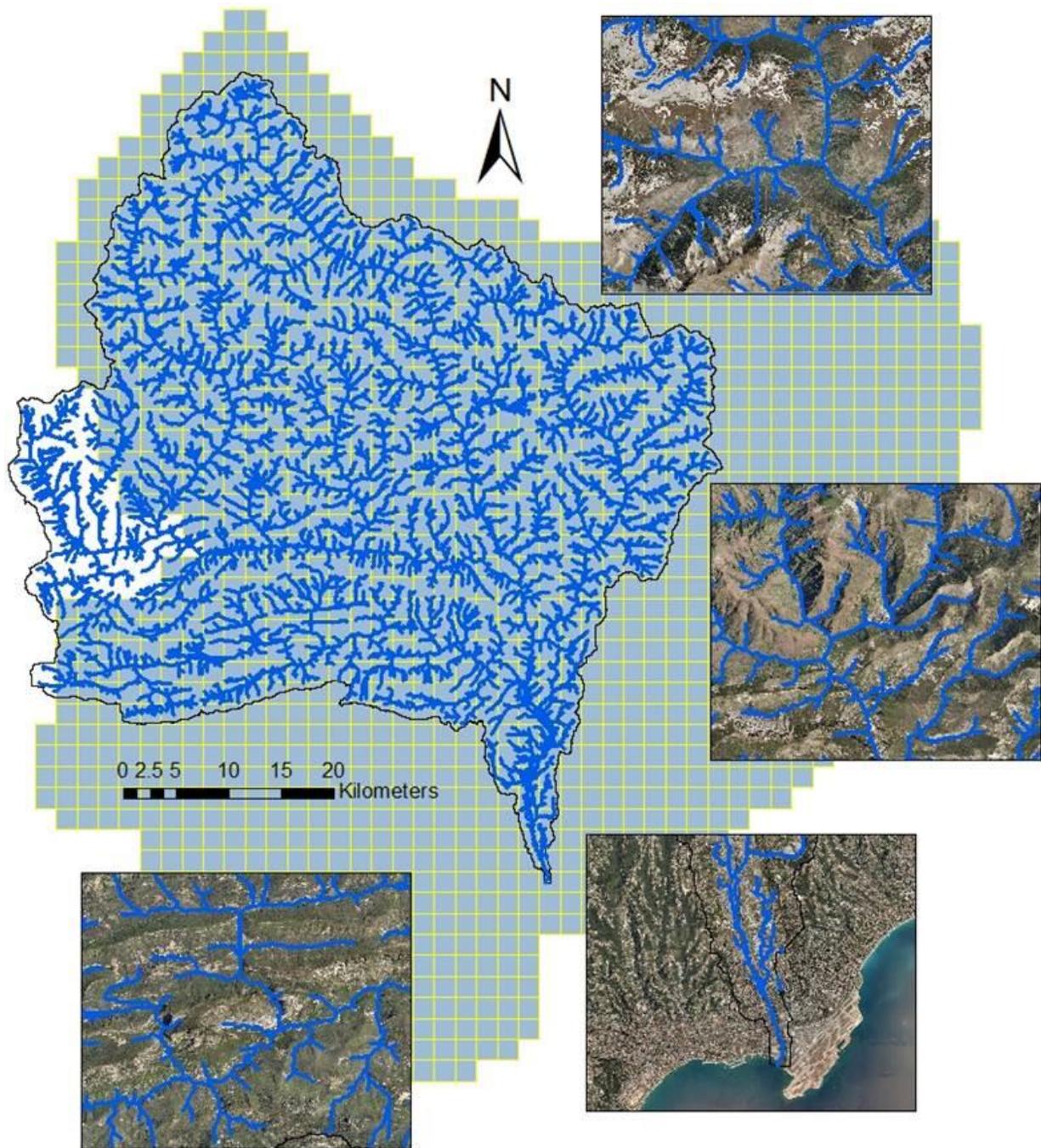


Figure 65: Double checked the branches existing in Var with reference of photography images.

In the small windows of the figure above, by checking with the photography data, the “fake branches” which indicated the potential flow paths could be clearly identified by reviewing the images. Then, through GIS tools, the drainage network in Var could be simplified by manually deleting those potential flow paths. The final river network in Var was showed in Figure 66.

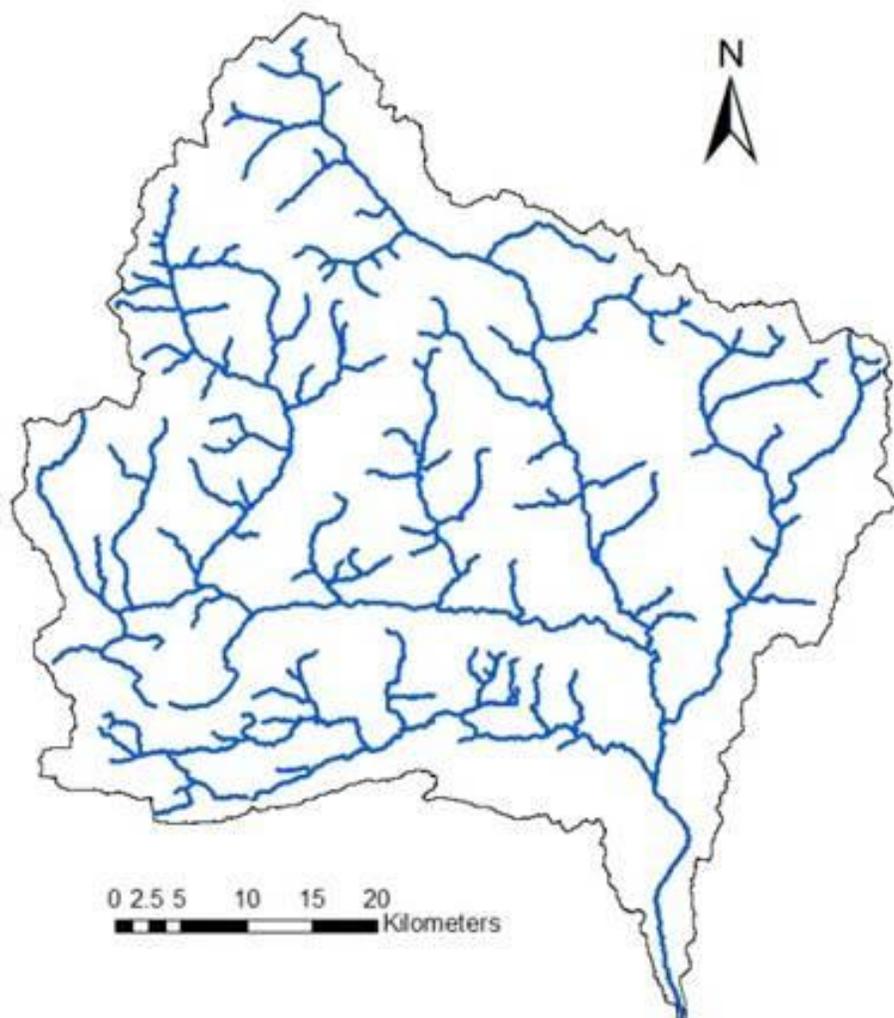


Figure 66: Var river network (based on 5 m DTM).

After simplifying the river network directly detected from 5 m resolution DTM, 126 branches in total were identified in Var. However, not all of them would be described in the MIKE SHE simulation coupling with MIKE 11. It is mainly due to the difficulty to keep stable condition in the numerical calculation of MIKE 11 with a large numbers of branches having steep slope. Besides, some of the small branches detected in the figure are only appeared in certain season (flood season). If they are added in the MIKE 11 model, during the dryer season, in reality there should be no water existed in that branch, but in the model simulation, to make the computation could be continued, the model will add a small amount of water in the channel. Then with more “dryer” branches added in the model, the amounts of water of model input and output would not be balanced. Thus, one branches selection or called assessment of river network resolution should be implemented in the first step of MIKE 11 model set up process to make sure that all the significant branches were taken into account in the simulation, and less “dryer” branches were added in the model river network. To achieve this task, based on the length of the branches, the branches in Var could be categorized into 4 classes showed in Table 13. There is impossible to

have the discharge records at each branch, but in theory, the discharge of longer branch could not be ignored in the model simulation. Based on the experience of local experts, there is no doubt to add the branches belong to first three categories. The only question is how many branches with river length less than 5 km should be taken into account in the simulation.

Table 13: Define the branches with four classes.

Class	Definition	Numbers	Total length (km)
1	Main Branches	5	293.12
2	$10\text{km} \leq \text{length}$	18	256.69
3	$5\text{km} \leq \text{length} < 10\text{km}$	30	194.92
4	$\text{length} < 5\text{km}$	74	196.28

To evaluate the number of branches required in the MIKE SHE simulation in Var, one flood modelling assessment was implemented. We selected the flood event in 2011 as the modelling case study, which was the most serious flood disaster during the period from 2008 to 2014. The MIKE SHE model was set up based on the 25m resolution DTM instead of 5 m to reduce the computation time. Only the functions of “Overland Flow” and channel flow (“Rivers and Lakes”) were active in the simulation as the main objective more focused on the surface and channel flow movement.

In the first step of modelling process, only the “Main Branches” defined in the table were added in the MIKE 11 river network (Figure 67). Comparison between the observation (points in the hydrography) and the simulation (lines in the hydrography), the simulated discharge at each sub-catchment was much lower than the observation. It indicated that not enough water was transferred into the river channel in this Var simulation.

In MIKE SHE, the coupling with MIKE 11 is implemented by comparing the water level difference between the linking stage and beside cells. When there is no branches existed, the surface flow movement is only depended on the water level difference between each two cells. At this time, the topography may start to play significant role in the calculation. In reality, there is no river has continuous decreasing river bed elevation along the channel. Thus, in MIKE SHE overland calculation, at some places with raised surface elevation, the terrain variation may block some water on the ground surface (Figure 68). In this case, without defined branches, the only chance for the blocked water to be transferred to the next cell is when the accumulated water level at blocked area is over the elevation gaps to the surrounded cells and at same its water level higher than other cells.

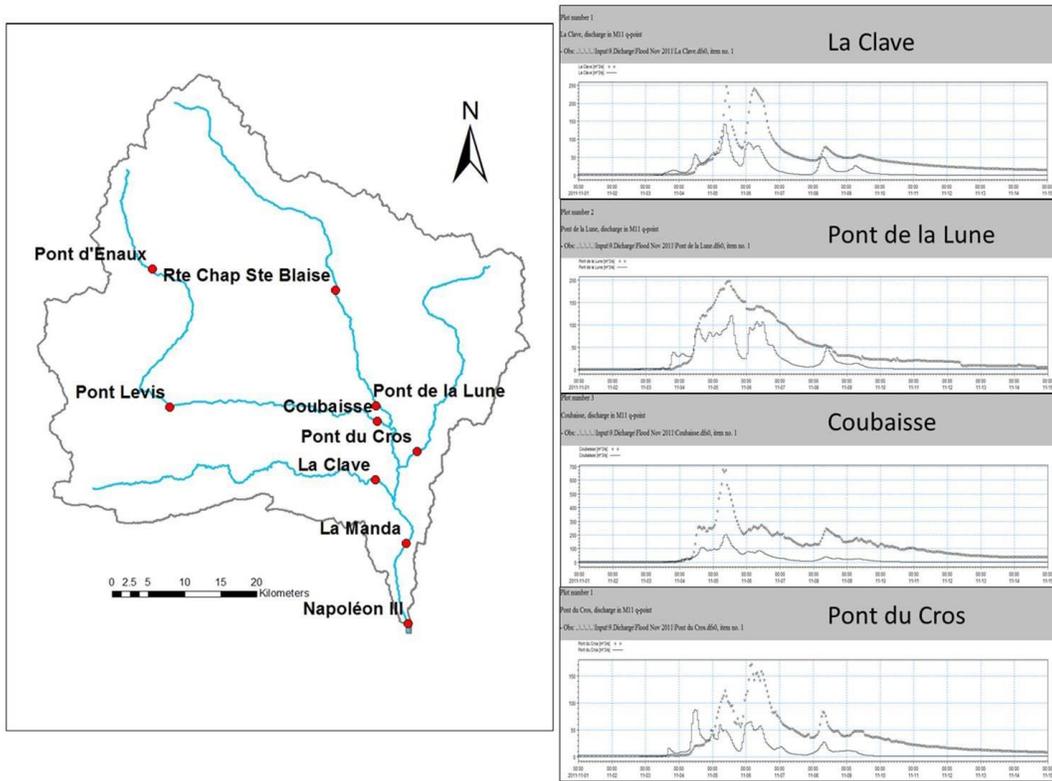


Figure 67: The simulated hydrographs with only main branches in the sub-catchment.

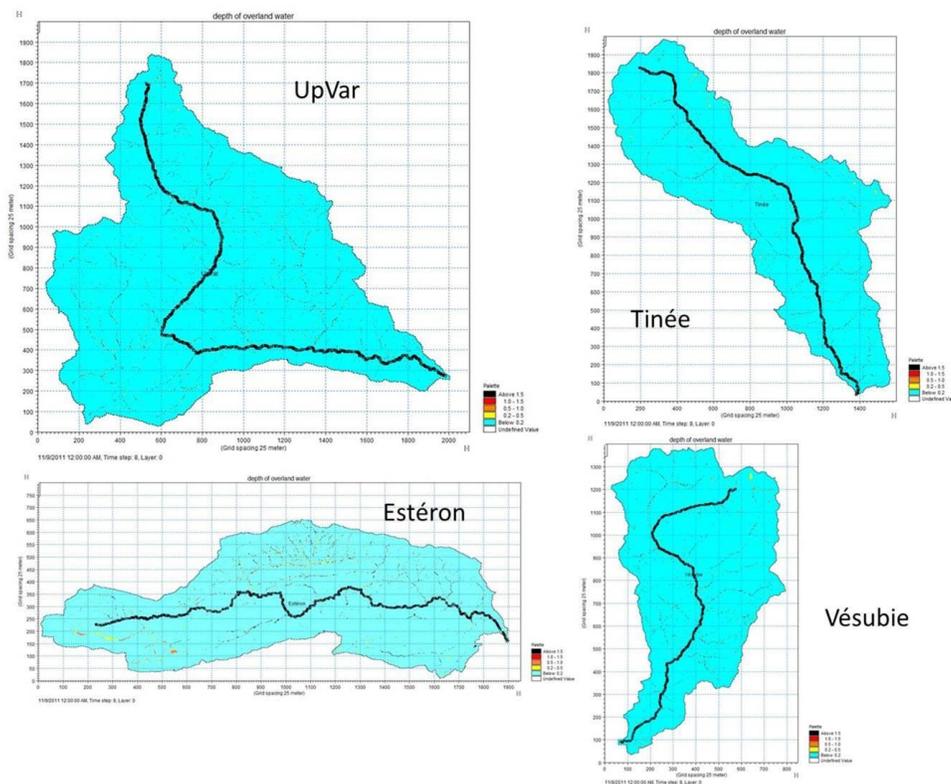


Figure 68: Water blocked at the “missing branches” area in Var catchment.

Then, the next step was added the branches in the second category with river length above 10 km in the MIKE 11 (Figure 69). With more branches added in the simulation, the hydrograph of simulated discharge at outlet of each sub-catchment had been moved up.

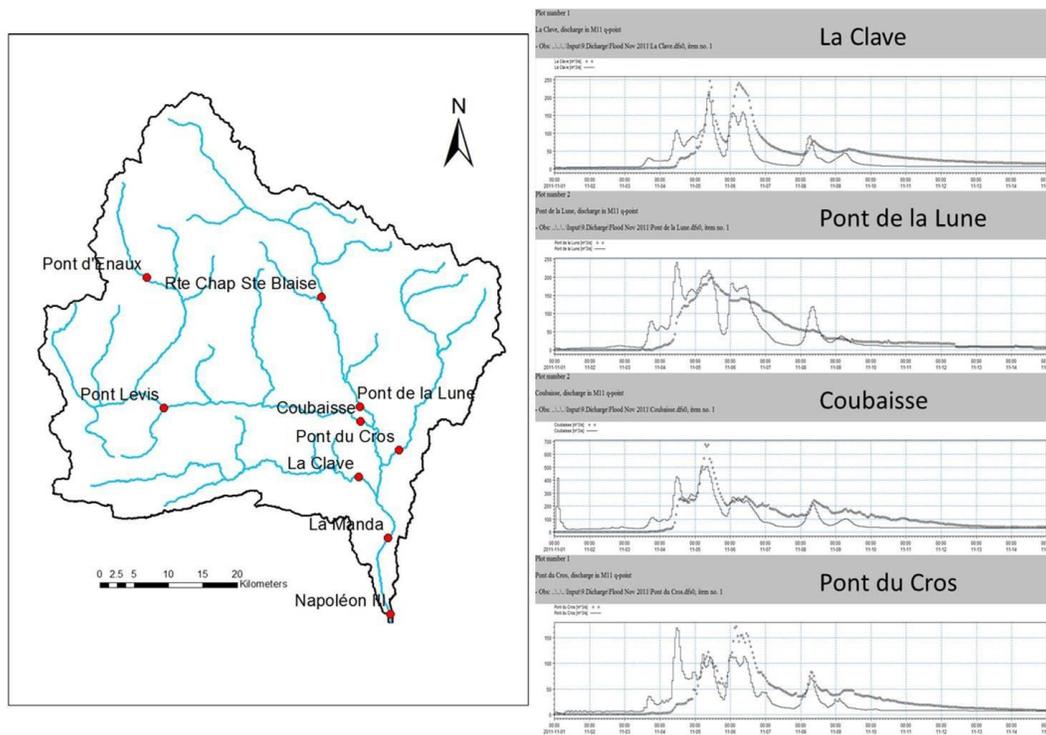


Figure 69: The simulated hydrographs with branches longer than 10 km in the sub-catchment.

Comparison between two simulations, both of the peak and low flows at each sub-catchment had been significant increased (Table 14). Moreover, compared to the growth of peak flow, for example at UpVar sub-catchment, increased from $202.78\text{m}^3/\text{s}$ up to $504.83\text{m}^3/\text{s}$, more obvious raise was found at the low flow which had increased 7 times more from $2.83\text{m}^3/\text{s}$ to $14.32\text{m}^3/\text{s}$. It indicated that in this modelling case with more branches added in the river network, less surface water flow was blocked in the overland flow simulation.

Table 14: Compared the hydrological elements simulated in 1st and 2nd model.

Station Name	Control Basin	1 st simulation		2 nd simulation	
		Peak flow (m ³ /s)	Low flow (m ³ /s)	Peak flow (m ³ /s)	Low flow (m ³ /s)
La Clave	Estéron	142.55	1.10	216.15	6.58
Pont de la Lune	Tinée	120.80	1.47	240.11	9.57
Coubaisse	UpVar	202.78	2.83	504.83	14.32
Pont du Cros	Vésubie	87.37	1.05	169.10	7.58

The next step was to continue adding the branches with river length longer than 5km in the simulated river network (Figure 70). However, compared to the previous improvement, added the branches which have total length in between 10km and 5km did not lead to significant increases of both peak and low flow values in Var catchment (Table 15). In the sub-catchments of Tinée, Vésubie and Estéron, the improvements of the peak and low flow were almost neglected. Even for the sub-catchment of UpVar which has biggest control area in Var catchment, the growth of the peak and low flow values in the simulation were just 18.39% and 15.36% respectively.

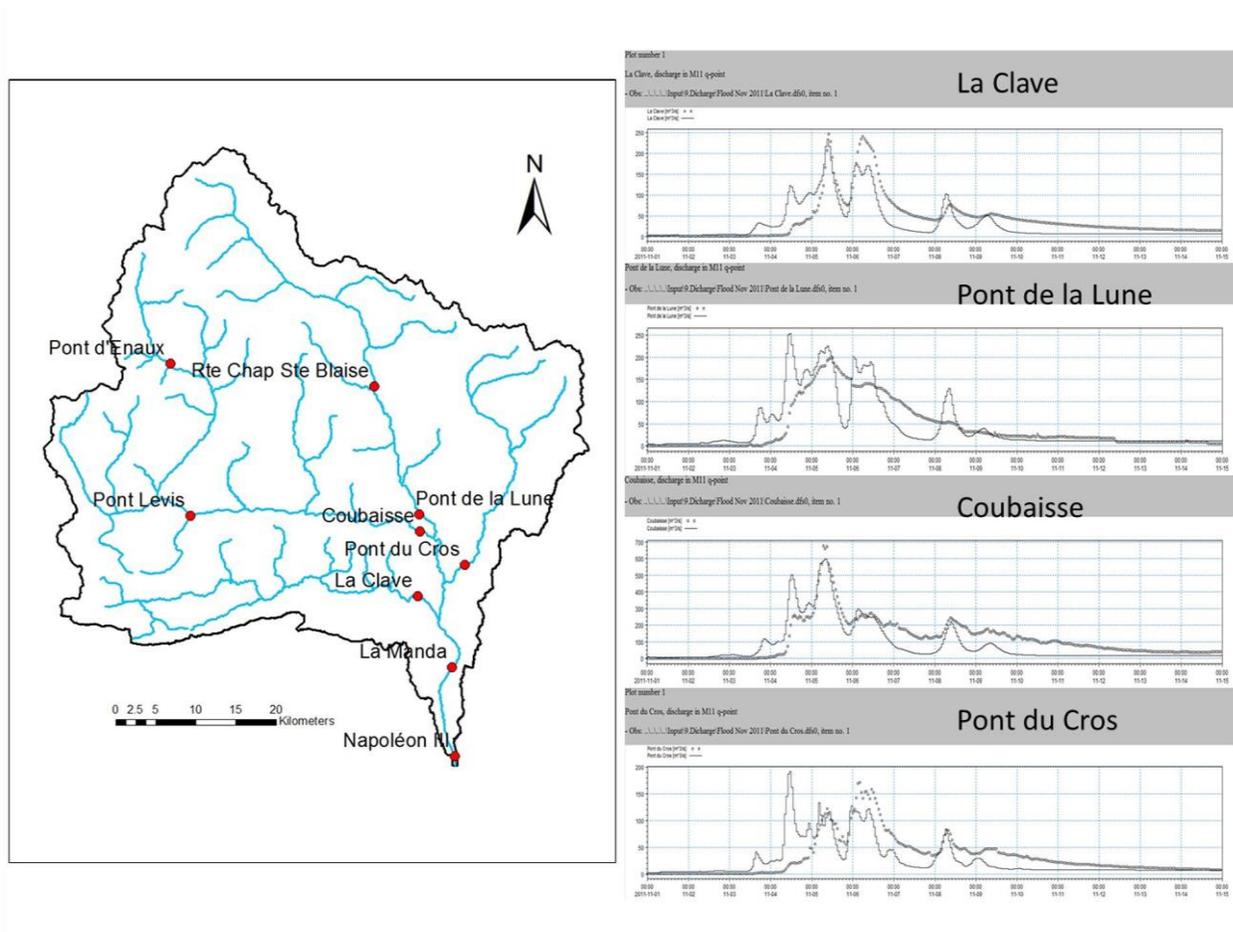


Figure 70: The simulated hydrographs with branches longer than 5 km in the sub-catchment.

Table 15: Compared the hydrological elements simulated in 2nd and 3rd model.

Station Name	Control Basin	2 nd model		3 rd model	
		Peak flow (m ³ /s)	Base flow (m ³ /s)	Peak flow (m ³ /s)	Base flow (m ³ /s)
La Clave	Estéron	216.15	6.58	234.03	7.07
Pont de la Lune	Tinée	240.11	9.57	253.48	10.98
Coubaisse	UpVar	504.83	14.32	597.67	16.52
Pont du Cros	Vésubie	169.10	7.58	191.44	7.63

As we mentioned before, the main objective of the model simulation is to represent the real phenomenon. In theory, all the branches existing in the study catchment should be added in the model simulation. However, due to the data and model limitation, in most of the modelling cases, some hypotheses were applied in the modelling strategy to reduce the number of added branches in the simulation. As same as the 2D overland flow, which based on the computation cells, we expected a threshold value of the number of branches added in the river network, which optimized the simulation accuracy and computational time. If we simply named the number of branches added in the simulated river network as the “resolution” of the stream system in the model, as same as the overland simulation, it is necessary to catch the suitable resolution of stream flow simulation in the MIKE SHE application in Var.

Comparison among three MIKE SHE modelling cases and observed hydrography, the simulation included all the branches longer than 5 km already added to produce reasonable representation of the real hydrological system in Var. Moreover, in the 3rd simulation, 53 branches in total were already added in the model simulation, considering the high slope in Var catchment, to add more branches in the simulation, the unstable possibility of the stream flow simulation in the model would be strongly increased. Therefore, for the branches which have total length less than 5 km, more detail discussion should be implemented at each sub-catchment.

- 1) For the Tinée sub-catchment, including the main branches, there were 10 branches added in the 3rd simulation. Considered the terrain of this catchment is mainly consisted with mountainous area, both ground surface and streams in this catchment has steep slope which often caused unstable problems in the model calculation, we decided to not add more branches in this catchment for the next step of modelling test. Moreover, as the simulated peak flow in the 3rd modelling case in this catchment was almost caught the observed value, to continue improving the model accuracy, we would more focused on the parameters calibration.
- 2) The situation in Vésubie sub-catchment is more complex than Tinée. In this study area, it also classified as mountainous catchment with steep surface slope. However, compared to Tinée, the human activities were more intense in this area. There are two famous villages Saint Martin-Vésubie and Collège de la Vésubie and several lakes located in Vésubie sub-catchment. Moreover, one artificial channel is taken water from this catchment and transfers the water resources to NICE city. Unfortunately, the information of human influence on natural system was very limited, which could not represented well in the model simulation. Therefore, compared the simulated peak flow to the observed values in this catchment, we expected to added a bit more branches with total length less than 5 km at the upper part of this sub-catchment.
- 3) For the sub-catchment of Estéron, this area has special geological characteristics of karst. Especially for low flow period, we expected the exchange between surface and ground water would play more significant role on the stream flow variation in this catchment hydrological

system. A few branches at the upper part of this catchment were continued adding in the model simulation to reduce the gap between simulation and observation runoff at the outlet of the catchment. For the rest part of the catchment, as same as Tinée area, more improvements of the simulation were expected in the calibration of model parameters especially the soil parameters.

- 4) The UpVar catchment has the largest control area in Var catchment concentrating the most part of the surface runoff to the downstream flow. This catchment could be slightly divided into two parts with different surface slope situation. In the upper part where the main terrain is as same as the Tinée sub-catchment consisted with mountainous area, several springs located in this area which produced the flow from underground to the surface. With limited information of the geological layers in this catchment, some branches were considered to be added in the simulation at the upper parts of UpVar sub-catchment to bring the blocked surface water into the main channels. Moreover, for the lower part of this catchment, its characteristics were more similar to the Estéron sub-catchment, which strong exchange between surface and underground. In this case we would like to follow the same strategy as in Estéron to not add more branches in the simulation. In addition, as the photograph data was missed in the department 04, the actual situation of the stream distribution in this area were not clear as in the area of department 06, several short branches in the mountainous area were added step by step.

The final river network in MIKE 11 coupled with MIKE SHE in Var catchment could be found in Figure 71 with all the cross section extracted from 5m resolution DTM in 500 m distance interval.

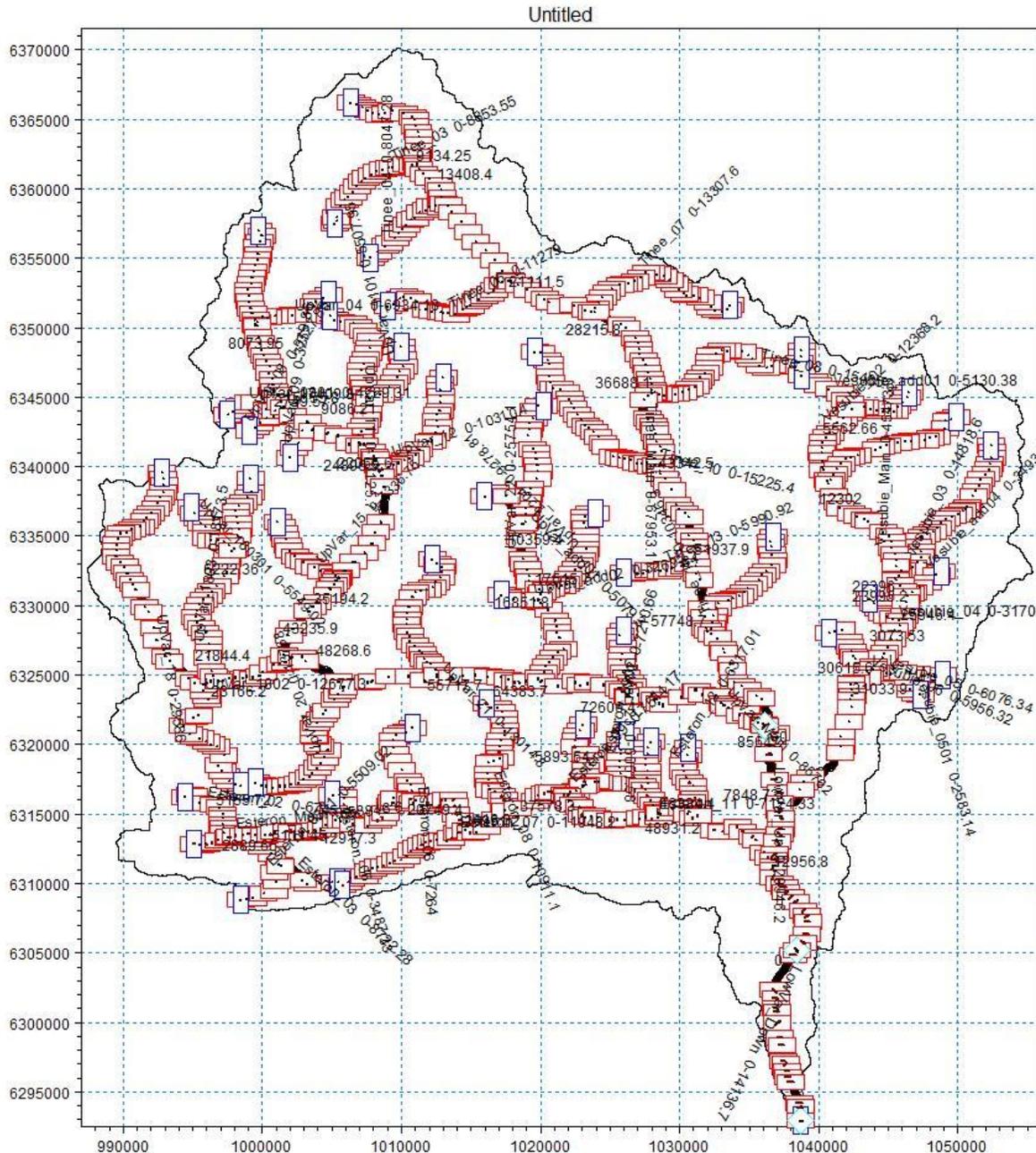


Figure 71: River network applied in the MIKE 11 model coupled with MIKE SHE in Var catchment.

In theory, the overland flow simulation was based on the computation cells and the stream flow simulation was along the branches. As we mentioned before, in both cases, the model has a suitable simulation resolution which optimize the model accuracy, running time and also the computation stable condition. Therefore, for the MIKE SHE application in Var catchment, the suitable model simulation resolution should integrated take into account those two kinds of model resolutions. One test of resolution impacts were implemented by the simulation of flood 1994.

In MIKE SHE simulation, the model supported the model calculation integrated with different computation layers including ground surface, unsaturated zone and saturated zone with different computation resolutions. As we mentioned before, the most important function in the simulation is related to the surface water movement and often applied to define the suitable simulation resolution. Therefore to assess the impacts of surface water simulation resolution, the test should more focus on the surface flow variation.

The case study applied to define the river branches numbers was the flood event recorded at 2011 which has more information available in the data collection. Especially for each sub-catchment, the runoff values of its outlet were feasible to be used as reference of cases evaluation. However, as we introduced in the review of historical events, the exchange flow between surface and underground water could not be ignored during the flood disaster. Therefore, to assess the resolution impacts on the surface water flow, this event was not suitable for achieving our tasks. Instead of this, the flood event recorded at 1994 was selected mainly due to the groundwater flow impacts could be neglected during the flood.

The test was implemented by comparison among three modelling cases with different overland resolutions of 300 m, 150 m and 75 m and same river network defined in MIKE11. To make sure that the assessment was fully focused on the resolution impacts, all the parameters including the Manning coefficients in the model simulation were defined with same values. The model results were shown in Figure 72.

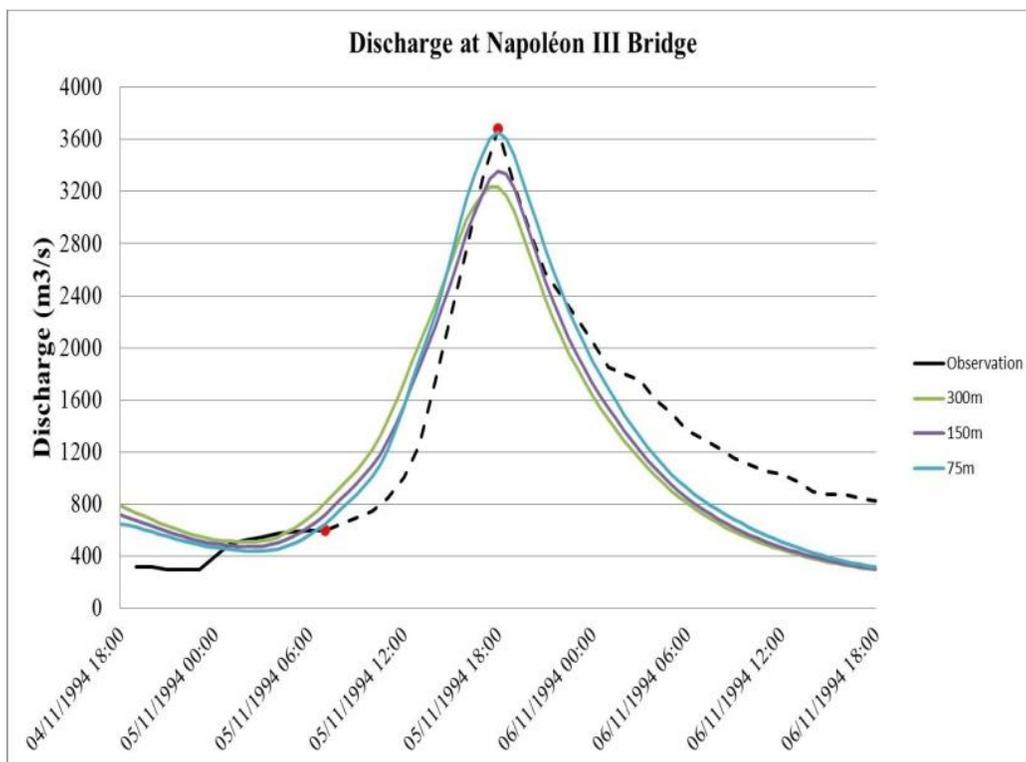


Figure 72: The hydrography of the simulation with different topography resolution.

As we introduced before, there was no runoff measurements available during the event. In the hydrography, all the runoff values after $600\text{m}^3/\text{s}$ were estimated after the event (dash line). Hence, catching the peak value was not the only evaluation criteria in this assessment. The peak time of the simulation may play more significant role among the modelling comparison.

It was obvious to notice those simulated peak values were increased with the raise of simulation resolution. Moreover, we could also find that in the simulation with coarse resolution (300m resolution), not only the simulated peak flow low than other simulations, but also the peak time was earlier than other simulation in 1 hour. The main reason of it could be as results of the flatter surface slope represented by coarse resolution topography input leads to the surface water moving fast before the peak time. Hence, in the simulation with 300m resolution topography input, the stream flow before the peak was slightly higher than other simulation cases. And after the flood peak, with flatter terrain, its simulated stream flow was fell down faster in the comparison hydrograph.

Comparison between 150m and 75m resolution simulations, both of them have same peak time as same as the observation. However, the peak value with higher resolution is clearly more than in lower resolution, but it simulation time was also significantly increased from several minutes to multi hours. Due to the peak value of observation has big uncertainty, both two simulation results could be considered as acceptable. Furthermore, considering the simulation time, the lower resolution simulation (150m) was recommended in the MIKE SHE application in Var catchment.

After assessing the suitable surface flow simulation resolution, in conclusion, the river network consisted with the branches more than 5km with the topography resolution in range between 75m and 150m could be evaluated as the suitable simulation resolution range of MIKE SHE in Var. Further consideration including the soil and land use inputs with 500m and 100m resolution respectively, the computation cells size was better in integral multiple relationships. Therefore, the suitable MIKE SHE simulation resolution in Var catchment was defined with $100\text{m} \times 100\text{m}$.

4.3. The Role of Spatial Distributed Rainfall in Var Simulation

The accuracy of deterministic distributed hydrological simulation is deeply depended on the quality of input data, especially the precipitation, which is often considered as the key factor in the hydrological process. The studies of [Arnaud et al. \(2002\)](#), [Tao \(2009\)](#) and [Zhao et al. \(2013\)](#) were clearly presented the rainfall spatial variability has strong impacts on not only the surface flow generation but also on other hydrological processes in catchment hydrological simulation. More studies related to the evaluation of rainfall distribution impacts in the hydrological simulation could be found in the assessment of spatial rainfall made by [Beven and Hornberger \(1982\)](#), who found that its spatial patterns significantly affect the peak flow distribution and timing, but for the flow volume, its impacts were almost negligible. Also, [Chaubey et al. \(1999\)](#) noted that the rainfall spatial variability could lead to big uncertainty of model parameters during the calibration process.

The accuracy of distributed rainfall data is affected by the catchment characteristics and other factors such as the rain gauge density. Many researchers has same conclusion that more dense measurement network will produce better spatial distributed rainfall, but there is still one debate related to the criterion of the numerous gauges per area. [Tao \(2009\)](#) highlighted that the best measure to improve the quality of spatial distributed rainfall is to increase the density of monitoring network. In the work of [Obled et al. \(1994\)](#), they recommended to implemented 5 rain gauges in 71km² catchment at South of France. And in the study of [Segond et al. \(2007\)](#) at Lee catchment in UK, they suggested for large rural area, a gauging network with density of 16 rain gauges for 1000 km² could be considered as acceptable and for smaller area such as 80-280 km², between 4 and 7 gauges were recommended as the minimum requirement. However, its recommended gauging density is difficult to be implemented on large catchment as Var with significant surface elevation variation. [Nicótina et al. \(2008\)](#) demonstrated in a large catchment (3500 km² similar as Var) the impacts of rainfall spatial variability is more serious and evidently effects on the runoff simulated by modelling tools. After reviewing previous studies, in the case of Var, to have more accurate simulation, a good interpolated rainfall distributed over whole catchment based on limited gauging stations was highly required.

Recently, several interpolation methods have been utilized to re-construct spatial distributed rainfall data in the hydrological simulation. In general those interpolation methods could be classified into two main categories including deterministic technique and geostatistical technique. The deterministic technique often considers the distance between interpolated point and the gauging points. Several famous methods could be highlighted here such as Thiessen polygon method, Inverse Distance Weight (IDW) method and Spline method. And the geostatistical technique could allow the interpolation considering more geo-factors such as topography, wind and distance to the sea. In theory, the interpolation with deterministic technique is more simple to be applied, but its results may be not that accurate mainly due to the missing of geostatistical factors in the process ([Goovaerts, 2000](#); [Mair and Fares, 2010](#); [Tobin et al., 2011](#)).

[Brunsdon et al. \(2001\)](#) introduced the relationship between rainfall and altitude in UK, it varied from 1.5 mm/m to 4.5 mm/m depends on the catchment. From the studies of [Basist et al. \(1994\)](#) and [Gouvas et al. \(2009\)](#), we noticed that the precipitation typically increased with growth of elevation. However, one valuable study of [Allamano et al. \(2009\)](#) assessed 567 gauging stations in alpine Italy, identified the rainfall dependence of rainfall due to the surface elevation. On the

contrary to our expectations, the maximum annual precipitations of short duration were found to be strongly decreased when elevation raise up. Other researches were related to take into account the impacts of climate factors such as wind (Johansson and Chen, 2003; Johnson and Hanson, 1995).

One of the most famous geo-statistical techniques is the Kriging interpolation method which we already introduced before. Many studies had proved that this method could produce reasonable rainfall interpolation results for hydrological simulation (Mair and Fares, 2010; Tao, 2009). Recently, one improvement interpolation method named as Geographically Weight Regression (GWR) are more commonly applied in the rainfall distribution which has advantages of being much simpler than previous multiple regression approaches and also incorporating the varying relationship between rainfall and other geo-statistical factors (Al-Ahmadi, 2013; Bostan and Akyürek, 2009; Lloyd, 2005; Chu, 2012).

However, even in theory the interpolation method in geo-statistical technique supposed to produce more accurate rainfall distribution information, due to the different characteristics of the study catchments, there is no clear conclusion of the best interpolation method. Therefore, in the case study of hydrological simulation in Var, it is necessary to evaluate the results of different interpolation method before setting up the MIKE SHE model.

In this section, the interpolation methods including Thiessen polygons, IDW, Spline, Natural Neighbor, Kriging and GWR were assessed with cross validation method evaluated by Nash coefficient to find the most suitable interpolation function in Var catchment located at French Mediterranean region. The study introduced here had identified the added value of each method and their applicability in Var catchment. The analysis process could also be generalized and used as one operational function for other large catchments.

4.3.1 Methods of rainfall interpolation assessment

Thiessen Polygon interpolation method

The interpolation method of Thiessen Polygon assumes each precipitation gauge does not get same weight as in the arithmetic method (Figure 73)

$$P = \frac{\sum_i^n P_i A_i}{A} \quad \text{Equation 21}$$

where P_i : recorded precipitation at gauging station i .

A_i : control area of the polygon created based on stations i .

A : total area of the study catchment

n : number of rainfall gauging stations available in the catchment.

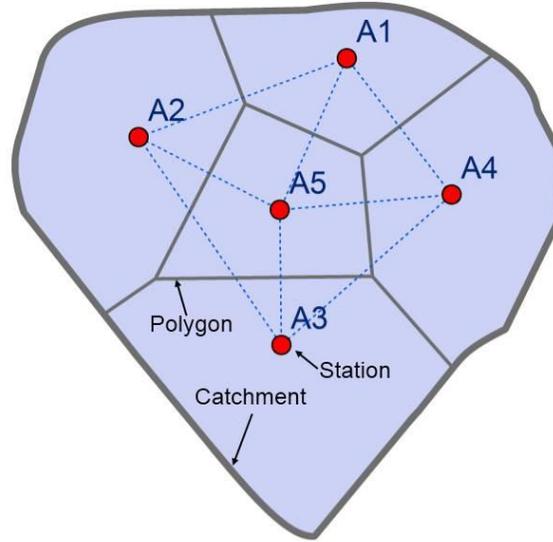


Figure 73: Thiessen Polygon interpolation method.

Inverse Distance Weight (IDW) interpolation method

The IDW interpolation was developed by US National Weather Service in 1972 which estimated the cell values by using a weight average of sample points in neighborhoods (Goovaerts, 2000). Obviously, the accuracy of the interpolation results highly depends on the gauge density. When the neighboring gauging points were unevenly distributed, the quality of interpolation results will be decreased.

Several formulas were conceived to define the weight values in IDW interpolation process. Here the simplest form proposed by Shepard (1968) was applied to join the discussion of interpolation methods comparison. The Shepard method suggests the weight function w_i could be defined through the following equation:

$$w_i = \frac{h_i^{-p}}{\sum_{j=0}^n h_j^{-p}} \quad \text{Equation 22}$$

where p is an arbitrary positive real number called the power parameter (typically $p=2$) and h_i is the distance from the dispersion points to the interpolation point which calculated by:

$$h_i = \sqrt{(x - x_i)^2 + (y - y_i)^2} \quad \text{Equation 23}$$

where (x, y) and (x_i, y_i) are the coordinates of the interpolation point and dispersion point respectively. The weight function varies with a value of unity at the dispersion point to a value close to zero as the distance to the dispersion point increase. The weight functions are normalized as a sum of the weights of the unit. Thus, the interpolated value of the electric field $P_{(x,y)}$ is given by:

$$P_{(x,y)} = \sum_{j=0}^n w_j P_{(x_j,y_j)} \quad \text{Equation 24}$$

Spline interpolation method

The Spline interpolation method is the method estimating the value based on a mathematical function of minimizing overall surface curvature and resulting in a smooth surface passes exactly through the inputs gauging points (Tao, 2009). The algorithm used for Spline interpolation tool in ArcGIS software was given as follow:

$$P_{(x,y)} = T_{(x,y)} + \sum_{j=1}^n \lambda_j R(r_j) \quad \text{Equation 25}$$

Where n: the number of points

λ_j : coefficients found by the solution of a system of linear equations

r_j : distance from the point (x,y) to the j^{th} point

$T_{(x,y)}$ and $R(r)$: defined differently, depending on the selected options

Natural Neighbor interpolation method

The Natural Neighbor interpolation is a geometric estimation technique which depends on the natural neighbourhood regions generated around the gauging points. Instead of finding an interpolated point's value using all of the input points weighted by their distance, Natural Neighbor interpolation creates a Delauney Triangulation of the input points and selects the closest nodes that form a convex hull around the interpolation point, then weights their values by proportionate area (Figure 74).

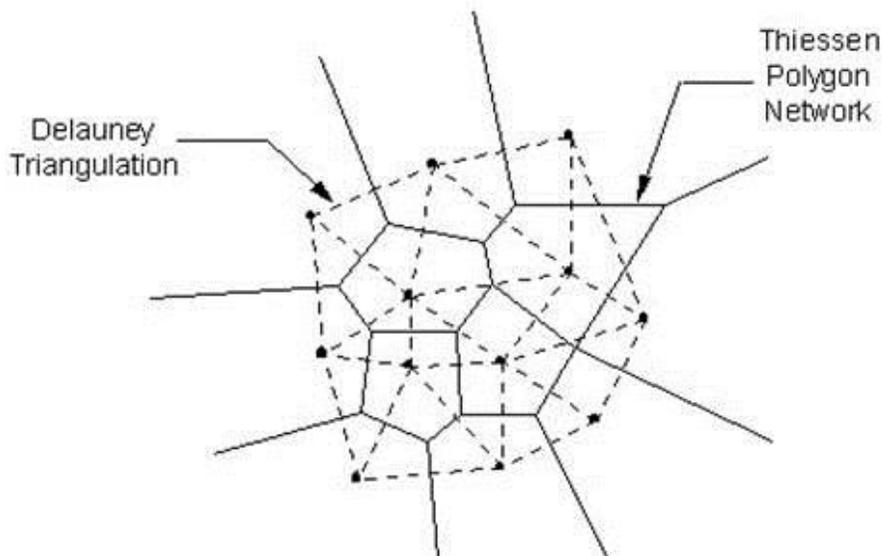


Figure 74: Delauney Triangulation defined in Natural Neighbor interpolation method (Source: Google image).

$$G_{(x,y)} = \sum_{i=1}^N w_i f(x_i, y_i) \quad \text{Equation 26}$$

Where $G_{(x,y)}$: estimated value at location (x, y)

w_i and (x_i, y_i) : are the weight at known value at location (x_i, y_i)

Kriging interpolation method

The Kriging interpolation method is well known as one of the best solution of interpolation which consisted of a family of least-square linear regression algorithms applied to estimated random fields from observed data (Goovaerts, 1997; 1998; Tobin et al., 2011). The equations in Kriging method are similar as IDW method, but the weight coefficient w_i here is not only referenced by the distance between the gauged points and the predication locations but also calculated with overall spatial arrangement of the measured points.

To apply the spatial arrangement in the weights estimation, the spatial autocorrelation should be quantified. In this assessment, the Spherical and Linear Kriging interpolation process were implemented in the function available in ArcGIS software.

Geographically Weight Regression (GWR) interpolation method

The GWR interpolation method is a new local spatial statistical method used to examine and determine the spatial non stationary distribution when the relationships among variables vary from location to location (Fotheringham et al., 2003). In this case, by using the ArcGIS software, the GWR function taking into account the elevation difference was implemented in the assessment.

Method applied to evaluate function performance

The effectiveness of each interpolation method was assessed by using cross-validation method which temporarily removes one observation point at a time from the database and re-estimates the removed values from the remaining data by using different tested interpolation methods (Mair and Fares, 2010). The correlation coefficient (R), root mean squared error (RMSE) and Nash-Sutcliffe coefficient (NSE) were utilized to evaluate the correlation between each stations and the accuracy of each interpolation method. The formulas and their performance levels were shown as follow:

$$R = \frac{\sum_{i=1}^n (X_{obs,i} - \bar{X}_{obs})(X_{model,i} - \bar{X}_{model})}{\sqrt{\sum_{i=1}^n (X_{obs,i} - \bar{X}_{obs})^2 \sum_{i=1}^n (X_{model,i} - \bar{X}_{model})^2}} \quad \text{Equation 27}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (X_{obs,i} - X_{model,i})^2}{n}} \quad \text{Equation 28}$$

$$NSE = 1 - \frac{\sum_{i=1}^n (X_{obs,i} - X_{model,i})^2}{\sum_{i=1}^n (X_{obs,i} - \bar{X}_{obs})^2} \quad \text{Equation 29}$$

where $X_{obs,i}$ and $X_{model,i}$: are the observed and modeled values at time step i, \bar{X}_{obs} and \bar{X}_{model} : are the average of observed and modeled values.

Table 16: Performance criteria for model evaluation (Wang et al., 2012).

Performance indicator	Excellent	Good	Fair	Poor
R	>0.95	0.85-0.95	0.75-0.85	<0.75
NSE	>0.85	0.65-0.85	0.5-0.65	<0.5

After reviewing many previous rainfall interpolation studies, there are two points we would like to be highlighted in advance of implementing the assessment in our case. The first one is many studies already demonstrated the rainfall distribution was highly affected by many factors in aspects among geology, meteorology or even human activities. And for each impact factor, its weight in the interpolation function showed dramatic changes in different study areas. Until now, there is no clear definition of premier impact factor in the rainfall interpolation. The second one is in most of the rainfall interpolation studies, their assessed samples were collected with big time interval such as annual data or monthly data. There is few case study applied the short time interval records as the interpolation reference. One of the reasons could due to the randomness of the short time rainfall which it difficult to be interpolated based on the recorded data. Another reason is due to the measurement uncertainty which may confuse the researchers the sources of uncertainty in the interpolation result is from the method or data itself.

However, in this case study in Var catchment, as we mentioned before, due to the steep slope in the catchment which lead to the short response time for the rainfall-runoff process, to represent the real time hydrological situation in the catchment and to be able to forecast further phenomenon, the simulation at least should be implemented with daily time interval (more or less equal to the response time). Thus the two problems discussed above will be all faced by the modelers in Var. To find the most suitable rainfall interpolation function in Var catchment, the designed working process was described in Figure 75.

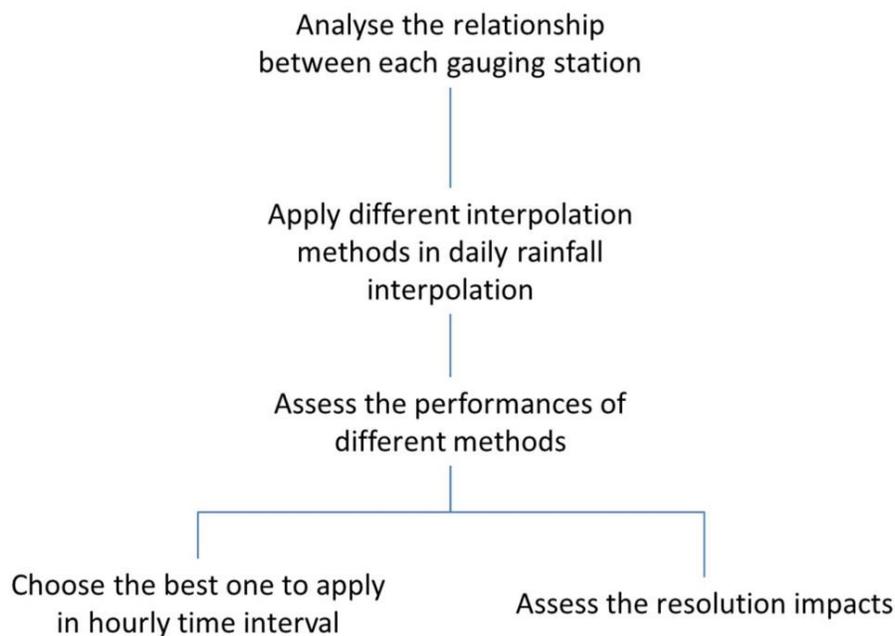


Figure 75: Designed working process for rainfall interpolation assessment in Var.

4.3.2 General statistical analysis of different interpolation results

As we mentioned before, the rainfall in short time may show higher randomness, so the study was started from the correlation analysis between each station. In this case, the daily rainfall records at 16 gauging stations and hourly records at 10 gauging stations were applied as the main reference samples. The correlation assessment among different rainfall stations with monthly, daily and hourly records were listed in Appendix which clearly response to our expectation which the rainfall correlation at different stations showed decreased trend with the increase of distance and decrease of the records time interval. The average correlation value of monthly rainfall in Var catchment is around 0.9, but when tested with daily records, it reduced to around 0.8. And the average hourly correlation among different rainfall gauges was just 0.47 which almost indicated the hourly rainfall distribution has the highest randomness in Var catchment and there could be big uncertainty in the hourly rainfall interpolation results.

Firstly, for the Thiessen Polygon interpolation method, the map of Thiessen Polygon was showed in Figure 76. However, as we mentioned the correlation between each station showed decreased trend with short time interval, the Thiessen Polygon method which assumed the rainfall in each cell located in the polygons as same as the records at the control stations may not suitable for estimating the short time rainfall distribution in Var.

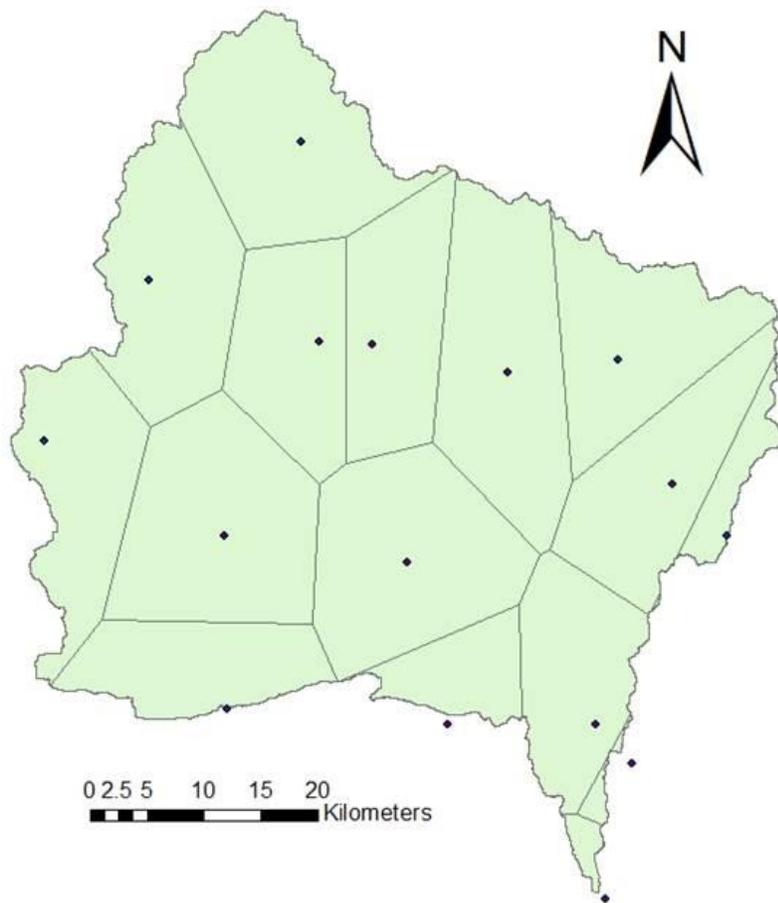


Figure 76: Thiessen Polygon over Var based on 16 daily stations.

Then, the cross-validation process was applied for other interpolation methods with the selected stations inside the monitoring network (Figure 77). In the figure, among 16 daily stations available in Var catchment, only the stations in green colour (9/16) were selected in the test with the main reason due to the limits of some interpolation required reference sample at the boundary (e.g. Natural Neighbor).

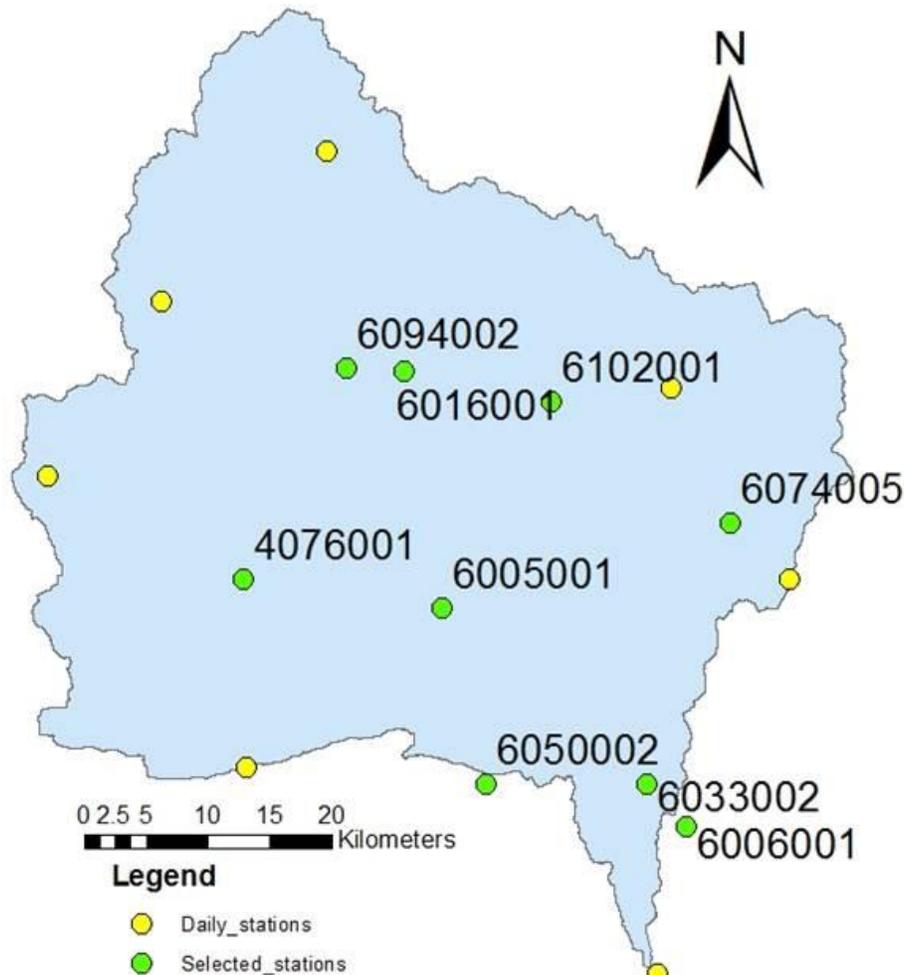


Figure 77: The selected stations for the cross-validation process.

The assessment results were shown in Table 17. Among 7 interpolation methods assessed in this cross-validation process including IDW, Spline, Natural Neighbor, Ordinary Kriging with Spherical semivariogram model (Kriging_S), Ordinary Kriging with Linear semivariogram model (Kriging_L), GWR considering the elevation impacts (GWR_Z) and GWR considering impacts from elevation and its distance to the sea (GWR_ZD), all their statistical coefficient showed good performance in Var. None of the interpolation results had REMS bigger than 5 and NSE lower than 0.75 which is in the performance level of “Good”. However, comparison among different interpolations, the results from IDW and Kriging_S showed the better performances in this test with higher NSE numbers of 0.87 and 0.86 respectively and lower RMSE of 3.2 and 3.3. Even though, the differences between the best interpolation results based on IDW method and the worst interpolation results generated by Spline were almost negligible (NSE: 0.87 vs. 0.72; RMSE: 3.2 vs. 4.52). Thus, if we make the decision only depends on the cross-validation results

which are mainly assessed by statistical coefficients, all the interpolation functions were acceptable in the Var catchment where located at the French Mediterranean region.

Table 17: Statistical coefficients of rainfall interpolation methods.

RMSE										
Stations Methods	4076001	6005001	6006001	6016001	6033002	6050002	6074005	6094002	6102001	average
IDW	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20
Spline	4.52	4.52	4.52	4.52	4.52	4.52	4.52	4.52	4.52	4.52
Natural	3.29	3.29	3.29	3.29	3.29	3.29	3.29	3.29	3.29	3.29
Kriging_S	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30
Kriging_L	3.38	3.38	3.38	3.38	3.38	3.38	3.38	3.38	3.38	3.38
GWR_Z	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64
GWR_ZD	3.58	3.58	3.58	3.58	3.58	3.58	3.58	3.58	3.58	3.58
NSE										
Stations Methods	4076001	6005001	6006001	6016001	6033002	6050002	6074005	6094002	6102001	average
IDW	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87
Spline	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
Natural	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86
Kriging_S	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86
Kriging_L	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
GWR_Z	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
GWR_ZD	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83

However, there were two points that should be highlighted here in this interpolation assessment:

- All the interpolation results showed good performance with statistical analysis. The main reason of that could be due to the selection of the tested stations, where no boundary stations were taken into account in the cross-validation process. As the average daily correlation between each station was around 0.8, getting the NSE of all the interpolation above 0.75 is not surprised for us.
- It is also interesting to notice that, in Var catchment, both the IDW and Kriging interpolation results showed higher performance and considered their statistical coefficients, IDW interpolation seems the most suitable interpolation function in Var catchment. This conclusion may out of our expectation before, as in theory, the geostatistical technique which considering more geo-factors supposed to produce more accurate results. Especially for the GWR_ZD interpolation process which taken into account both the elevation impacts and the sea impacts (distance to the sea), its statistical results did not show good performance and even worse than the results produced by Kriging interpolation. However, in the study of [Tao et al. \(2009\)](#), who assessed the different interpolation methods' effects in small catchment with high density rainfall in Lyon, France, which is not so far from here, they demonstrated there is no obvious difference between the interpolation results from Kriging and IDW, and in the area of Lyon, the IDW interpolation seems more suitable for the rainfall interpolation process. This judgment contributes a part to confirm our results.

4.3.3 Detail statistical analysis of different interpolation results

In the previous assessment, the boundary stations were not taken into account in the analysis mainly due to the limits of some interpolation requires the boundary stations as the main reference in the calculation. Right now, if we took these stations into the assessment and only tested the interpolation methods which don't have the computation limits (IDW, Spline, Kriging_S and Kriging_L), the results showed that the IDW still had the highest NSE value of 0.85 and Spline had the lowest NSE values of 0.78. However, compared with the previous cross-validation results which the NSE values of IDW and two Krigings were almost same, the new cross-validation results showed that the NSE values of two Krigings were all decreased to 0.79. It may also contribute a part to confirm our interpolation selection of IDW in Var catchment.

However, recently, the statistical coefficients are commonly applied to evaluate the performance of the model simulation, and in many cases, it had been considered as the premier or only criteria to validate the quality of simulated results. However, based on our modelling experience in AquaVar project, compared to the statistical assessment, the uncertainty analysis of the model results which in detail checking both the simulated results and observed data may play more significant role in the model (or method) validation. Thus in this section, more detail analysis were concentrated on some special event records in Var catchment during the period from 2008 to 2014.

As we mentioned before, the meteorological characteristics of Var catchment could be identified with the typical Mediterranean Climate with two obvious flood periods respectively in spring and winter and one dry period existed at summer time. To have a clear view of the interpolation qualities among different methods, the interpolated rainfall time series at three stations respectively located at the upper (6094002, elevation: 1784m), middle (6005001, elevation: 1173m) and lower (6033002, elevation: 78m) parts of Var were selected in the periods of spring flood from 20th April to 9th May in 2013, winter flood from 1st November to 11th November 2011 and a part of drought event from 20th July to 8th August 2012.

In the spring flood event at 2013 (Figure 78), higher intensity rainfall recorded in Var catchment was concentrated in the day of 28th and 29th of April. However, the peak values recorded in different places had slight difference. In the upper and middle parts of the catchment, the peaks rainfall were all recorded at 29th of April but in the lower part, it was detected one day earlier. For the amount of the rainfall landed in the catchment, the rainfall intensity was raised with the elevation increase lead to most of the precipitation concentrating at the upper part of Var catchment.

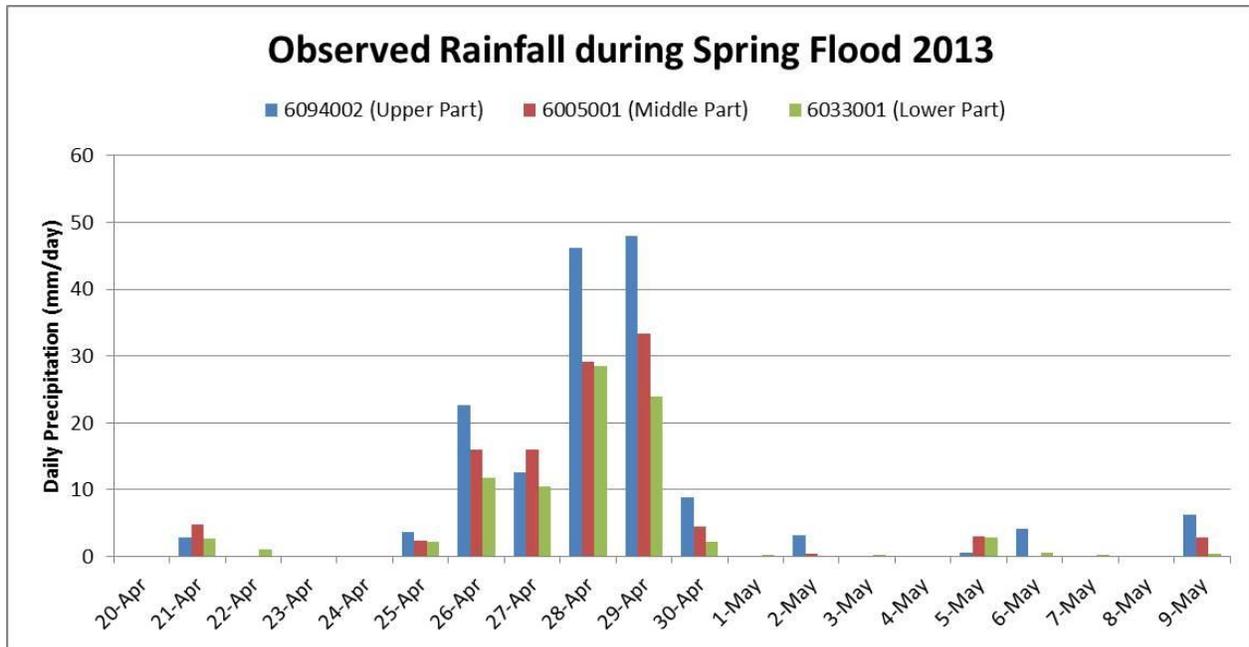


Figure 78: Rainfall distribution among upper, middle and lower part of Var catchment in spring flood 2013.

If we checked the statistical coefficients calculated for this event (Table 18) at different places, in the upper part of Var, the interpolated rainfall produced by Natural Neighbor interpolation method showed best performance with lowest RMSE value of 2.16 and highest NSE value of 0.98. However, at the middle part of the catchment, the performance level of Natural Neighbor interpolation had been significantly decreased. GWR_ZD interpolation function supposed to produce the best rainfall estimation due to its RMSE value equal to 1.47 and NSE value equal to 0.98 which were the lowest and highest values among various interpolation results at this place. Furthermore, in the lower part of Var, with less rainfall landed during this event, the Kriging_L interpolation showed best statistical performance among all the tested interpolation functions.

Linked to the analysis of observation data recorded during this event, it was logical to get this conclusion which three different interpolation methods were respectively suitable for three parts of the catchment. In the upper part, as results of more rainfall concentrated in this area, the correlation between different gauging stations located in this region may more intense than rest parts of Var. Therefore, the Natural Neighbor interpolation which estimated the rainfall values highly depends on the surrounded neighbour samples was reasonable to have higher statistical performance. Moreover, as we discussed before, the rainfall distribution in Var was integrated affected by both the Mediterranean Climate and its surface elevation variation, thus in the middle part, the GWR_ZD interpolation function which taken into account the geo-factors consisted with elevation and distance to the sea was more suitable to estimate the rainfall distribution in this area. Besides, for the lower part of Var where is closer to the Mediterranean Sea with lower surface elevation (78 m), the topography impacts were not as important as other parts. Consequently, the Kriging_L interpolation was expected to work better for this area. After applying the cross-validation method including these three parts of Var, the GWR_ZD interpolation method showed best statistical performance among 7 interpolation functions with 1.93 of RMSE and 0.94 of NSE.

Table 18: Evaluation factors of rainfall interpolations at different parts of Var catchment in flood 2013.

6094002 (Upper Part)								
Indicators	Obs	IDW	Spline	Natural	Kriging_S	Kriging_L	GWR_Z	GWR_ZD
28th difference (mm/day)	-	-9.58	-4.93	-7.61	-8.02	-9.26	-7.90	-7.98
29th difference (mm/day)	-	0.76	7.51	4.06	3.34	3.29	7.70	7.26
RMSE (-)	-	2.42	2.51	2.16	2.26	2.43	2.73	2.68
NSE (-)	-	0.97	0.97	0.98	0.97	0.97	0.96	0.96
Total amount (mm)	158.50	149.51	163.97	155.64	152.55	152.31	167.39	166.28
Total difference (mm)	-	-8.99	5.47	-2.86	-5.95	-6.19	8.89	7.78
Raining Days (-)	11	19	14	16	19	19	18	19
6005001 (Middle Part)								
Indicators	Obs	IDW	Spline	Natural	Kriging_S	Kriging_L	GWR_Z	GWR_ZD
28th difference (mm/day)	-	6.56	3.34	6.72	7.40	8.66	7.96	-1.19
29th difference (mm/day)	-	7.56	-0.72	8.36	9.43	9.20	10.99	-0.58
RMSE (-)	-	2.37	2.26	2.67	2.83	3.03	3.21	1.47
NSE (-)	-	0.94	0.95	0.93	0.92	0.90	0.89	0.98
Total amount (mm)	112.10	129.66	119.65	133.27	133.48	136.11	138.48	102.86
Total difference (mm)	-	17.56	7.55	21.17	21.38	24.01	26.38	-9.24
Raining Days (-)	10	18	14	17	17	17	18	18
6033001 (Lower Part)								
Indicators	Obs	IDW	Spline	Natural	Kriging_S	Kriging_L	GWR_Z	GWR_ZD
28th difference (mm/day)	-	5.03	5.53	5.89	3.70	3.26	-1.42	3.33
29th difference (mm/day)	-	-2.25	-4.99	-0.96	-2.54	-2.20	-3.69	5.52
RMSE (-)	-	1.36	1.77	1.49	1.22	1.16	1.52	1.63
NSE (-)	-	0.97	0.95	0.96	0.98	0.98	0.96	0.96
Total amount (mm)	86.80	88.56	86.64	94.53	91.22	92.22	72.73	101.70
Total difference (mm)	-	1.76	-0.16	7.73	4.42	5.42	-14.07	14.90
Raining Days (-)	14	18	14	16	16	16	16	17
Cross-Validation								
Indicators		IDW	Spline	Natural	Kriging_S	Kriging_L	GWR_Z	GWR_ZD
28th difference (mm/day)		0.67	1.31	1.67	1.03	0.88	-0.46	-1.95
29th difference (mm/day)		2.02	0.60	3.82	3.41	3.43	5.00	4.07
RMSE (-)		2.05	2.18	2.11	2.10	2.21	2.49	1.93
NSE (-)		0.96	0.96	0.96	0.96	0.95	0.94	0.97
Total amount (mm)		122.58	123.42	127.81	125.75	126.88	126.20	123.61
Total difference (mm)		3.44	4.29	8.68	6.62	7.75	7.07	4.48
Total absolute difference (mm)		59.16	64.22	64.69	67.13	70.61	78.27	63.37
Raining Days (-)		19	14	17	19	19	18	19

However, except considering their statistical performance, the other physical factors of these interpolation results were also important and necessary to be taken into account in the evaluation

process. For instance, in hydrological simulation, precipitation was assumed as the premier water source in the model simulation, thus its amount supposed to highly influence model simulation results. Therefore, in this case, not only the difference between observed and simulated total rainfall during the event was considered as one important factor of the interpolation comparison, the absolute difference of their total rainfall amount was also taken into account in the assessment. In Table 18, the highest total difference compared to the observation was produced by the Natural Neighbor interpolation method which was expected due to the decrease correlation among the stations located at middle and lower parts of Var. Moreover, both two Kriging interpolations also showed higher total difference with 6.62 mm for Kriging_S and 7.75 mm for Kriging_L. Compared to the GWR_ZD which took into account the impacts of both elevation and distance to the sea, the GWR_Z had higher error in the total rainfall amount estimation. Among 7 interpolation methods, the IDW results had lowest error of total rainfall amount and absolute difference with 3.44 mm and 59.16 mm in 20 days. Thus, integrated considering all the evaluating factors, IDW method was selected as the best interpolation method for estimating rainfall distribution during this spring flood event in 2013.

When we plotted the rainfall series estimated by various interpolation methods and compared to the observations (Figure 79), all the interpolated rainfall time series could catch the rainfall temporal variation during this event with no shift of peak time.

It is interesting to find that for the peak rainfall recorded at 28th April in upper part of Var, there is no interpolation method could produce good estimation results, different to the simulation of other peaks in rest parts of Var catchment, all the interpolation results showed under-estimated situation. One explanation could be the rainfall recorded at 28th April at the upper station was a region precipitation process which has limited impacts area. In addition, it is clear to find that for the GWR_ZD interpolation method, its interpolated rainfall was highly over-estimated in the peak time at both upper and lower parts of Var catchment, which also confirmed our selection of IDW method among 7 test interpolation functions.

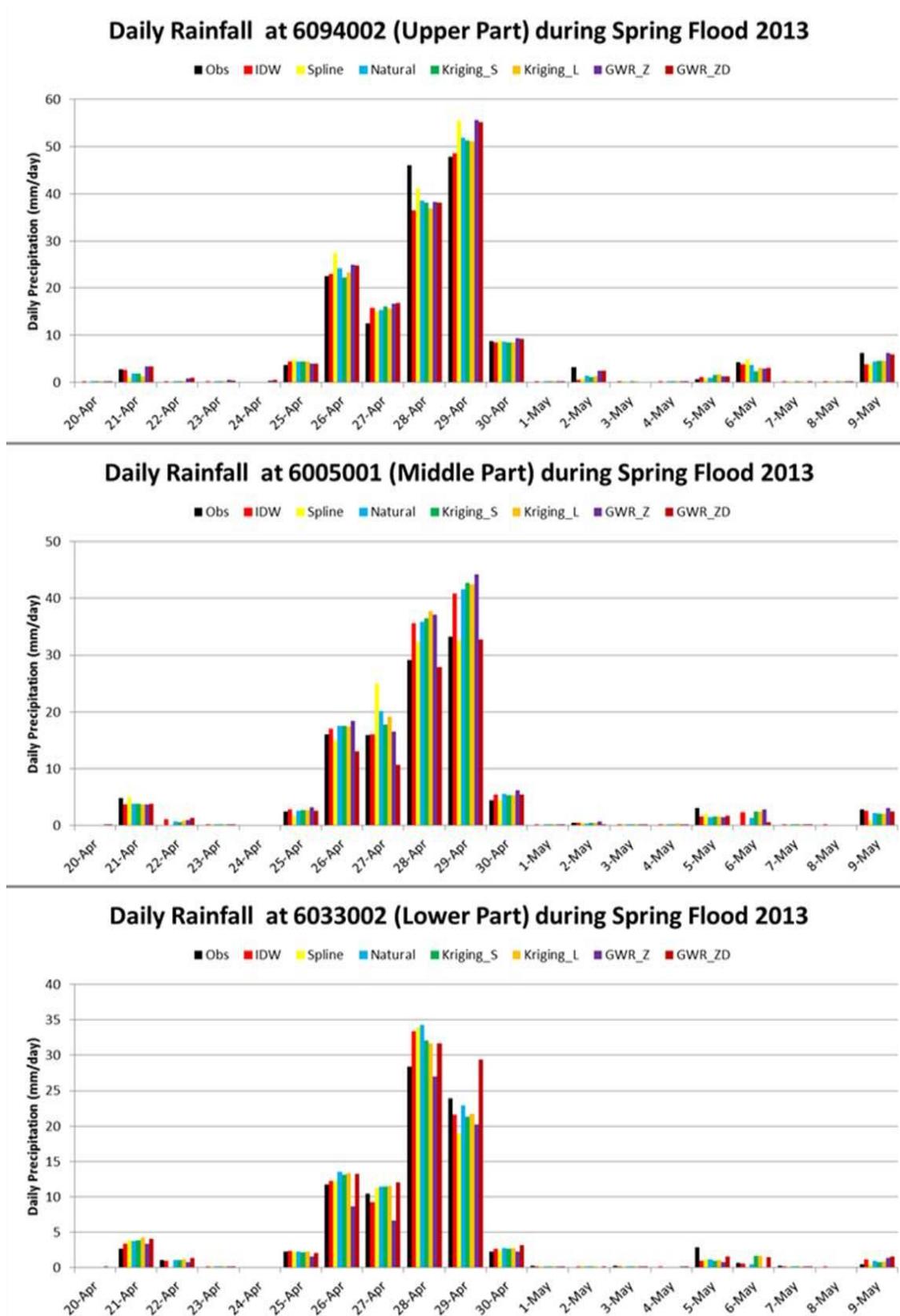


Figure 79: Comparison among different interpolation results at upper, middle and lower part of Var catchment in spring flood event 2013.

In case of winter flood recorded at 2011 (Figure 80), its daily rainfall intensity was much higher than in the spring flood at 2013. Moreover, different to the spring flood, the peak time and peak rainfall amount showed an obvious shift from upstream to downstream. At beginning of the flood event, much more precipitation was observed at the upper part of the catchment (405mm/day at 3rd November and 112mm/day at 4th November). However, just one day after, the centre of the precipitation had been shifted from upper part to the lower part. At 5th of November, the daily rainfall recorded at the upper part had been reduced to 36.8mm/day, and in the lower part of Var catchment it had been increased from 33.5mm/day (4th November) up to 87.6mm/day. Due to the short time duration and higher values fluctuation, it may difficult to expect the correlation between each station which could lead to the big uncertainty existed in our interpolation results.

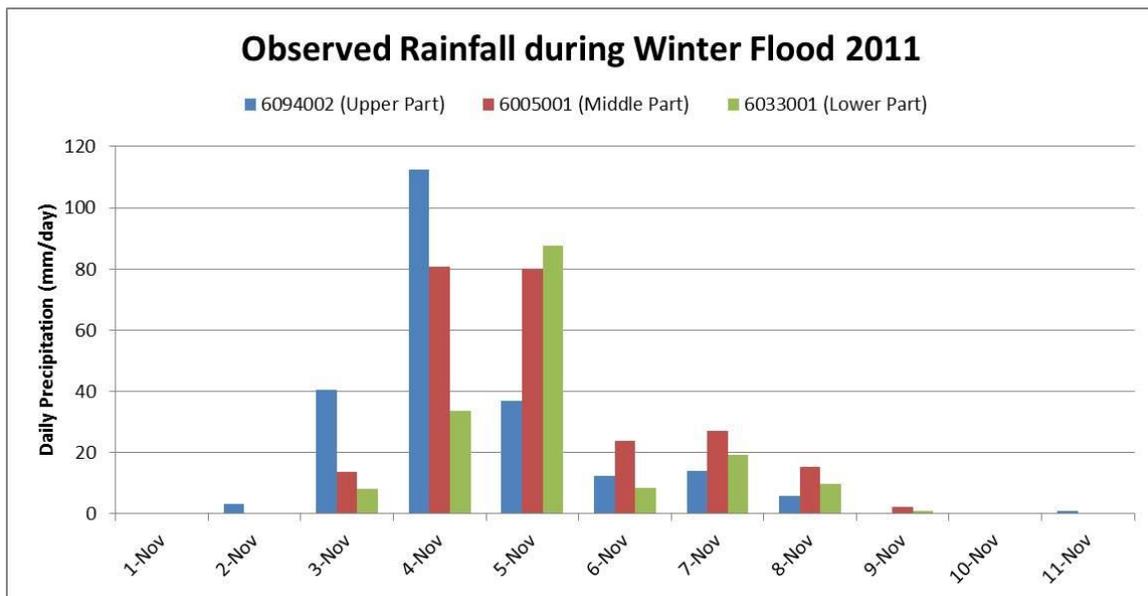


Figure 80: Rainfall distribution among upper, middle and lower part of Var catchment in winter flood 2011.

Different to the case of spring flood 2013, in Table 19, it showed that for the upper part of Var catchment, both the interpolation methods of Kriging_S and Kriging_L showed the excellent statistical performance with 2.71 and 2.84 of the RMSE value and 0.99 NSE respectively. The worst interpolation results in this area were produced by the Spline interpolation with 6.02 RMSE and 0.94 NSE. However, for the middle and lower part of Var catchment, in this winter flood 2011, the IDW interpolation results showed best statistical performance in both two areas with 0.97 and 0.96 NES and 3.85 and 3.51 RMSE respectively. Moreover, one point we would like to highlight here is for those two parts of Var catchment, the interpolated rainfall produced by GWR_ZD interpolation method showed the worst statistical performance with NSE values lower than 0.9 and REMS values higher than 5. In contrast with the spring flood 2013, the distributed rainfall produced by interpolation method of GWR_Z showed better performance than GWR_ZD over whole catchment area. It may indicate that the sea impacts during this event could be considered as very limited.

Moreover after checking the total difference among three parts in Var catchment, the IDW results showed lowest error over whole catchment. Even in the upper part of Var catchment, the rainfall estimated by Kriging interpolation showed higher statistical performance, the difference between

observation and simulations presented that the IDW's error (3.71mm) was significant lower than Krigings' (22.01mm and 18.35mm)

Table 19: Evaluation factors of rainfall interpolations at different parts of Var catchment in flood 2011.

6094002 (Upper Part)								
Indicators	Obs	IDW	Spline	Natural	Kriging_S	Kriging_L	GWR_Z	GWR_ZD
4th difference (mm/day)	-	-8.11	21.29	7.95	6.77	6.13	12.29	11.38
5th difference (mm/day)	-	9.32	2.11	5.47	2.64	-1.52	15.90	17.65
RMSE	-	3.09	6.02	2.98	2.71	2.84	4.93	5.10
NSE	-	0.98	0.94	0.98	0.99	0.99	0.96	0.95
Total amount (mm)	226.20	229.91	261.98	246.78	248.21	244.55	268.23	269.54
Total difference (mm)	-	3.71	35.78	20.58	22.01	18.35	42.03	43.34
Raining Days (-)	9	11	10	11	10	10	11	11
6005001 (Middle Part)								
Indicators	Obs	IDW	Spline	Natural	Kriging_S	Kriging_L	GWR_Z	GWR_ZD
4th difference (mm/day)	-	-1.52	-19.45	1.02	4.32	3.39	7.59	-24.71
5th difference (mm/day)	-	-0.51	6.08	6.28	5.21	4.09	-5.23	-21.94
RMSE	-	3.85	4.83	4.23	4.45	4.28	5.17	8.42
NSE	-	0.97	0.95	0.96	0.96	0.96	0.94	0.85
Total amount (mm)	243.60	244.01	233.69	261.18	263.55	257.94	250.35	168.46
Total difference (mm)	-	0.41	-9.91	17.58	19.95	14.34	6.75	-75.14
Raining Days (-)	8	11	10	11	10	10	10	9
6033001 (Lower Part)								
Indicators	Obs	IDW	Spline	Natural	Kriging_S	Kriging_L	GWR_Z	GWR_ZD
4th difference (mm/day)	-	10.13	12.06	12.91	9.76	10.56	-0.73	18.63
5th difference (mm/day)	-	6.64	17.54	13.04	13.42	13.15	-1.34	6.60
RMSE	-	3.51	4.88	4.80	5.02	5.10	3.43	6.11
NSE	-	0.96	0.93	0.93	0.93	0.92	0.97	0.89
Total amount (mm)	168.0	200.85	205.37	213.62	213.75	214.71	183.20	226.40
Total difference (mm)	-	32.85	37.37	45.62	45.75	46.71	15.20	58.40
Raining Days (-)	8	11	8	10	10	10	9	10
Cross-Validation								
Indicators		IDW	Spline	Natural	Kriging_S	Kriging_L	GWR_Z	GWR_ZD
4th difference (mm/day)		0.16	4.63	7.30	6.95	6.69	6.38	1.76
5th difference (mm/day)		5.15	8.58	8.26	7.09	5.24	3.11	0.77
RMSE		3.48	5.24	4.00	4.06	4.07	4.51	6.54
NSE		0.97	0.94	0.96	0.96	0.96	0.96	0.90
Total amount (mm)		224.93	233.68	240.53	241.84	239.07	233.93	221.46
Total difference (mm)		12.33	21.08	27.93	29.24	26.47	21.33	8.86
Total absolute difference (mm)		93.29	131.06	109.15	110.65	112.81	115.73	189.79
Raining Days (-)		11	10	11	10	10	11	11

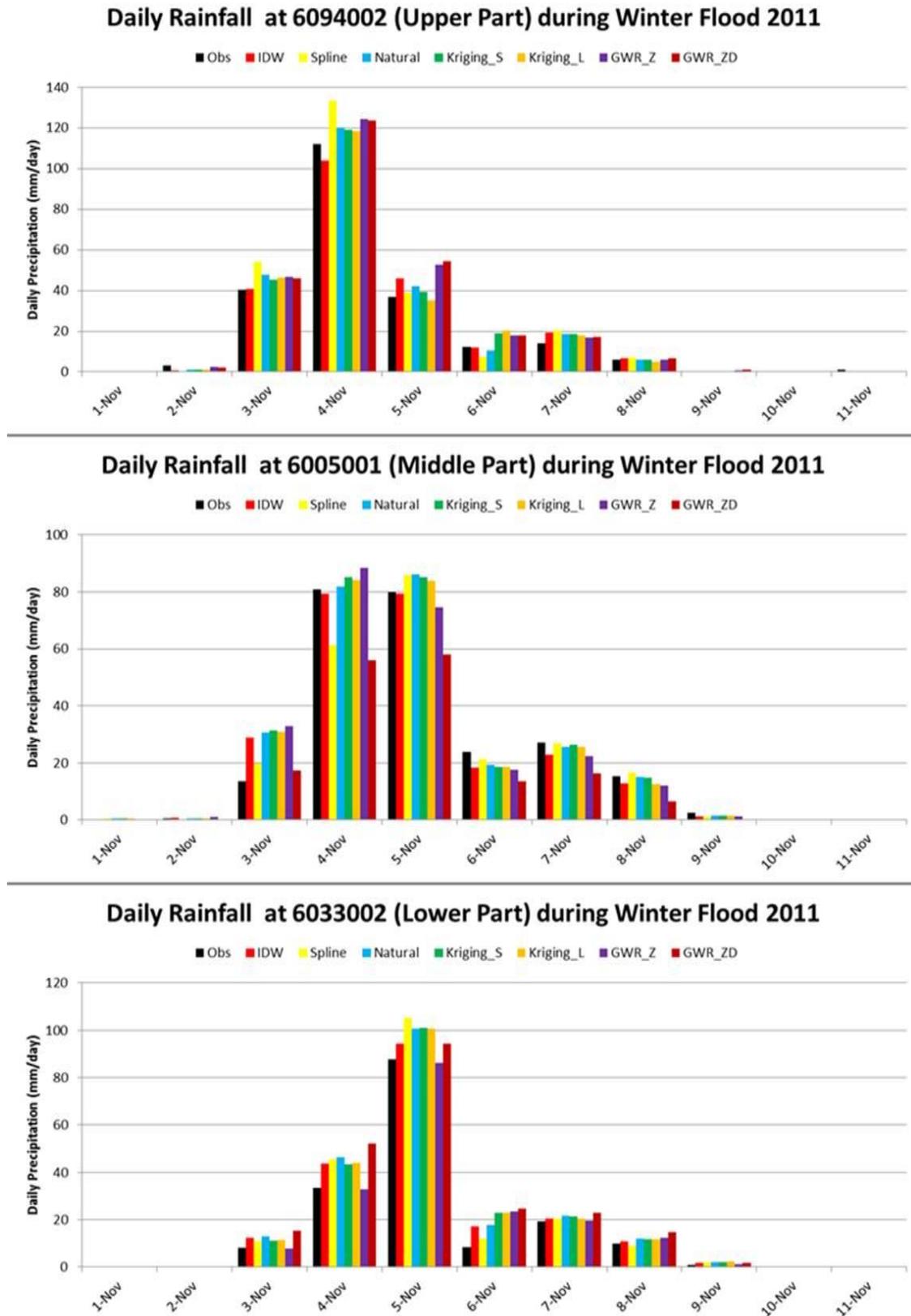


Figure 81: Comparison among different interpolation results at upper, middle and lower part of Var catchment in winter flood event 2011.

In the cross-validation assessment, most of the evaluation factors of IDW methods were obviously higher than rest of interpolations which clearly demonstrated the IDW interpolation method could be able to be considered as the most suitable interpolation function applied in the high intensity rainfall event in Var. Even through the GWR_ZD interpolation had the lowest total difference with 8.86mm in 11 days, as its total absolute difference was nearly twice more than IDW results. Our conclusion will not be changed. Moreover, as same as the assessment of spring flood, in this winter flood analysis, the estimated rainfall results created by various interpolation methods were also all plotted in figure above (Figure 81) which confirmed our conclusion of selecting IDW interpolation methods for estimating rainfall distribution during winter flood event.

The last assessment of interpolation method comparison was set up with the drought event recorded at 2012. In most of the case, one of the main courses of drought disaster is due to the less precipitation landed in the study catchment. In this case, we selected a part of the drought event with some rainfall existed in Var area to evaluate the quality of various interpolation results with low rainfall values (Figure 82).

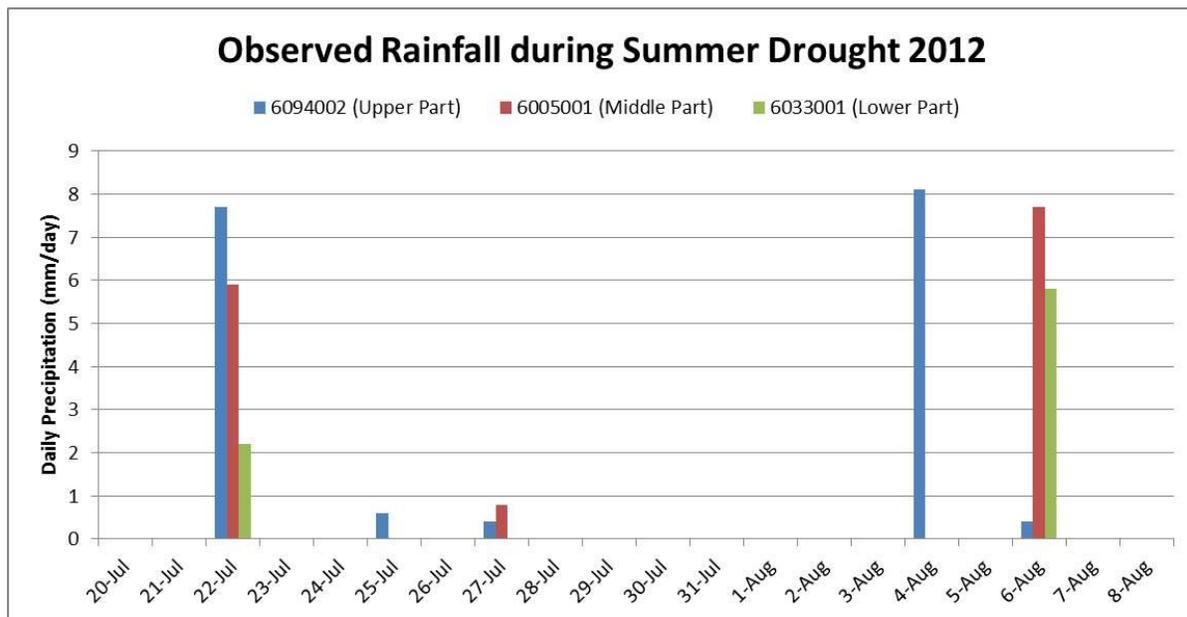


Figure 82: Rainfall distribution among upper, middle and lower part of Var catchment in drought 2012.

In this case, the rainfall recorded in Var catchment showed lower intensity and higher randomness during summer time. For example, at 4th of August, when 8mm rainfall recorded at the upper part of Var, there is no rainfall observed in the middle and lower part of the catchment. Then at 6th of August, when 7.7mm and 5.8mm precipitation respectively recorded at middle and lower parts of Var catchment, only 0.4 mm rainfall was measured at upper catchment. Therefore, we could expect the rainfall distribution during this drought event was seriously inhomogeneous and the rainfall correlation between each places in Var was very weak. The statistical coefficients calculated in Table 20 were perfectly responded to our expectation with NSE values of various interpolations at different place fluctuated from -0.29 to 0.89. Besides none of the NSE values calculated in cross-validation process were located in the rank of “Good” performance.

Table 20: Evaluation factors of rainfall interpolations at different parts of Var catchment in drought 2012.

6094002 (Upper Part)								
Indicators	Obs	IDW	Spline	Natural	Kriging_S	Kriging_L	GWR_Z	GWR_ZD
22th difference (mm/day)	-	1.24	4.54	2.12	1.57	0.30	1.23	1.50
4th difference (mm/day)	-	-7.35	-7.08	-7.32	-7.27	-7.30	-7.58	-7.61
RMSE	-	2.02	2.68	2.38	2.37	2.34	2.50	2.47
NSE	-	0.26	-0.29	-0.03	-0.01	0.01	-0.12	-0.10
Total amount (mm)	17.20	16.63	22.57	19.61	20.75	19.98	24.58	24.78
Total difference (mm)	-	-0.57	5.37	2.41	3.55	2.78	7.38	7.58
Raining Days	5	9	5	8	9	9	19	19
6005001 (Middle Part)								
Indicators	Obs	IDW	Spline	Natural	Kriging_S	Kriging_L	GWR_Z	GWR_ZD
22th difference (mm/day)	-	3.79	6.64	6.34	7.21	7.16	4.34	-4.46
6th difference (mm/day)	-	-5.82	-5.61	-5.87	-5.76	-5.75	-6.20	-2.44
RMSE	-	1.58	1.95	1.95	2.09	2.08	1.75	1.17
NSE	-	0.55	0.32	0.32	0.21	0.22	0.45	0.75
Total amount (mm)	14.40	13.40	15.00	15.26	16.90	17.00	14.57	7.71
Total difference (mm)	-	-1.00	0.60	0.86	2.50	2.60	0.17	-6.69
Raining Days	3	5	3	5	6	6	6	5
6033001 (Lower Part)								
Indicators	Obs	IDW	Spline	Natural	Kriging_S	Kriging_L	GWR_Z	GWR_ZD
22th difference (mm/day)	-	2.35	3.98	3.87	3.05	2.28	0.76	5.11
6th difference (mm/day)	-	-4.85	-3.05	-4.85	-3.70	-3.70	-3.34	-4.42
RMSE	-	1.21	1.12	1.39	1.09	0.99	0.77	1.51
NSE	-	0.74	0.77	0.65	0.79	0.82	0.89	0.59
Total amount (mm)	8	5.74	8.94	7.05	8.15	7.37	5.50	8.88
Total difference (mm)	-	-2.26	3.20	-1.89	1.11	-0.78	-1.87	3.38
Raining Days	2	5	2	3	4	4	4	5
Cross-Validation								
Indicators		IDW	Spline	Natural	Kriging_S	Kriging_L	GWR_Z	GWR_ZD
22th difference (mm/day)		2.46	5.05	4.11	3.94	3.25	2.11	0.72
RMSE		1.60	1.91	1.91	1.85	1.80	1.67	1.72
NSE		0.51	0.27	0.31	0.33	0.35	0.41	0.41
Total amount (mm)		11.93	15.50	13.97	15.27	14.78	14.88	13.79
Total difference (mm)		-1.27	3.05	0.46	2.38	1.53	1.89	1.42
Total absolute difference (mm)		40.70	39.81	41.36	39.91	41.35	41.84	39.60
Raining Days		9	5	8	9	9	19	19

In Figure 83, it clearly indicated the over-estimation produced by two GWR methods at the upper part. Considering the drought case, with less rainfall estimated (IDW total difference: -1.27mm) in the model, it could be easier to achieve worst situation in the simulation. Therefore, IDW interpolation method was confirmed again as the selected interpolation function in Var catchment.

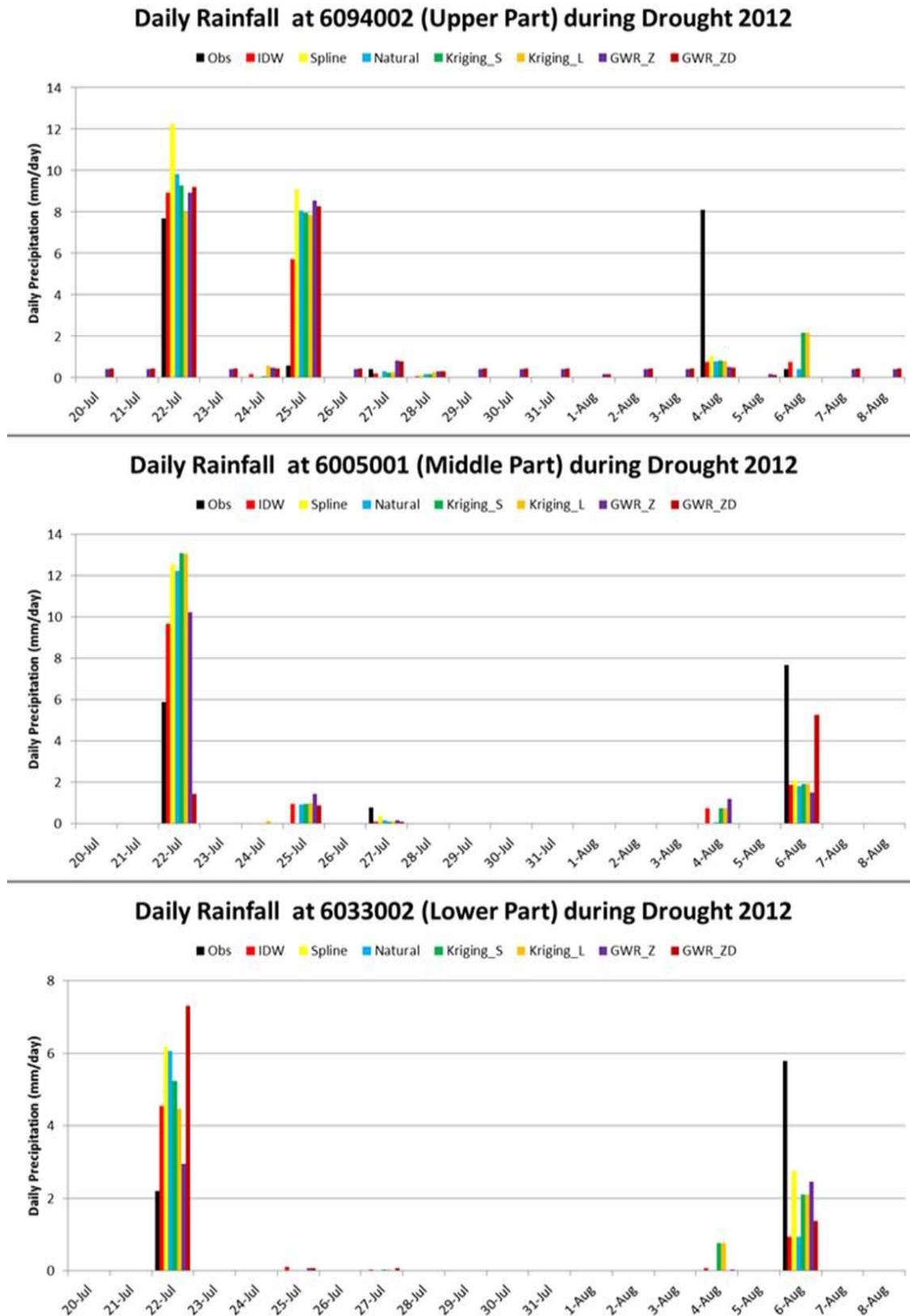


Figure 83: Comparison among different interpolation results at upper, middle and lower part of Var catchment in drought event 2012.

4.3.4 Hourly rainfall interpolation assessment

Integrated considering the statistical performance detected by the cross-validation process and other evaluation factors (e.g. water balance detection), the results produced by IDW interpolation method presented better performance at most parts of catchment and caught the rainfall variation (spatial and temporal) in a longer time series including several spring and winter floods and summer drought disaster. Consequently, the next step in AquaVar rainfall interpolation process was applying the selected function to produce hourly rainfall distribution based on the limited recorded data. As we mentioned before, due to the decrease of recorded time interval (from daily to hourly), both the uncertainty and randomness of the recorded data was strongly increased and led to the reduction of interpolation accuracy.

Like most of the catchments in the world, the hourly rainfall assessment in AquaVar project had to face two difficulties mainly caused by the data collection. Compared to the daily rainfall recorded at 16 gauging stations distributed in Var catchment, the hourly rainfall records were only available at 10 stations in the catchment. Moreover, the hourly rainfall stations showed inhomogeneous distribution with an obvious missing area existed in middle part of UpVar sub-catchment. Because of the missing data existed in the hourly rainfall time series, how to fill these missing gaps for each gauging time series was another difficulty faced in the rainfall distribution process in this project.

For filling the missing data, in this project, we applied the average estimation which assumed the temporal variation of hourly rainfall in one day was homogeneous. It could help us to conveniently transfer the daily rainfall into hourly rainfall by dividing the daily record with 24 hours. After filling the missing stations, the cross-validation process was also applied in the hourly rainfall evaluation based on the selected interpolation method of IDW. The comparison results between daily and hourly IDW interpolation were showed in Table 21.

Table 21: Comparison between daily and hourly IDW interpolation results.

Stations	Hourly Interpolation				Daily Interpolation			
	RMSE	NSE	Total difference (mm)	Total absolute difference (mm)	RMSE	NSE	Total difference (mm)	Total absolute difference (mm)
4115001	0.0023	0.3674	-62.71	6306.46	0.0792	0.7776	-277.73	3578.14
6005001	0.0019	0.4800	-798.87	5523.16	0.0636	0.8522	-1030.72	2978.96
6033002	0.0024	0.4658	-913.65	5853.34	0.0431	0.9463	-666.97	1893.44
6050002	0.0027	0.5043	3158.78	7212.56	0.1269	0.7683	2573.35	4367.82
6074005	0.0022	0.4691	-62.87	5917.10	0.0987	0.7117	-843.54	3606.92
6088001	0.0022	0.5047	-707.82	4428.36	0.0802	0.7817	-1382.37	3506.13
6094002	0.0022	0.4852	443.56	5712.74	0.0549	0.9029	285.21	2657.71
6102001	0.0020	0.3498	-599.98	5896.78	0.0694	0.7831	-1196.37	3062.95
6120004	0.0015	0.6274	-13.89	4379.11	0.0674	0.8269	-495.89	3369.24
6125001	0.0020	0.5207	1530.65	6131.95	0.0850	0.8250	1212.32	3744.67
Cross-Validation	0.0021	0.4774	197.32	5736.16	0.0768	0.8176	-182.27	3276.60

In the statistic assessment, compared to the daily interpolation, all the evaluation factors' values of hourly rainfall estimation were significantly decreased. The cross-validation results of hourly rainfall interpolation showed with "Poor" performance even its RMSE value was just 0.0021 which is obviously lower than the daily result. Moreover, compared to the daily interpolation, the total difference between observation and simulation showed the hourly interpolation results were 197.32mm over-estimated. It could be explained with the hypothesis we applied to fill the missing data which average the daily rainfall to the missing hours.

To further evaluate the hourly interpolation results, the flood 2011 without any missing data in hourly rainfall time series was selected as the assessment case. Due to the data availability of hourly recorded, in this case, only the results from 6094002 and 6033002 which respectively located at the upper and lower parts of the catchment were tested in the analysis.

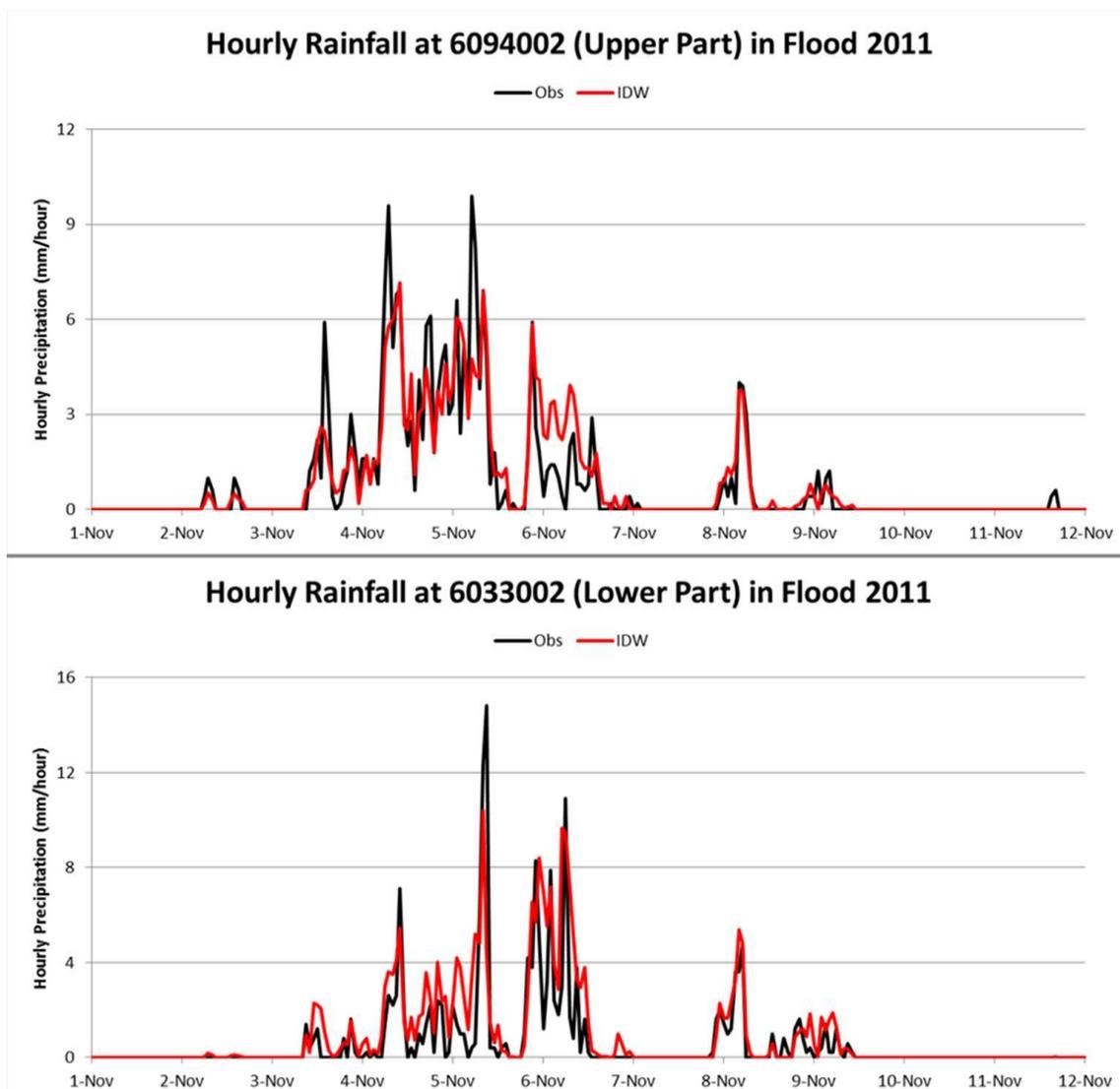


Figure 84: Compared the estimated hourly rainfall to the observation in upper and lower parts of Var catchment in case of flood 2011.

In Figure 84, it clearly presented the performance of hourly rainfall estimation. With no missing data, the IDW method was only able to catch the general rainfall condition in Var. For the peak values and time, the interpolation results did not show good performance. Moreover, compared to the upper parts estimation, in interpolation results in lower parts presented better performance with the caught peak time in flood 2011, one of the explanations could because of the number of available hourly stations located at the lower parts of Var catchment was a little more than in the upper parts.

Furthermore, assessment of one small rainfall event in 2008 with 4/10 stations had missing data was analyzed here (Figure 85). Similar as no missing flood in November 2011, the peak values interpolated by IDW were under-estimated. But the peak rainfall time in both upper and lower parts were caught in this case. One point should be highlighted here is the over-estimated at no rainfall time which mainly due to the hypothesis applied to fill missing data. This could be considered as the main reason of over-estimating the total rainfall showed in cross-validation.

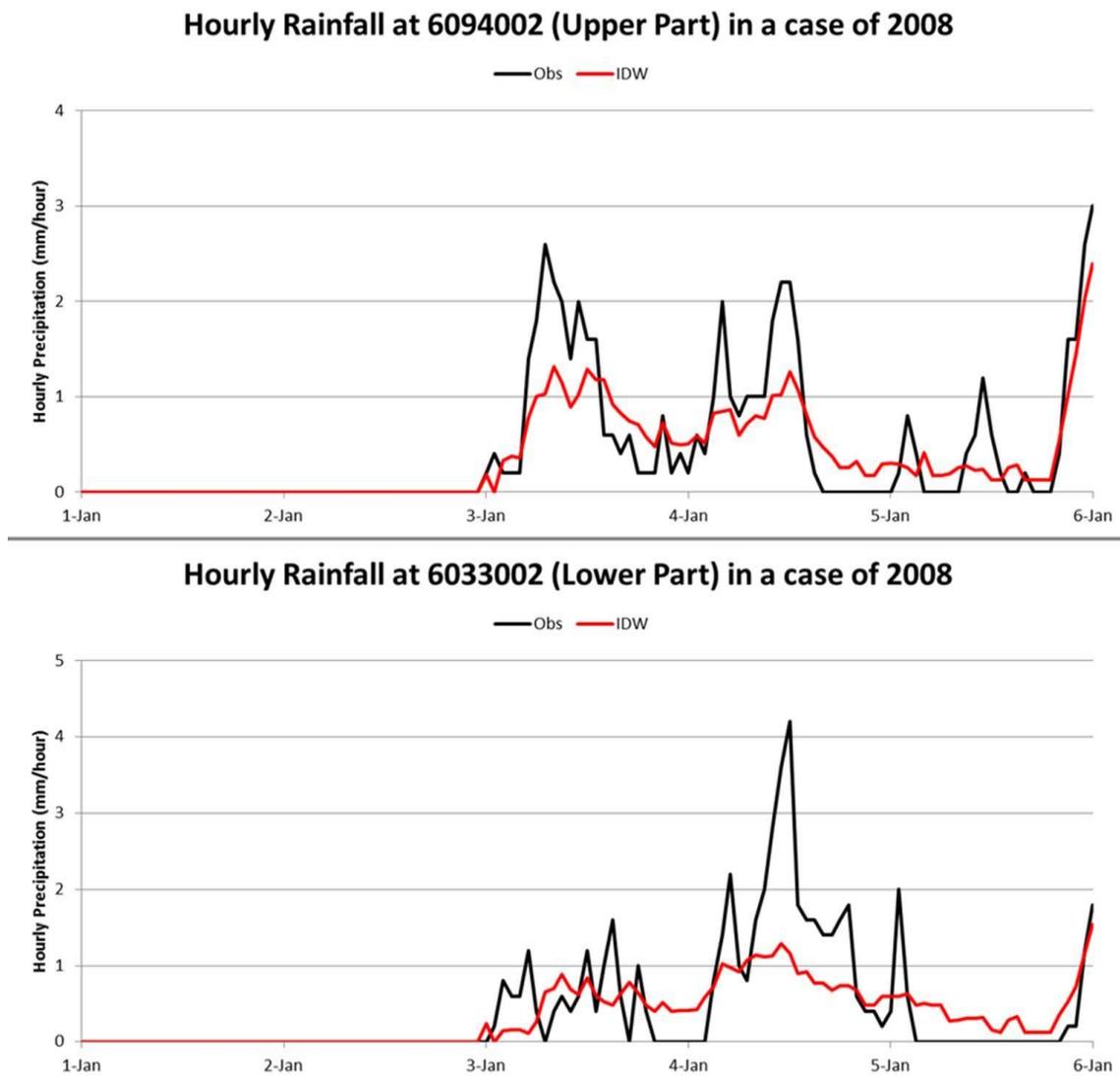


Figure 85: Compared the estimated hourly rainfall to the observation in upper and lower parts of Var catchment in case of one rainfall event 2008 (4 stations have missing data).

In conclusion, the hourly rainfall distribution in Var has higher randomness and also its data has higher uncertainty. The hourly IDW interpolation results could not catch the good performance as same as the daily interpolation, but it was still meaningful to be applied to describe the general rainfall condition especially when the data has higher quality (no or less missing). As the interpolated peak time and peak values could be respectively slightly different to the observation, we could expected the hourly hydrological modelling simulation may have big uncertainty of the simulated peak discharge lower than the observations and the simulated peak time slightly shift several hours after the observation.

4.3.5 Rainfall resolution assessment

As same as the topography maps, for the distributed rainfall, its resolution also has significant impacts of the quality of the data, especially the total amount of the rainfall. In this resolution test, the peak rainfall recorded at flood 2011 (8:00am 2011/11/05) was selected to compared the rainfall amount estimated by IDW with three different resolution (100m, 1000m and 2000m).

Table 22: Comparison among rainfall distribution with different resolution at 8:00am 2011/11/05.

Resolution	Number of cells (-)	Mean Value (mm/hour)	Maximum Value (mm/hour)	Minimum Value (mm/hour)
100 m	530,100	7.35	21.00	0.08
1000 m	7,200	7.54	20.99	1.20
2000 m	1,715	7.53	20.83	1.23

In Table 22, there were several points we would like to highlight here:

- With the increasing of the resolution, the number of the cells in the map had been exponentially increased after the resolution achieved 1000m resolution.
- With the increasing of the resolution, the maximum rainfall in the map had been slightly decreased. However, the minimum rainfall showed the opposite changing trend.
- For the mean value of the rainfall distribution in different resolution, firstly, there was almost no difference between coarse resolution results (e.g. only 0.01mm/hour difference between 1000m and 2000m interpolation). But when the resolution kept increasing until achieve a threshold value, (e.g. 100m), the improvements started to be more obvious. Secondly, it is interesting to notice that with the increasing of resolution, not as same as maximum and minimum which had one-way changing trend, the mean value of rainfall showed slightly increasing trend until a certain resolution value, then started to be decreased.

Further, by checking the interpolation maps, we could easily notice that, of course, the higher resolution maps could describe more detail information of the rainfall distribution in Var

catchment (Figure 86). But for the location of the peak rainfall (black color), there is no clear difference among three resolution maps.

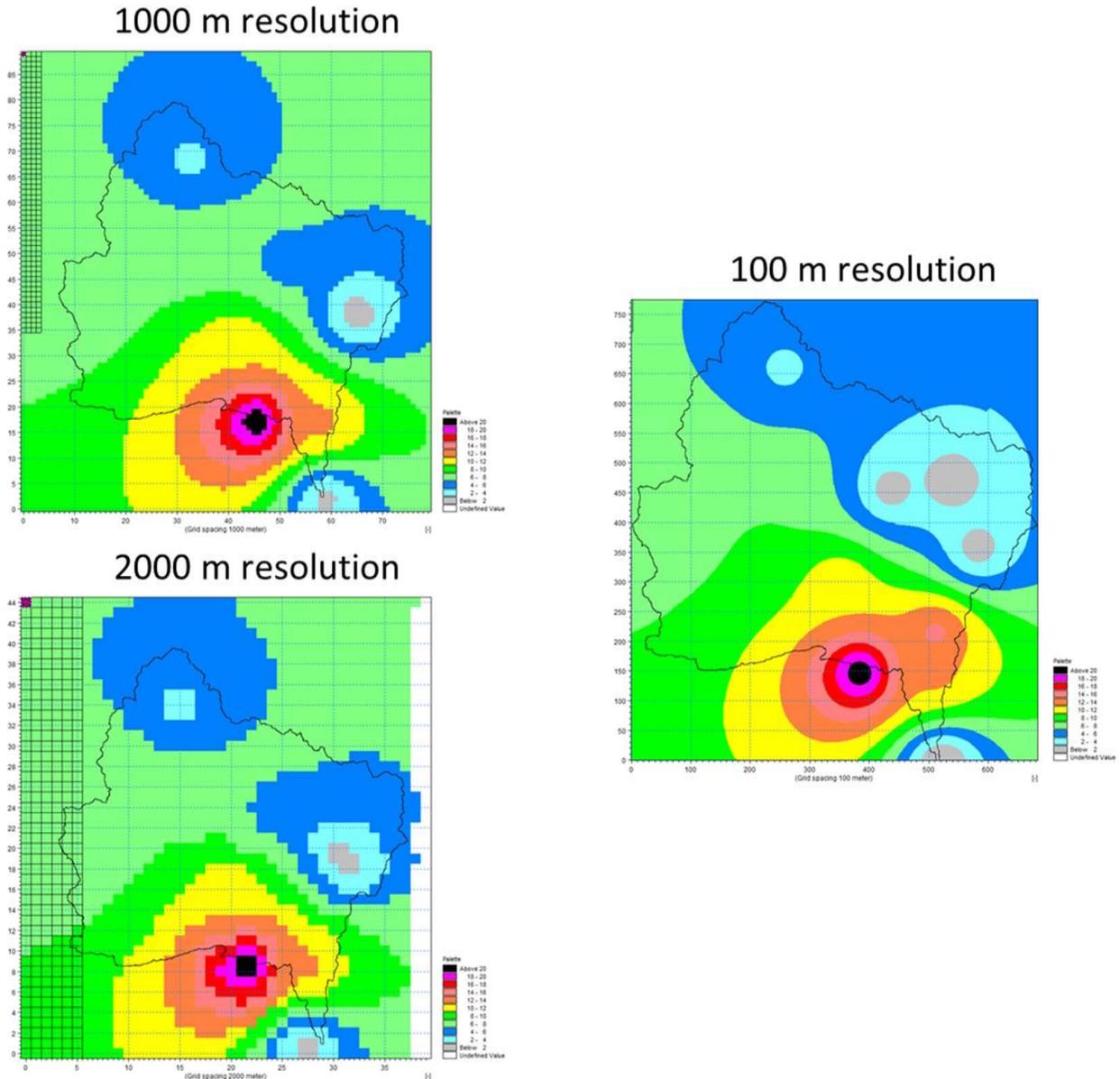


Figure 86: Comparison among rainfall distribution with different resolution at 8:00am 2011/11/05.

Considering the interpolation results among different resolutions, as the 1000m resolution rainfall could produce higher mean values which may benefit to simulate the worst situation of flood scenario and its data size (number of cells) was more reasonable to be input into the model and save or transferred on the online platform. The 1000m resolution hourly rainfall interpolated by IDW interpolation method was applied in the hydrological simulation of Var.

4.4. Modelling Set up of MIKE SHE in Var catchment

In the function selection process, all the hydrological components were selected in the MIKE SHE modelling structure of Var catchment simulation including overland flow, river and lakes, unsaturated flow, evapotranspiration, saturated flow. Consequently, the MIKE SHE model simulation was expected to integrated represent the complex hydrological system of Var catchment in both daily and hourly time scale as well as to reduce the impacts of missing data.

4.4.1 Set up the model domain and topography

The main topography data resource in MIKE SHE application of Var catchment was based on the 5m DTM data collected from Métropole NICE Côte d'Azur. However, to apply this data directly in the hydrological simulation, some problems were detected in the simulation test related to the water accumulation: we defined the model domain and resolution as same as the topography input (5m DTM), then added 1 m water depth overall the catchment and run the simulation for several days to check water accumulation. In some parts, the water was blocked by the topography variation as there is no river network considered in the simulation. But in some places, the water was blocked by some structures or trees which supposed to be removed from the topography data (Figure 87).

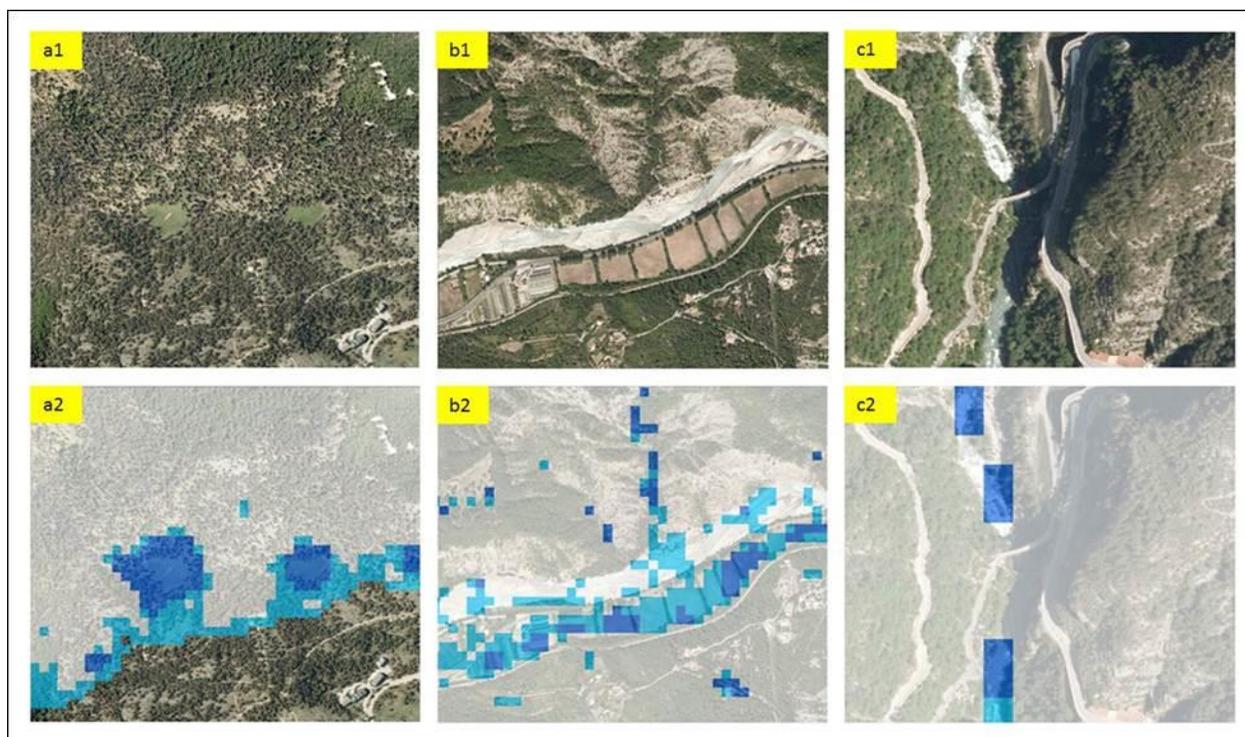


Figure 87: Checking the topography input of MIKE SHE (a: mountain area; b: floodplain; c: mountainous stream)

For instance, compared the pictures of a1 and a2, the water accumulation places was the tops of hills but surrounded by some trees. Actually, the water could not be accumulated on these hills but due to the around trees were not removed, the terrain here was described as a “swimming pool” in the data. Similar in the b1 and b2, instead of flowing into the river channel, the water

was blocked at the floodplains. Moreover, in c1 and c2, the flow through the mountainous area was divided into several parts as result of the bridge in between was not removed from the DTM.

Therefore, before adding the DTM into the model simulation, some “sink” should be fill by the modeler through ArcGIS software. Then based on the discussion conclusion of suitable model resolution, the 100m resolution domain was defined in MIKE SHE with the topography input in 25m resolution which full filled the sinks and reduced data size (Figure 88).

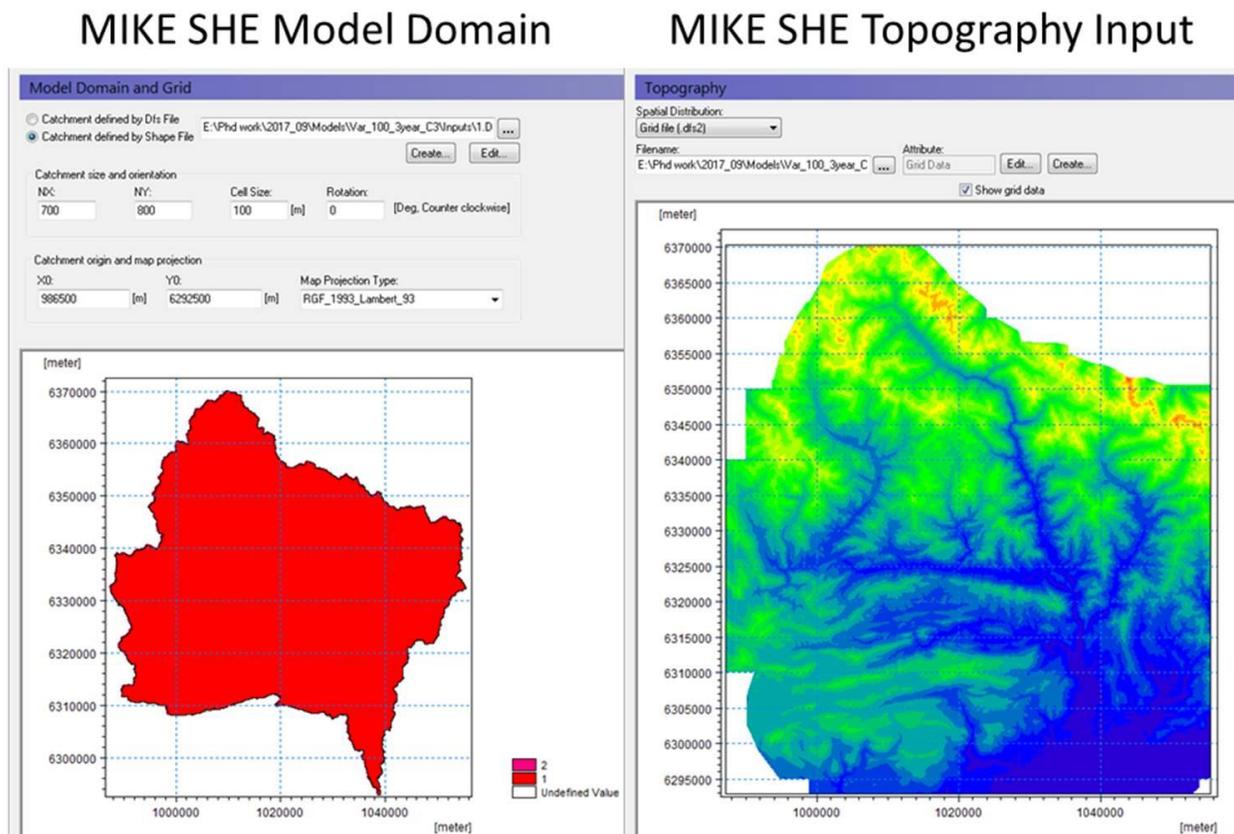


Figure 88: Model domain and topography input in MIKE SHE simulation of Var catchment.

4.4.2 Set up the climate

In the climate function of MIKE SHE simulation, all the information related to precipitation, air temperature, evapotranspiration and snow cover could be input into the model calculation. By analyzing the effect of rainfall interpolation, the daily and hourly rainfall distribution respectively in 500m and 1000m resolution estimated through IDW interpolation based on 16 and 10 gauging stations were added in to the model (Figure 89).

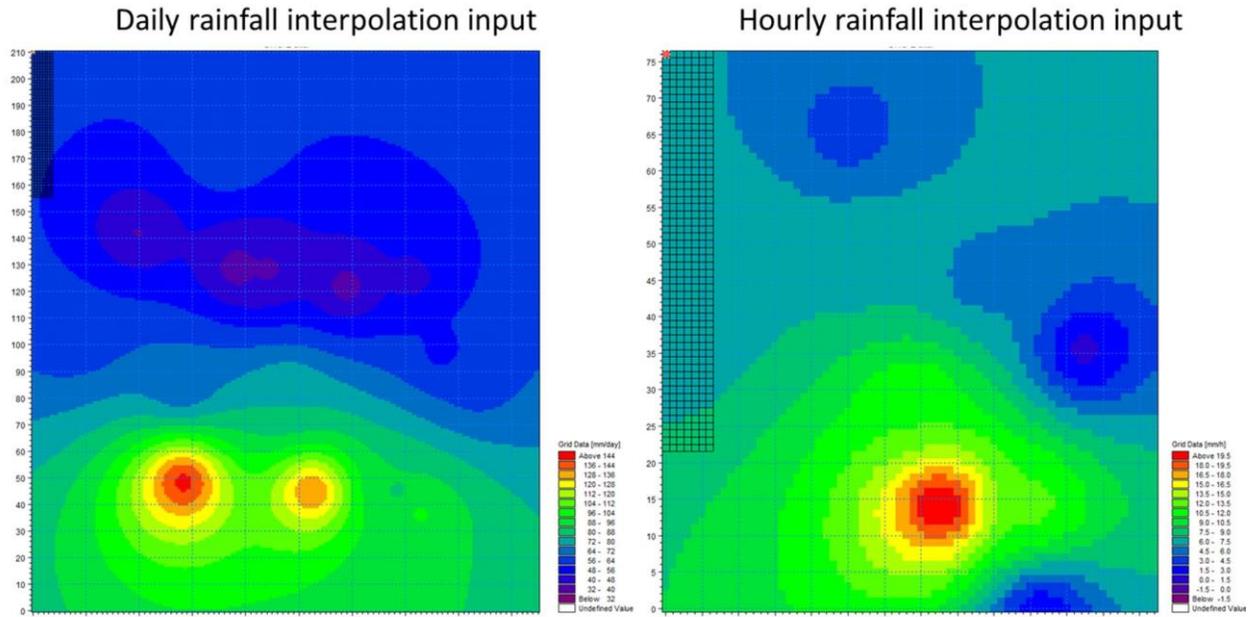


Figure 89: Precipitation input in MIKE SHE of Var catchment (e.g. peak rainfall in flood 2011).

For the air temperature and evapotranspiration, both the station based air temperature from 10 gauging stations and SAFRAN evapotranspiration collected from Météo-France were input into the MIKE SHE model (Figure 90).

Station based
air temperature

SAFRAN
evapotranspiration

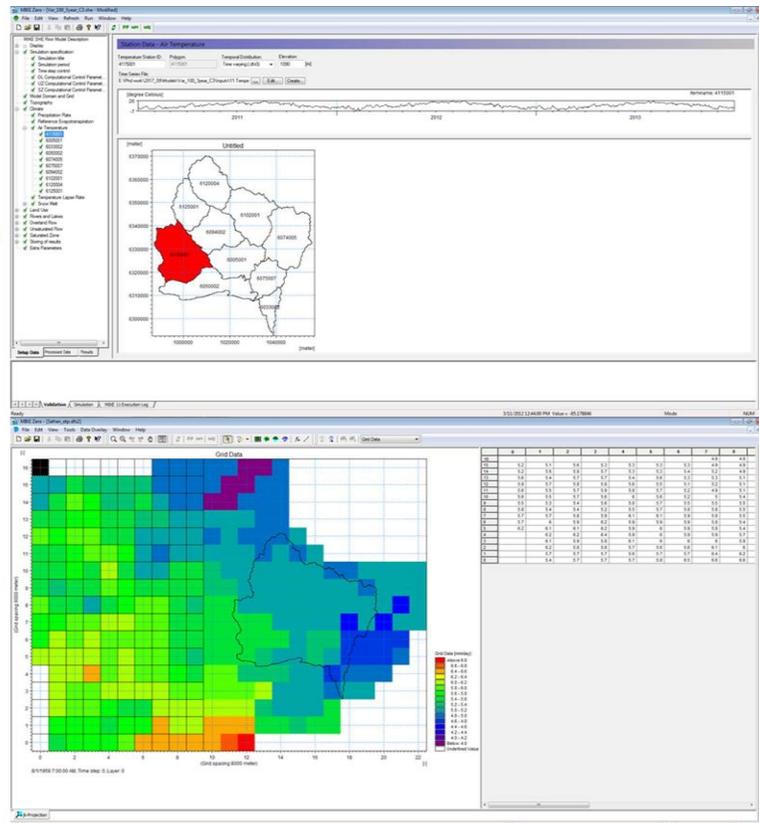


Figure 90: Station based air temperature and SAFRAN evapotranspiration.

The snow melting process was also considered in the model simulation, thus the initial snow cover was defined based on the data collected in ALIRHYS project. Moreover, as the snow melting process in Var catchment was affected by both the temperature variation and sunshine duration, the elevation correction of air temperature and the distributed melting coefficient was also defined in the model.

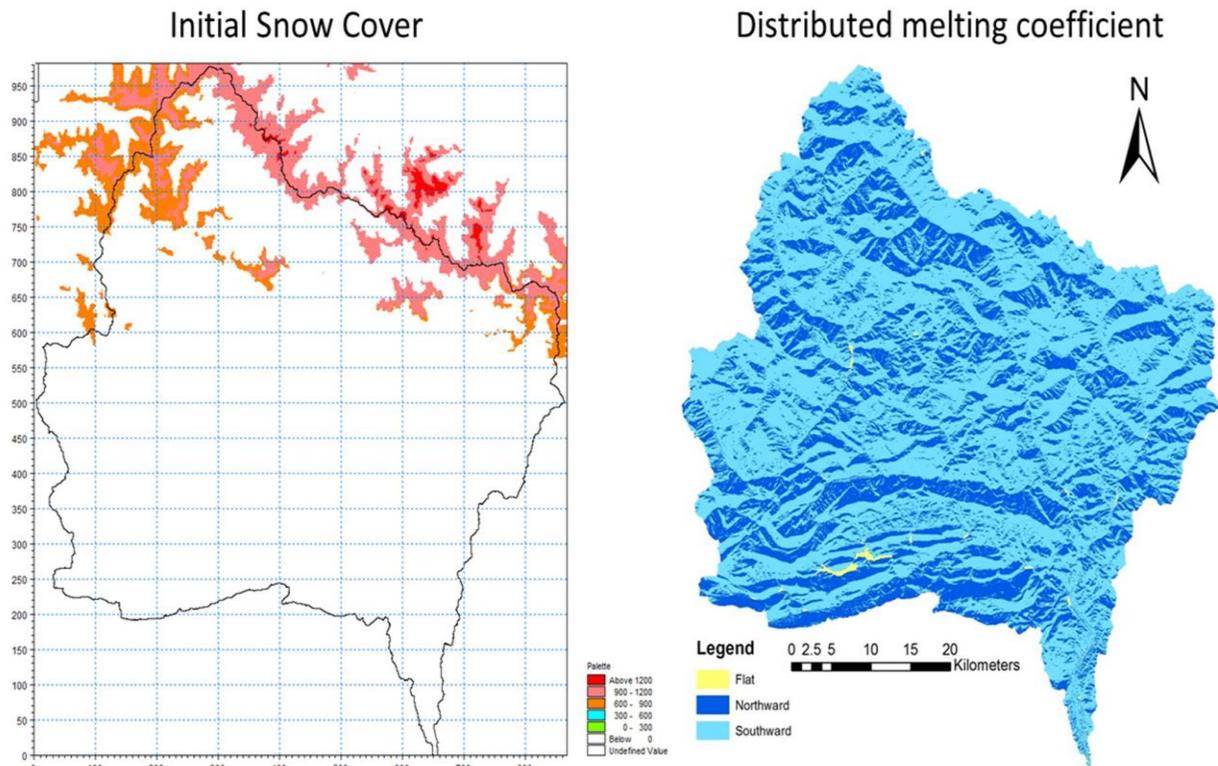


Figure 91: Correction of air temperature with elevation and defined the initial snow cover and melting coefficients.

Here, the values of the melting coefficients were given by the surface slope direction. In Var catchment, the snow cover on the mountainous area was often melting from end of spring when both the air temperature and sunshine duration started to increase. Observed from some field works, we noticed that it depends on its different surface slope direction, the duration of land surface receiving the sunshine during one day has obvious difference. Therefore, based on the difference surface slope direction, the values of melting coefficients were given for three classes of flat, southward and northward (Figure 91).

4.4.3 Set up the land use and vegetation

The vegetation parameters (LAI and RD) were involved in the calculation of interception and soil water evaporation. Based on the 100m land use map and the vegetation data published by DHI 2012, 8 classes of vegetation including three type of grass, grains, broad-leaved forest, Coniferous forest, Mixed forest and bare soil were described in MIKE SHE simulation in Var catchment (Figure 92).

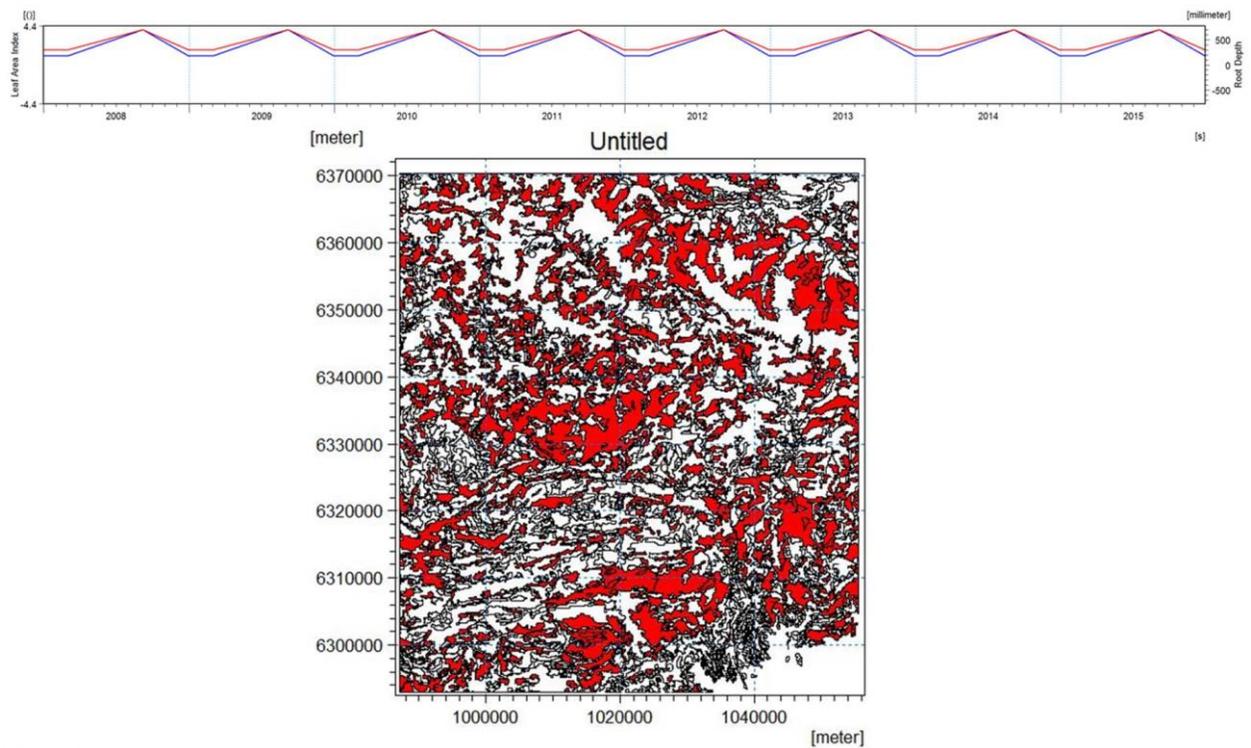


Figure 92: Vegetation parameters defined in MIKE SHE simulation of Var catchment (e.g. Grass).

4.4.4 Set up the river network

As we mentioned before, the river network in MIKE SHE was simulation by coupling with MIKE 11 model. After assessing the “resolution” of branches in MIKE 11, 53 branches with the cross section extracted by 5m resolution DTM was applied to represent the stream flow in MIKE SHE simulation in Var catchment (Figure 93). Moreover, for running the model, the boundary condition for each branch was estimated by the minimum discharge recorded at the outlet of each sub-catchment (Table 23).

Table 23: Boundary condition defined in MIKE 11.

Sub Basin	Branches	Minimum Discharge at outlet (2008-2014)	Boundary condition of each branch
UpVar	20	7 m ³ /s	0.35 m ³ /s
Tinée	9	3.85 m ³ /s	0.45 m ³ /s
Vésubie	9	1 m ³ /s	0.1 m ³ /s
Estéron	12	1.5 m ³ /s	0.15 m ³ /s

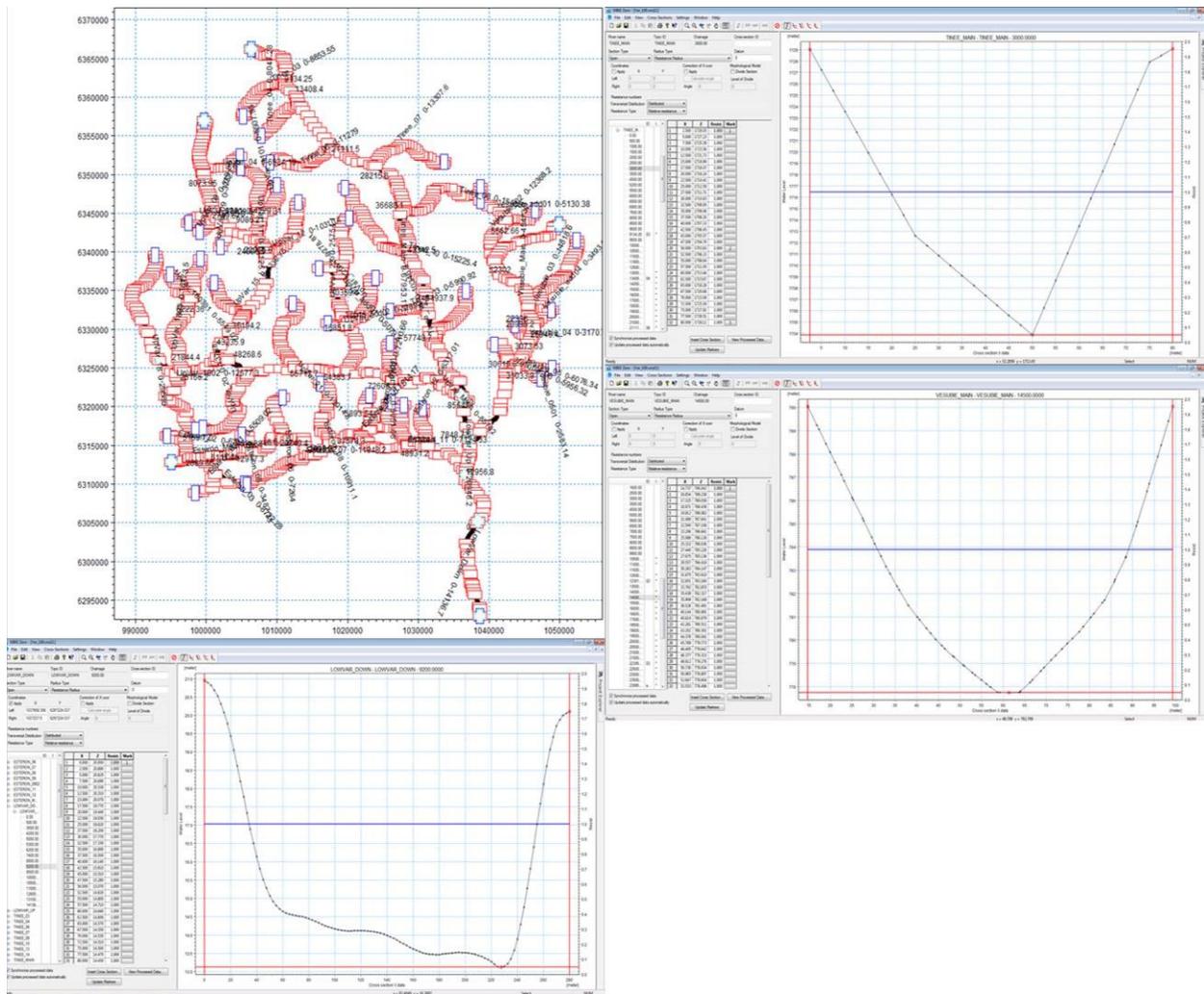


Figure 93: River network and cross section described in MIKE 11.

In reality, the rainfall-runoff process could be simply considered as precipitation water lands on the ground then flows through surface ground into the branches. However, during the flood event, the water in streams could also flow back from the branches to the surface ground causing the flood damage in the floodplain. Therefore, in the simulation, the exchange between overland and stream flow should not be unidirectional. In MIKE SHE model the cells closed to the branches could be defined with flood code which identify the computation cells having the possibility to transfer the water in both direction between river and ground. In this case, based on the locations of the branches distributed in the catchment the area of its floodplain was defined in (Table 24) (Figure 94).

Table 24: Defined the radius of the floodplain in Var catchment.

Branches locations	Buffer of floodplain (radius) (m)
Upper part of Var	50
Middle part of Var	75
Lower part of Var	150

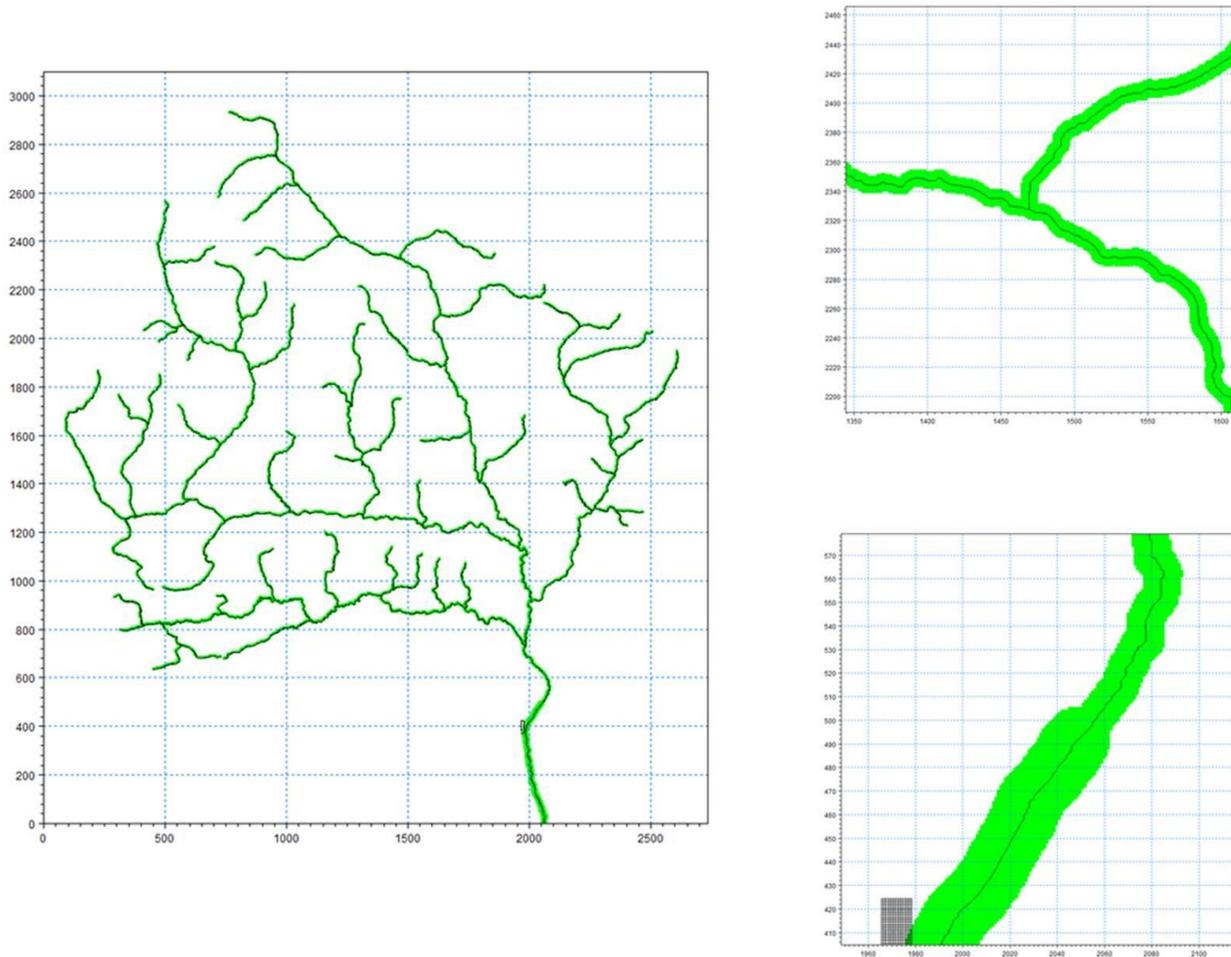


Figure 94: Floodplain defined in MIKE SHE simulation in Var catchment.

4.4.5 Set up the overland flow

In the overland flow simulation, one of the main input factors was the Manning coefficient or called Strickler coefficient describing the roughness of the land surface in the calculation, which is defined by the land use information in the project. Depending on the different land use the initial Strickler coefficient in MIKE SHE was given in Table 25, and its distribution maps was showed in

Table 25: Define the Strickler coefficient based on the different land use types.

Land use Type	Strickler Coefficient ($m^{1/3}/s$)
Artificial surfaces	50
Agricultural areas	25
Grassland	2.5
Forests	2
Open spaces with little or no vegetation	5
Water bodies	20

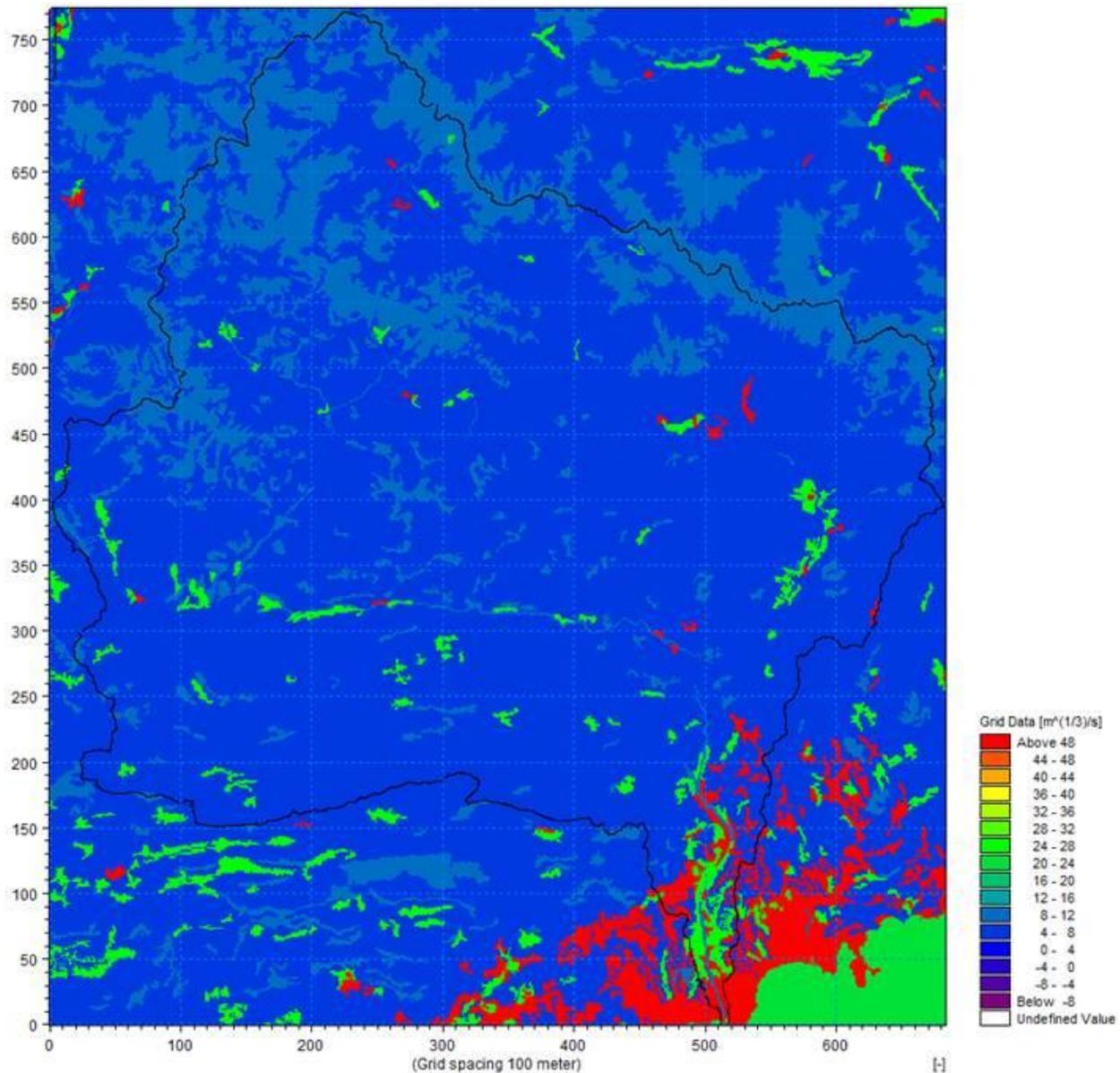


Figure 95: Distribution of Strickler coefficient defined in Var catchment.

4.4.6 Set up the unsaturated flow

In the simulation of the unsaturated flow, the soil types should be defined in the model simulation. Based on the percentage of soil materials collected from the European Soil center, through the “Soil Texture triangle”, four soil types were defined in the MIKE SHE model of Var catchment (Figure 96).

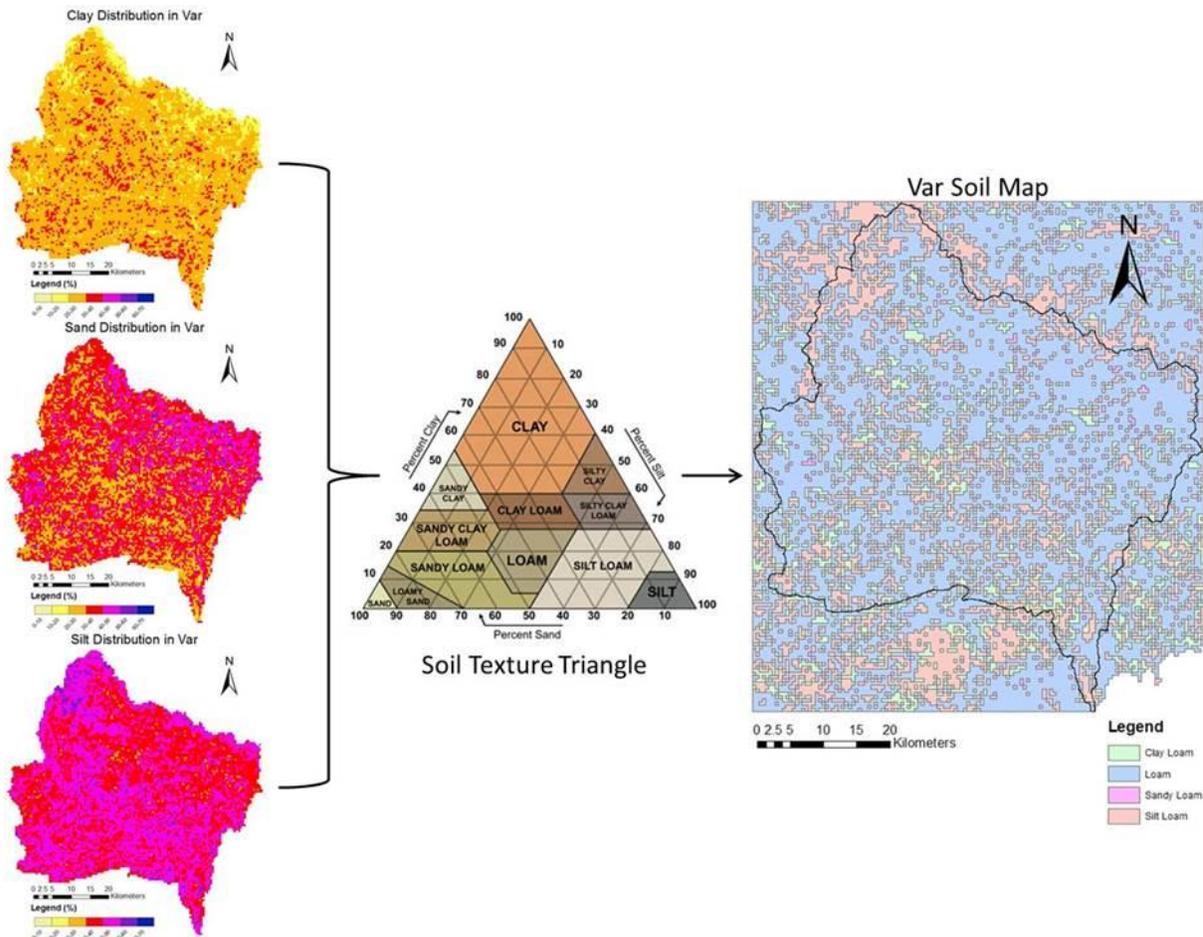


Figure 96: Define the soil types based on the percentage of soil material and “Soil Texture Triangle”.

Moreover, due to the data limitation, the “2-layers” function in MIKE SHE was selected in the unsaturated zone simulation. The initial data applied in the model was showed in Table 26.

Table 26: Initial values of soil parameters defined in MIKE SHE simulation in Var catchment.

Parameters	Clay Loam	Loam	Sandy Loam	Silt Loam
Water content at saturation (-)	0.5	0.5	0.38	0.46
Water content at field capacity (-)	0.36	0.28	0.18	0.31
Water content at wilting point (-)	0.22	0.14	0.08	0.11
Saturated hydraulic conductivity (m/s)	2.50E-06	6.00E-06	1.00E-03	2.50E-05

4.4.7 Set up the saturated flow

In the saturated flow simulation, the characteristic of aquifer is mainly represented by depth of the soil, horizontal hydraulic conductivity and vertical conductivity. Because of few field measurements of hydraulic conductivity was available over whole Var catchment, two uniform constant values were respectively defined for horizontal and vertical conductivities with the relationship of horizontal hydraulic conductivity divide by vertical hydraulic conductivity in

range from 0.1 to 0.5 (Todd, 1980). And the depth of the soil was also estimated by the surface slope (Table 27) (Figure 97).

Table 27: Initial values of soil depth estimated by surface slope.

Surface slope (°)	Soil Depth (m)
0-10	-12
20-30	-5
20-30	-5
30-40	-5
40-50	-1
50-60	0
60-90	0

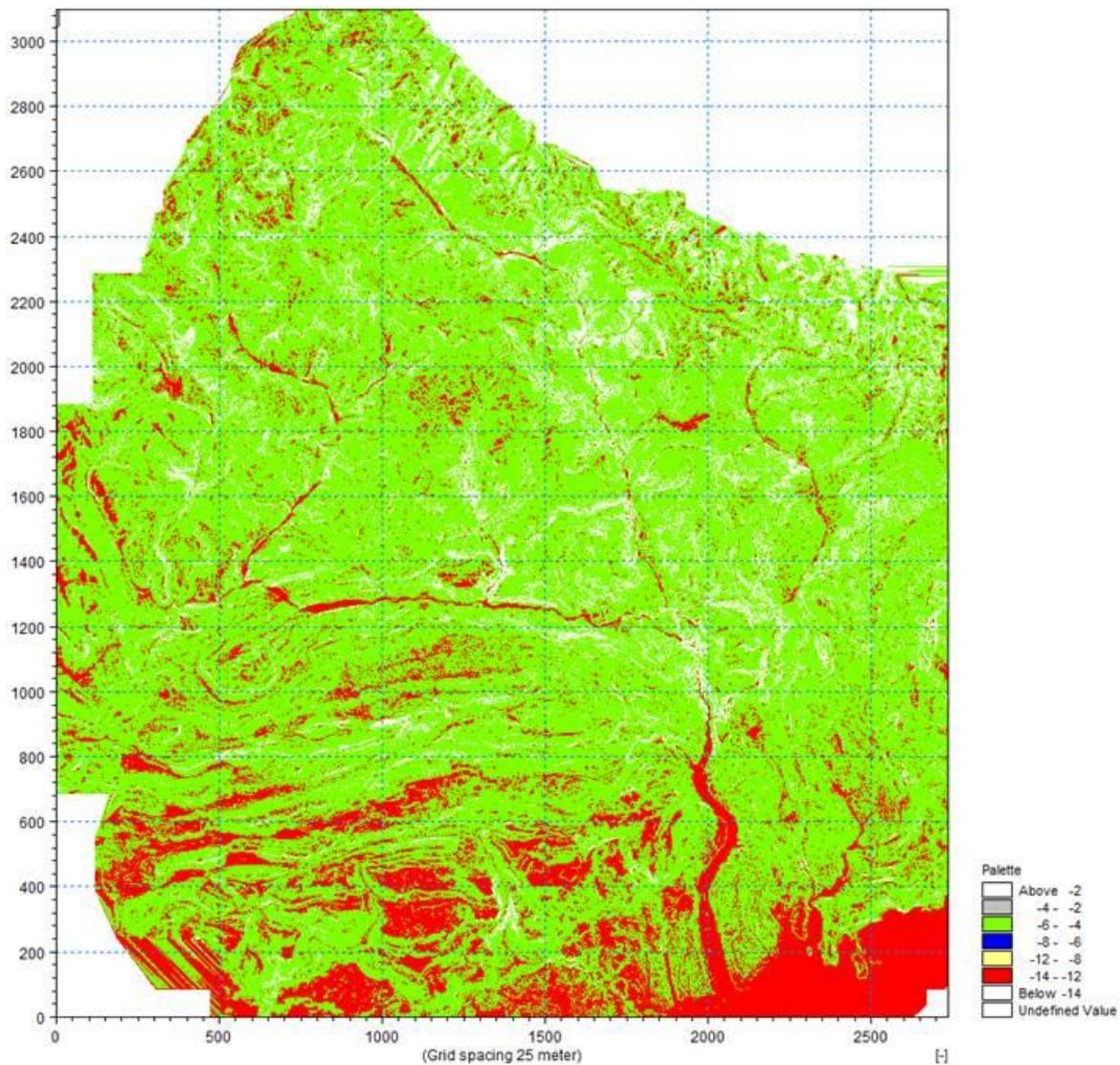


Figure 97: Initial values of soil depth defined by surface slope.

CHAPTER 5: RESULTS DISCUSSION AND UNCERTAINTY ANALYSIS

The deterministic distributed hydrological modelling simulation was expected to generate more accurate and detail representation of multi-hydrological processes in the catchment. In theory, the parameters involved in its calculation should be directly defined based on the catchment physical characteristics which monitored from the field survey (Refsgaard et al., 1995). However, it expectation is the very ideal situation which almost never happened in the reality. Even through in case of no missing data in the interested catchment, due to the uncertainty existed in the data itself and the coarse simulated resolution, the distributed model simulation could not precisely represent all the physical properties of the study area (Gurtz et al., 1999). Consequently, those data and simulation limitations caused the reduction on the simulated performance of the model.

In the MIKE SHE simulation in Var, the limitations caused by the missing information about the catchment characteristics was more obvious and required several hypothesizes to be applied for filling the gaps between data availability and model requirements. Therefore, it is necessary to implement the calibration process in the model strategy in Var to find the optimal set of parameter values which could describes the catchment behaviors as accurately as possible (Cunge, 2003; Guinot and Gourbesville, 2003).

However, the calibration process of MIKE SHE simulation in Var catchment was very complicated as results of numerous parameters were applying in the simulations of various hydrological processes. It is unnecessary to take into account all the parameters in the calibration process as many of them may have insignificant impacts on the hydrographs. Besides, the suggestion of Refsgaard et al. (1995) was recommended to keep the number of subjected parameters which needs to be adjusted as small as possible and only focus on the parameters which have obvious impacts of the model results. To identify those model parameters, on one hand, we could get some hints from the numerical equations applied in the model calculation; on another hand, the sensitivity analysis could be implemented to achieve this task as in various catchments with different characteristics, the impacts of the parameters may slightly have some differences.

In sensitivity analysis of called elasticity analysis applied in the MIKE SHE application in Var catchment, the elasticity or called sensitivity ratio (SR) which commonly applied in the modelling assessments in many aspects including science, engineering and economics was expected to exhibit more clearly the level of impacts of each parameters towards river flow (Maidment and Hoogerwerf, 2002).

$$SR = \frac{\left(\frac{\Delta Y}{Y}\right)}{\left(\frac{\Delta X}{X}\right)} \quad \text{Equation 30}$$

where ΔY is the change of the model output
 Y is the baseline value of the output
 ΔX is the change of the model parameter
 X is the baseline value of the input parameter

In the hydrological system of Var catchment, which consisted with multi-hydrological processes interacted in the catchment, the interaction between each model parameters should also be taken into account in the assessment (Mishra, 2009; Muleta and Nicklow, 2005; Sivapalan et al., 1987; Wang et al., 2007). In this case, the sensitivity analysis of MIKE SHE simulation in Var catchment was implemented by changing the modelling parameters one by one and assessing the responses of discharge variation at the outlet of the catchment (Napoléon III Bridge). It supposed to quantify the dependent rate of discharge on the change of all the tested parameters and help the modeler to complete the calibration process more accurate and faster. Based on the available data, the tested model was set up for a longer period from beginning of 2011 until end of 2013 which including one serious flood event recorded at November 2011, one spring flood event observed at April 2013 and one drought event occurred at July 2012. The variations of the discharges at those three events were defined as model response factors to evaluate the sensitivities of the test parameters.

Subsequently, in the second section of this chapter, based on the conclusion of the sensitivity analysis the model was calibrated with four year simulation from 2008 to 2011 and validated by four years simulation from 2011 to 2014 with some statistical coefficients such as NES or KGE (Kling-Gupta efficiency) (Gupta et al., 2009).

However, based on the experience of evaluating the rainfall interpolation processes, the statistic assessment was able to produce general view of the simulation performance, but to evaluate the fitness of simulation results towards to our modelling objectives, more detail analysis were necessarily required in the calibration and validation process. Thus, after integrated assessing all the evaluation factors, the calibrated MIKE SHE simulation in Var was able to produce reasonable simulation results to satisfy our modelling requirements and be applied in the EDSS of AquaVar project supporting other modelling processes in the system.

Furthermore the uncertainty analysis linked the modelling results and the data collected in the field was also discussed in this chapter to have more detail understanding of the quality of observation and simulation in Var. The chapter was ended by the conclusion including assessment of simulation quality and summery of the experience about optimized modelling strategy for setting up the deterministic distributed hydrological model in Var catchment which has serious missing field information.

5.1. Results of Sensitivity Analysis

Due to the big uncertainty caused by the missing data in Var catchment, the MIKE SHE model had been set up with many hypothesizes and under several conditions. The sensitivity analysis for this model was more focused on the calculation parameters which are involved in the numerical computation for various hydrological functions in the model. Some of the tested parameters were typical “numerical” parameters which are not link to the catchment physical characteristic, and the others were the physical parameters supposed to directly describe the physical phenomenon of the study area.

Table 28: Tested parameters in the sensitivity analysis of MIKE SHE simulation in Var catchment.

Functions	Parameters	Units
Time Step Control	Max precipitation depth per time step	mm
	Max infiltration amount per time step	mm
	Input precipitation rate requiring its own time step	mm/hour
Climate	Degree-day coefficient	mm/°C/day
Rivers and Lakes	Bed resistance	m ^(1/3) /s
	Leakage coefficient	/s
Overland Flow	Manning number of Forest	m ^(1/3) /s
	Manning number of Grassland	m ^(1/3) /s
	Manning number of Open space	m ^(1/3) /s
	Manning number of Artificial area	m ^(1/3) /s
	Manning number of Agriculture area	m ^(1/3) /s
Unsaturated Zone	Hydraulic Conductivity of Loam	m/s
	Hydraulic Conductivity of Silt	m/s
	Hydraulic Conductivity of Clay	m/s
	ET Surface Depth	m
Saturate Zone	Horizontal hydraulic conductivity	m/s

In Table 28, all the parameters involved in this sensitivity analysis were listed including 3 numerical parameters controlled the calculation time step and 13 parameters represented the physical characteristics among catchment Climate, stream flow (Rivers and Lakes), Overland flow and flow through Unsaturated and Saturated Zone. All of them play significant role in the model simulation as the main factors applied in the computation equations and supposed to have various impacts on the simulated discharge at the outlet of the catchment. Moreover, their impacts on the catchment runoff were expected not only on the simulation amount but also on the temporal variation of the peak discharges. The baseline values of the parameters and the responses of river flow versus the variation of tested parameters were showed in Table 29a, b and c.

Table 29a: Response of catchment stream discharges of spring and winter peak and summer low flow versus MIKE SHE parameters' variation in Var.

Functions	Parameters			Units	Δ winter peak flow (m ³ /s)	Δ summer low flow (m ³ /s)	Δ spring peak flow (m ³ /s)
Time Step Control	Max precipitation depth per time step	P _{Max depth}	100(baseline)	mm			
			10		-1.76	2.15	-10.84
			20		0	0	0
			50		0	0	0
			200		0	0	0
	Max infiltration amount per time step	P _{Max infiltration}	100(baseline)	mm			
			10		-62.50	-1.81	-12.97
			20		-62.37	-1.82	-12.62
			50		-52.25	-1.54	-12.11
			200		102.37	11.45	130.74
	Input precipitation rate requiring its own time step	P _{Input rate}	10(baseline)	mm/hour			
			0.1		10.76	1.00	-1.45
			2		1.83	1.35	-13.76
			5		-11.67	1.15	-13.61
			20		0	0	0
Climate	Degree-day coefficient	C _{Degree day}	2(baseline)	mm/°C/day			
			1		-25.07	10.98	-17.14
			4		13.79	0.45	-24.36
			8		12.86	-2.37	-53.65
Rivers and Lakes	Bed resistance	M _{Bed}	20(baseline)	m ^(1/3) /s			
			10		-5.43	0.56	-2.42
			30		2.62	0.28	8.96
			40		-18.78	0.38	-13.06
			50		7.31	3.68	-13.21
	Leakage coefficient	C _{Leak}	1.00E-05(baseline)	/s			
			1.00E-07		-175.82	1.50	-68.61
			1.00E-06		-112.96	1.97	-47.07
			1.00E-04		36.78	-1.96	38.34

Table 29b: Response of catchment stream discharges of spring and winter peak and summer low flow versus MIKE SHE parameters' variation in Var.

Functions	Parameters			Units	Δ winter peak flow (m ³ /s)	Δ summer low flow (m ³ /s)	Δ spring peak flow (m ³ /s)
Overland Flow	Manning number of Forest	M_{Forest}	2(baseline)	$m^{(1/3)}/s$			
			1		-31.57	0.89	-7.40
			5		3.60	0.29	-10.47
			10		7.98	0.13	3.74
			20		15.82	2.43	-13.68
			50		1.50	0.91	-4.52
	Manning number of Grassland	M_{Grass}	2.5(baseline)	$m^{(1/3)}/s$			
			1		-27.35	-0.50	-17.05
			5		7.04	-1.51	-12.99
			10		1.85	2.19	-16.41
			20		8.05	2.09	0.08
			50		8.93	1.70	-10.27
	Manning number of Open space	$M_{Open\ space}$	5(baseline)	$m^{(1/3)}/s$			
			1		-1.71	0.11	-9.36
			10		-4.32	1.61	-14.21
			20		-4.09	1.00	-14.72
	Manning number of Artificial area	$M_{Artificial}$	50(baseline)	$m^{(1/3)}/s$			
			1		-13.85	0.54	3.19
			5		-10.99	0.20	-1.13
			10		-6.25	0.53	-0.85
	Manning number of Agriculture area	$M_{Agriculture}$	20	$m^{(1/3)}/s$	-17.71	0.84	-13.93
			25(baseline)				
			1		-5.35	0.97	-14.28
			5		-10.40	1.19	-11.80
10			-7.83		0.84	-2.60	
Manning number of Agriculture area	$M_{Agriculture}$	20	$m^{(1/3)}/s$	-15.49	1.43	-13.79	
		50		5.88	0.45	0.89	

Table 29c: Response of catchment stream discharges of spring and winter peak and summer low flow versus MIKE SHE parameters' variation in Var.

Functions	Parameters			Units	Δ winter peak flow (m3/s)	Δ summer low flow (m3/s)	Δ spring peak flow (m3/s)
Unsaturation Zone	Hydraulic Conductivity of Loam	$K_{uz\ Loam}$	5.00E-04(baseline)	m/s			
			1.00E-06		51.48	9.34	64.69
			5.00E-06		92.68	-1.45	40.49
			1.00E-05		94.13	7.93	30.72
			5.00E-05		2.95	3.14	-2.54
			1.00E-04		-0.58	0.50	6.56
	Hydraulic Conductivity of Silt	$K_{uz\ Silt}$	2.50E-05(baseline)	m/s			
			1.00E-07		13.30	3.66	-12.19
			5.00E-07		-27.12	1.20	6.11
			1.00E-06		22.77	2.51	10.70
			5.00E-06		2.18	2.23	4.21
			1.00E-05		-1.50	1.68	3.40
	Hydraulic Conductivity of Clay	$K_{uz\ Clay}$	2.50E-06(baseline)	m/s			
			1.00E-07		-17.71	2.70	1.35
			5.00E-07		-23.11	0.72	2.51
			1.00E-06		-17.40	0.41	-0.47
			5.00E-06		-11.42	1.00	-13.58
			1.00E-05		20.35	1.53	-14.91
	ET Surface Depth	$ET_{\ Depth}$	0.1(baseline)	m			
			0.2		-70.67	1.86	-23.89
			0.5		-311.84	0.68	-33.16
0.8			-489.30		0.41	-65.77	
1			-584.99		0.08	-78.73	
Saturated Zone	Horizontal hydraulic conductivity	$K_{sz\ Horizontal}$	7.50E-03(baseline)	m/s			
			1.00E-05		-849.07	-1.53	-251.94
			5.00E-05		-837.64	3.54	-321.53
			1.00E-04		-834.17	4.08	-334.71
			5.00E-04		-787.19	3.69	-321.83
			1.00E-03		-699.87	4.93	-278.02
			5.00E-03		-179.03	2.21	-80.06

5.1.1 Assessment of time step control

In the MIKE SHE simulation, each of hydrological functions runs with independent time step and the parameters in “Time step Control” are supposed to work for reducing the numerical instabilities by resampling the rainfall time series when the current computation time step is too long (DHI, 2012). If the total amount of rainfall in current time step exceeds the value defined by “Max precipitation depth per time step”, the model computation time step will be reduced by the increment rate (0.1 as we defined in the MIKE SHE simulation in Var catchment). Then the precipitation time series will be resampled with the new time step. This process will be continuously repeated until the precipitation amount per time step reach the defined maximum value.

In principle, if the value defined for “Max precipitation depth per time step” was even bigger than the max rainfall recorded in our input rainfall time series, there should be no impacts of this parameter on the simulation discharge. However, when its defined value is very small (e.g. small then the average value of rainfall time series), it supposed to have more impacts on the peak flow generated by high intensity rainfall by reducing the rainfall intensity at the peak time and cause the decrease of the peak discharge. In our case, increasing this value from 10mm up to 200mm, the only discharge variation was observed by changing the value from 10mm to 20mm with peak discharge respectively increased 1.76m³/s in winter flood (high intense rainfall event) and 10.86m³/s in spring flood event (low intense rainfall). Moreover, for the drought event, with less rainfall intensity and amount, the impacts of shifting the value from 10 to 20 caused the decrease of discharge with 2.15m³/s mainly due to the instability of the model calculation (Figure 98).

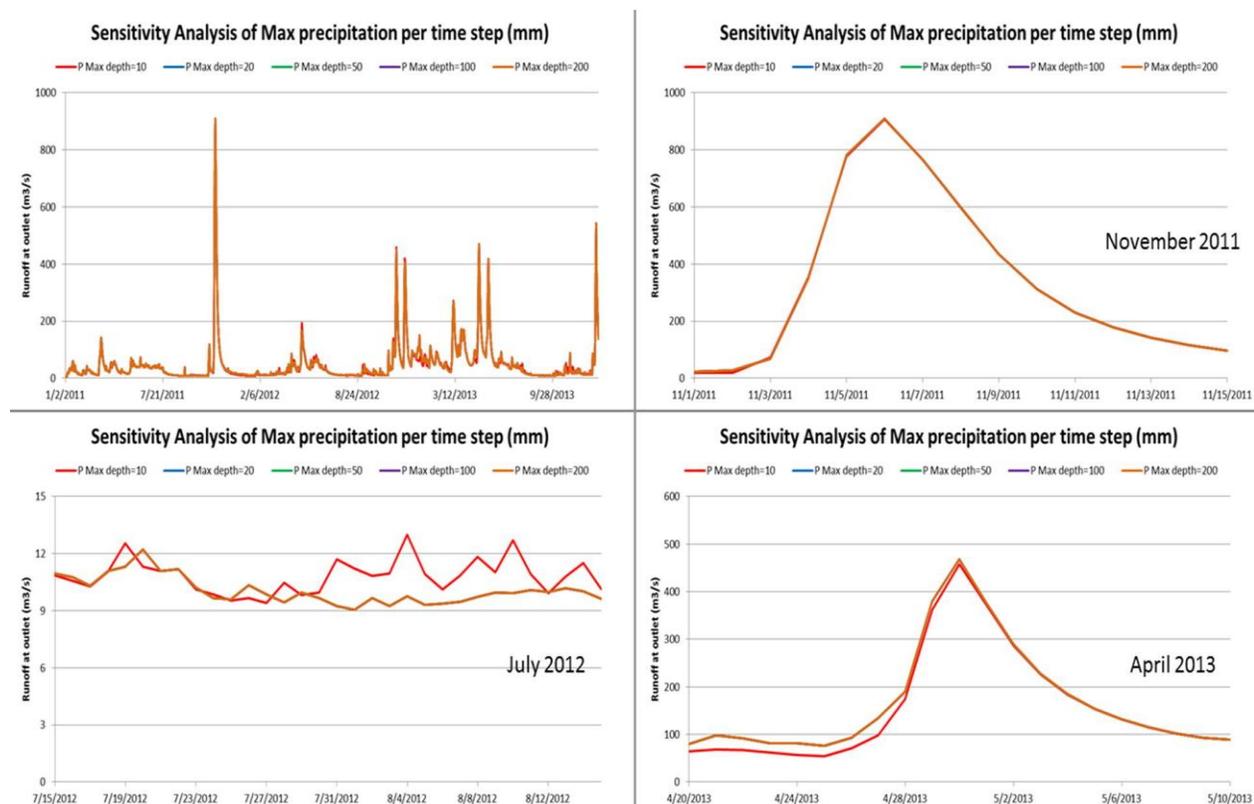


Figure 98: Sensitivity analysis of max precipitation depth per time step.

When the increases of “Max precipitation depth per time step” achieved 20mm, kept raised the value of this parameter, no impacts on the discharges were observed in the MIKE SHE simulation in Var. But the time of running the model has significantly growth up. Integrated considering the impacts of this parameter, its reasonable value was expected in range of 50mm to 100m.

The parameter of “Max infiltration amount per time step” supposed to work as same as the “Max precipitation depth per time step” in calculation of flow in unsaturated zone. Compared to the precipitation time step control, the impacts of infiltration time step control on the stream flow in Var catchment were more significant. Firstly, by increasing the value of this parameter, strong modelling instability was observed when its value achieved 200mm (Figure 99). Thus the simulated discharge by 200mm of max infiltration amount per time step was not considered in the assessment of discharge comparison among various simulations with different parameter values.

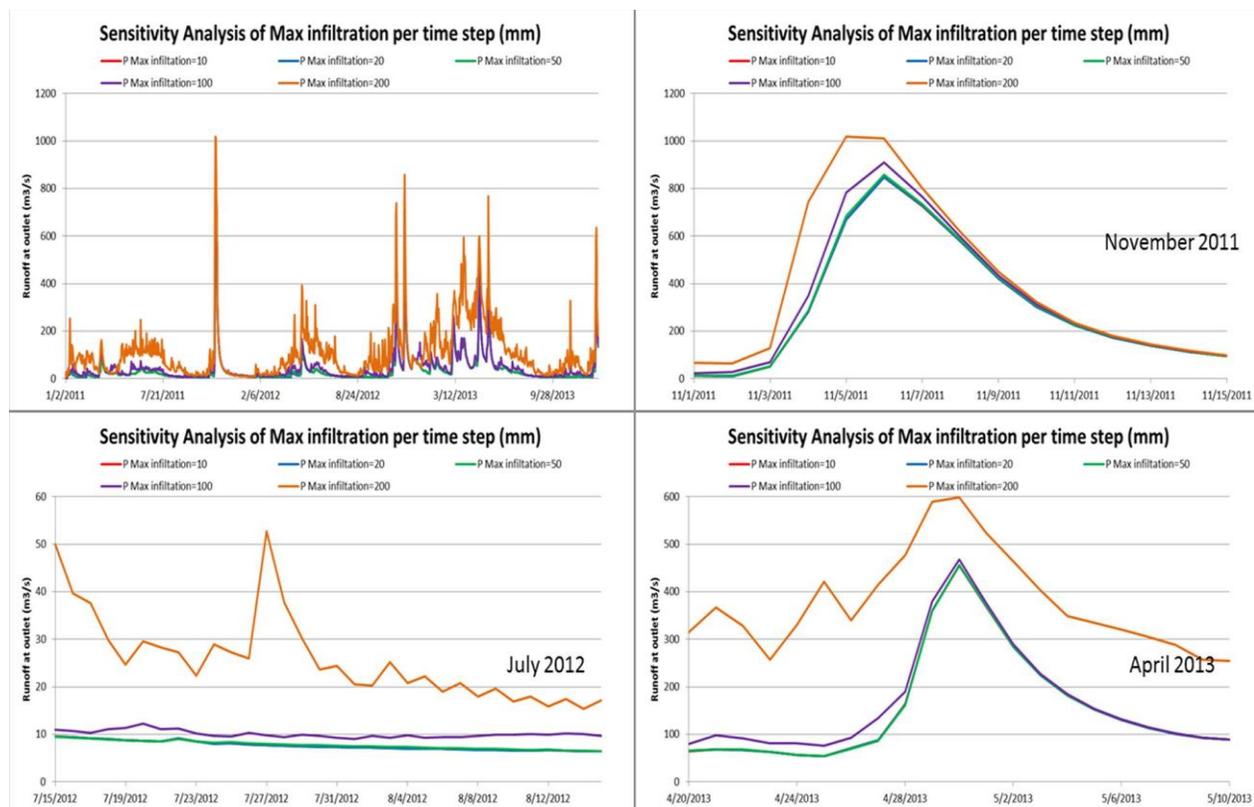


Figure 99: Sensitivity analysis of max infiltration amount per time step.

Secondly, compared the stream discharges simulated by various values of “Max infiltration amount per time step” increased from 10 mm up to 100m, either the peak flow in winter and spring floods or the low flow during the drought event showed an increasing trend with an exponential growth rate. Moreover, compared the its effects among the discharge in different event, more significant impacts were observed on the low flow discharge (19.98% increases by change its value from 10mm to 100mm). And further comparison between two peak flow caused by different rainfall intensities, more obvious impact was identified when high rainfall intensity rainfall occurred in Var (6.87 % increase of peak flow in November 2011 versus 2.77% increase

of peak flow in April 2013). Combined with the recommendation from DHI, “if you are using the 2-Layer water balance method, then you can set these conditions up by a factor of 10 or more”, 100mm of “Max infiltration amount per time step was expected as the most suitable value for this parameter.

The parameter of “Input precipitation rate requiring its own time step” added in the MIKE SHE simulation was supposed to capture the short term rainfall events. When the precipitation rate in the rainfall timer series is greater than the value of this parameter, the simulation will break the current time step at this computation time. In principle, with smaller value defined for this parameter, more detail of short term rainfall could be caught in the model simulation meanwhile the running time of the MIKE SHE would be increased. Moreover, the small value of this parameter may also cause instability problem in the numerical calculation. Thus, it was reasonable to notice that during the drought event when there was less water in the river channel, with the lower value of this parameter (e.g. 0.1mm/hour, 2mm/ hour or even 5mm/hour), the simulation showed numerical instability with the short term rainfall with small amount of water landed in the catchment (Figure 100). Moreover, after achieving the value of 10 mm/hour, there was not impact of this parameter on the discharge of stream flow observed in MIKE SHE simulation of Var catchment.

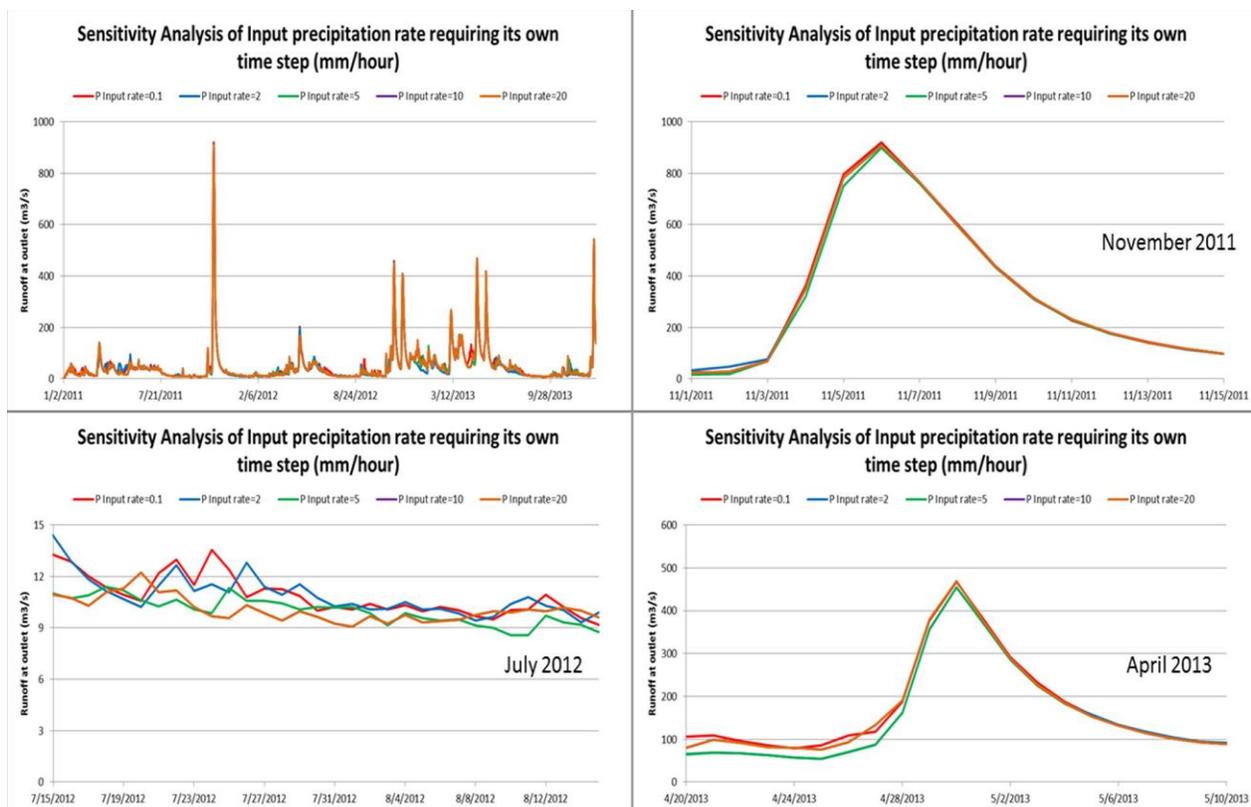


Figure 100: Sensitivity analysis of input precipitation rate requiring its own time step.

5.1.2 Assessment of climate (snow melting process)

The value of “Degree-day coefficient” could be considered to control the speed of snow melting and freezing in the catchment hydrological system. In principle, with higher value of “Degree-

day coefficient”, when the air temperature at computation cells is lower than 0°C, more water from precipitation or overland flow will be frozen as the snow cover store on the ground surface. In contrast, when the air temperature at the snow covered cell higher than 0°C, the higher value of “Degree-day coefficient” will lead to more snow melted within the computation time step.

In Var catchment the snow cover is often concentrated at the mountainous area with the variation of air temperature followed Mediterranean climate. In general, the snow melting process starts from beginning of March until end of July. Therefore, the discharges simulated by the MIKE SHE model in June included in the “melting period” were also check in the assessment of “Degree-day coefficient” sensitivity (Figure 101).

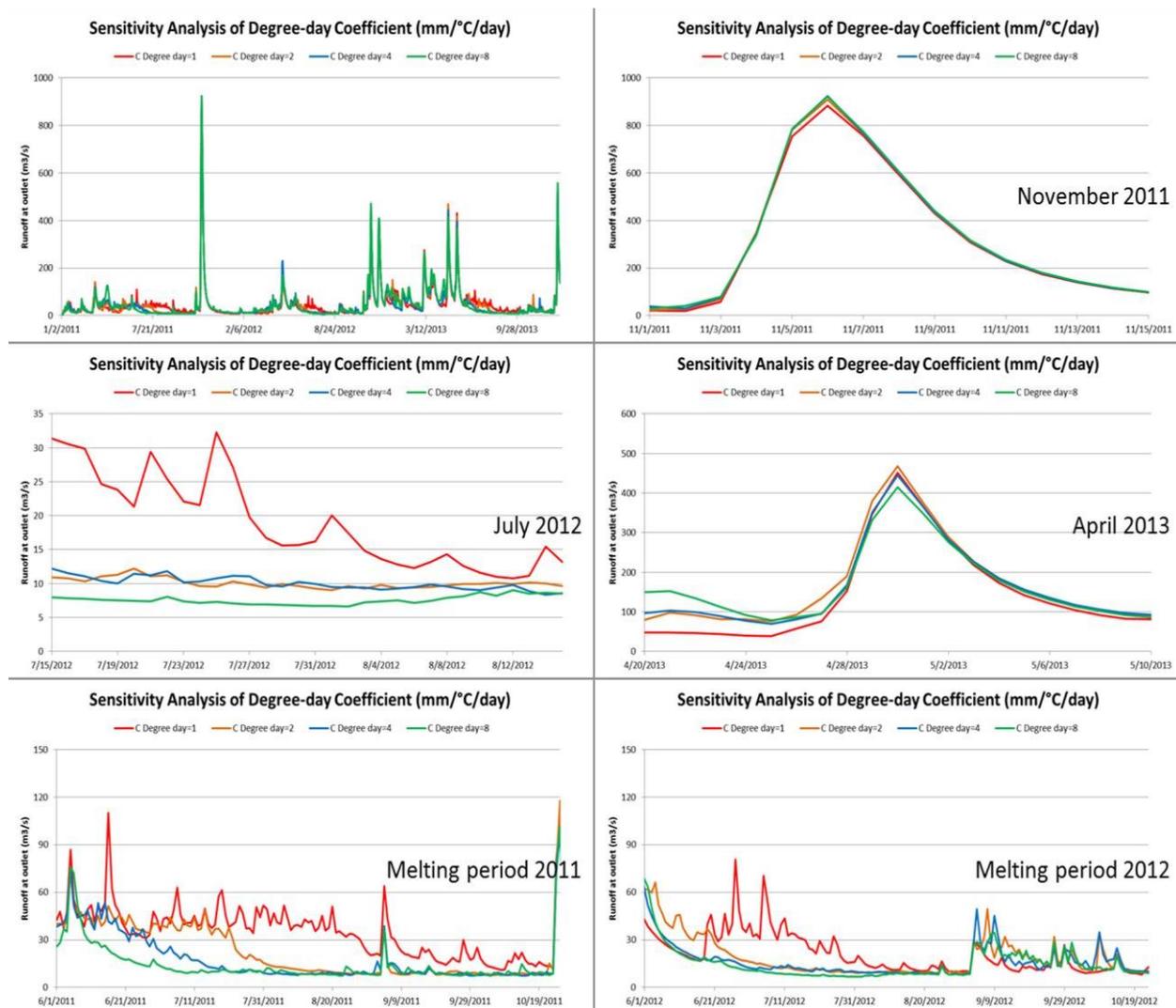


Figure 101: Sensitivity analysis of degree-day coefficient.

In the sensitivity analysis of this parameter, by increasing the parameter value of “Degree-day coefficient” from 1mm/°C/day up to 8mm/°C/day over the Var catchment, the promotion of the simulated peak flow caused by the high intensity rainfall in winter time (November) was very limited (+4.27 %). One of the explanations could be with the Mediterranean climate, the days of air temperature lower than 0°C in Var was not appeared so frequently especially at beginning of

November. Thus, due to the less difference between actual air temperature at the criteria value of snow melting and freezing (0°C), few rainfall could be frozen or melted at the mountainous area of Var catchment, which lead to the slight changes of the stream discharge in the catchment.

Moreover, compared to the impacts on the peak flow simulated at the winter time, the variation of the coefficient value could have more obvious effects on the discharge simulated during spring and summer time, which is normally considered as the melting period in Var. It is interesting to notice that with the increase of this coefficient, the simulated discharge showed one changing trend until its coefficient value achieved one threshold, then, it turn to an opposite direction. For example, in the simulation of spring flood event happened in April 2013 which normally considered as the begging of the melting period, with the coefficient value increased from $1\text{mm}/^{\circ}\text{C}/\text{day}$ up to $2\text{mm}/^{\circ}\text{C}/\text{day}$, the peak flow had been increased with $17.14\text{m}^3/\text{s}$. However, kept increasing the value of “Degree-day coefficient” from 2 to 4 $\text{mm}/^{\circ}\text{C}/\text{day}$, the peak flow discharge showed a decreasing trend with $-24.36\text{m}^3/\text{s}$ reduction. And when it changed to $8\text{mm}/^{\circ}\text{C}/\text{day}$, the decreasing of the peak discharge became more obvious ($-29.29\text{m}^3/\text{s}$). Moreover, for the low flow simulation during drought event which often contains less rainfall and higher air temperature, the low flow discharge simulated with $1\text{mm}/^{\circ}\text{C}/\text{day}$ of “Degree-day coefficient” was $20.04\text{m}^3/\text{s}$. Double increased its value in the simulated, the low flow was decreased to $9.06\text{m}^3/\text{s}$. Continuing to do this process, the discharge of lower flow during drought event at July 2012 presented with $9.50\text{m}^3/\text{s}$ discharge simulated by $4\text{mm}/^{\circ}\text{C}/\text{day}$ and $6.68\text{m}^3/\text{s}$ by $8\text{mm}/^{\circ}\text{C}/\text{day}$.

Furthermore, the hydrographs of melting period in 2011 and 2012 showed its impacts on the “speed” of snow melting process. Clearly, with $1\text{mm}/^{\circ}\text{C}/\text{day}$, there were still a lot of snow cover still existed in the catchment in June and July, the higher hydrograph generated by the simulation with this coefficient value may affected by some model instable problems. Then when the value of this parameter increased above $2\text{mm}/^{\circ}\text{C}/\text{day}$, the model became more stable and the simulated hydrograph showed a left hand moving trend with increasing of coefficient value. It indicated that with higher melting speed, the existed duration of the snow cover in Var catchment had been significant reduced and it impacts on spring flood could become more obvious. In contrast, its impacts during summer time were expected to be weakened.

5.1.3 Assessment of stream flow (river and lakes)

In theory, the Manning coefficient applied to describe the roughness of the river bed was expected to have significant impacts on the both the amount and peak time of stream flow simulated in MIKE SHE. However, the results with branches Manning values among 10, 20, 30, 40 and $50\text{m}^{1/3}/\text{s}$ in Var did not responded to our expectation. Its impacts on peak flow during flood period were very limited (Figure 102). Different hydrographs simulated during higher intensity rainfall flood event in November 2011 were almost the same. Their peak times were all occurring at 5th November 2011 and the variation of the simulated discharge was in range between $903.97\text{m}^3/\text{s}$ and $916.72\text{m}^3/\text{s}$. For the flood with lower intensity rainfall (e.g. April, 2013), the impacts of the Manning values on the stream discharge were more concentrated at the beginning part of the flood with lower rainfall landed on the catchment. As same as the flood in November 2011, the differences of peak flow and peak time among different simulation were almost negligible. More obvious impacts of Manning on discharge were observed during the drought event with less rainfall and lower channel flow. Consequently, integrated considered the

catchment characteristics of Var, we could expect due to the steep slope in Var, the Manning impacts on the discharge during higher rainfall period could be limited. But for the low flow period, with higher river bed Manning value which indicated much smoother of the channel, the discharge of lower flow could be slightly increased.

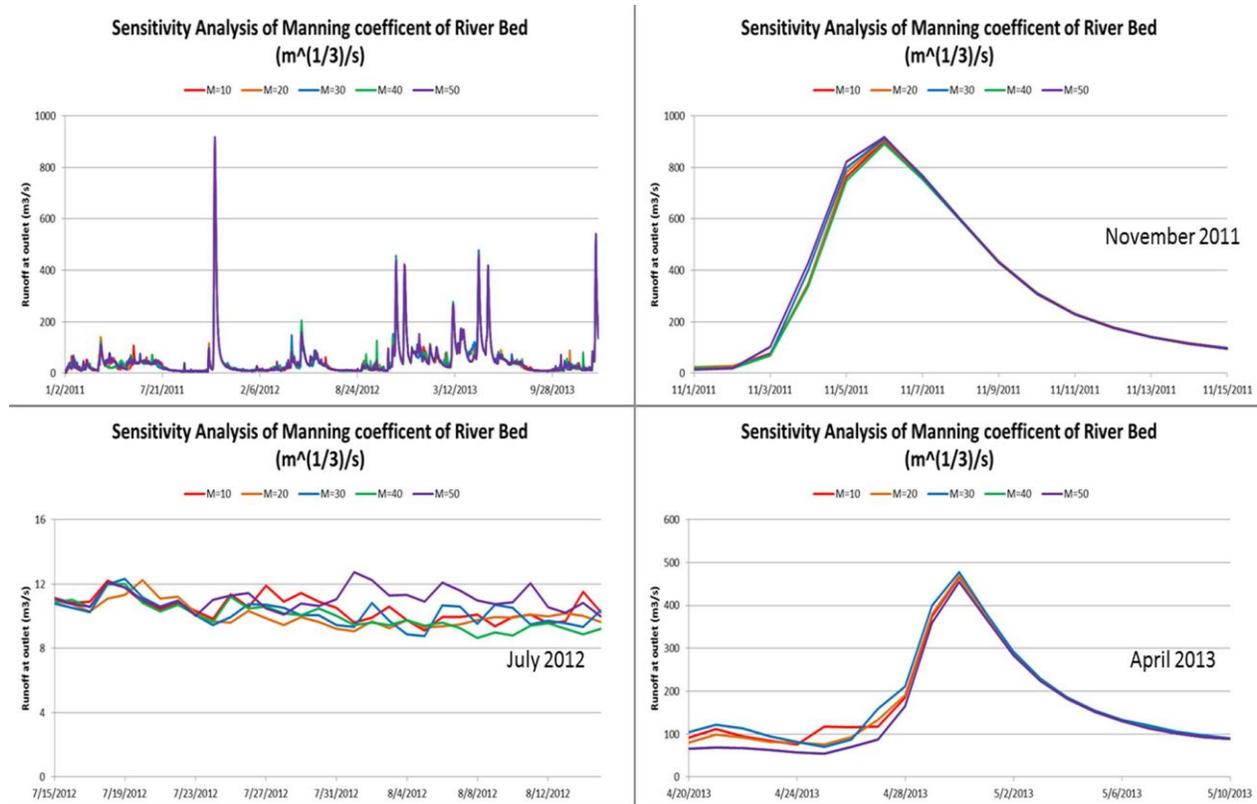


Figure 102: Sensitivity analysis of Manning coefficient of River bed.

The “Leakage coefficient” of the branch was expected to have impacts on the water exchange between groundwater and channel flows. It may confuse the modeler to consider it as a numerical parameter or physical parameters. However, based on the numerical equations applied in MIKE SHE, we could understand that with the higher value of this parameter, the exchange between groundwater and stream flow would become much easier.

$$Q = \Delta h \frac{\Delta x^2}{\frac{\Delta z}{2K_z} + \frac{1}{K_{leak}}} \quad \text{Equation 31}$$

where Q is the exchange flow between saturated zone and channel based on the Darcy equation.

Δz is the thickness of the layer.

K_z is the vertical conductivity of the layer.

K_{leak} is the specified leakage coefficient.

The exchange between the groundwater and channel flow simulated in MIKE SHE application is bidirectional. Its flow direction in the model is calculated based on the difference of water levels in the channel and the saturated zone. Thus, we could expect that the variation of this parameter could have impacts on both peak and lower flow discharges. During the flood period, when the

saturated zone was saturated by the infiltration, higher groundwater level may lead to the water flow from saturated zone to the channel. The higher value of “Leakage coefficient” could enhance this water transportation process and lead to the increase of peak flow discharge. In contrast, in the drought or dry period, when the saturated zone was not saturated and its water level lower than in the channel, the exchange flow from channel to the underground could be enhanced by increasing the parameter’s value, and then the stream discharge may have an obvious reduction (Figure 103).

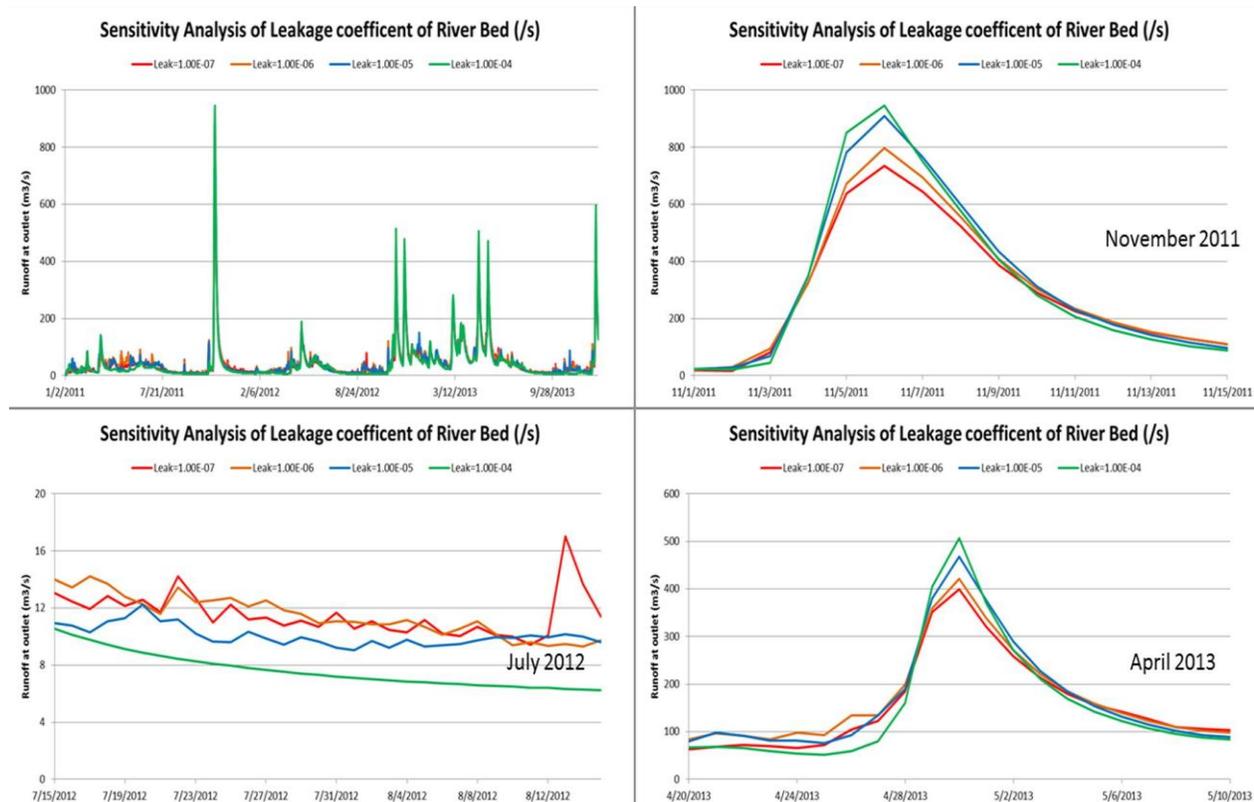


Figure 103: Sensitivity analysis of Leakage coefficient.

The simulation results showed above were perfectly responded to our expectation. When the value of “Leakage coefficient” increased from 1.00E-07/s up to 1.00E-04/s, the peak flow discharges at the flood events were grown respectively from 733.58m³/s and 399.79m³/s up to 946.18m³/s and 506.74m³/s. The increase percentages were +28.98% and +26.75%. But for the peak time, there was no difference among all the simulation cases. Moreover, for the low flow simulation, the discharge in the channel showed -32.75% decreases due to the raise of the parameter value from 1.00E-07/s up to 1.00E-04/s.

5.1.4. Assessment of overland flow

The overland flow function in MIKE SHE simulated the movement of ponded surface water across the topography (DHI, 2012). Instead of applying the Manning’s number (n), the Manning (M) used in MIKE SHE model is equivalent to the Strickler roughness coefficient with higher value describing more smooth ground surface. Therefore, by increasing the surface Manning, more water could move from one place to another within a certain time step. Its impacts were

expected to enhance the discharge with increasing the value of itself. However, in Var catchment simulation, due to the steep slope distributed in the catchment, as same as the Manning of river bed, the impacts of overland Manning also were mainly concentrated on the discharges at lower flow period (Appendix 5). In additional, the variation of the overland Manning also had the possibility to cause the instable problems of the numerical calculation in the model.

5.1.5. Assessment of flow in unsaturated zone

The unsaturated zone is usually heterogeneous and characterized by cyclic fluctuations in the soil moisture as water is replenished by rainfall and removed by evapotranspiration and recharge to the groundwater table. Thus, the flow through unsaturated zone plays important role in the hydrological system and supposes to have significant effects on the stream flow discharge in the catchment.

In the simulation of MIKE SHE in Var catchment, due to the data limitation, the 2-layers method was selected in the unsaturated flow simulation mainly because of its less data requirements. The physical characteristics of soil including water content at saturation, at field capacity, at wilting point and saturated hydraulic conductivity were input in the MIKE SHE model in Var. Among all the input factors, the saturated hydraulic conductivity supposed to have most significant impacts on either the values of peak and lower flow, or the peak time in the flood event. In Figure 104, took the example of Loam which covered 65.10% of Var catchment, its saturated hydraulic conductivity variation had impacts on the stream discharges along the whole simulation time series.

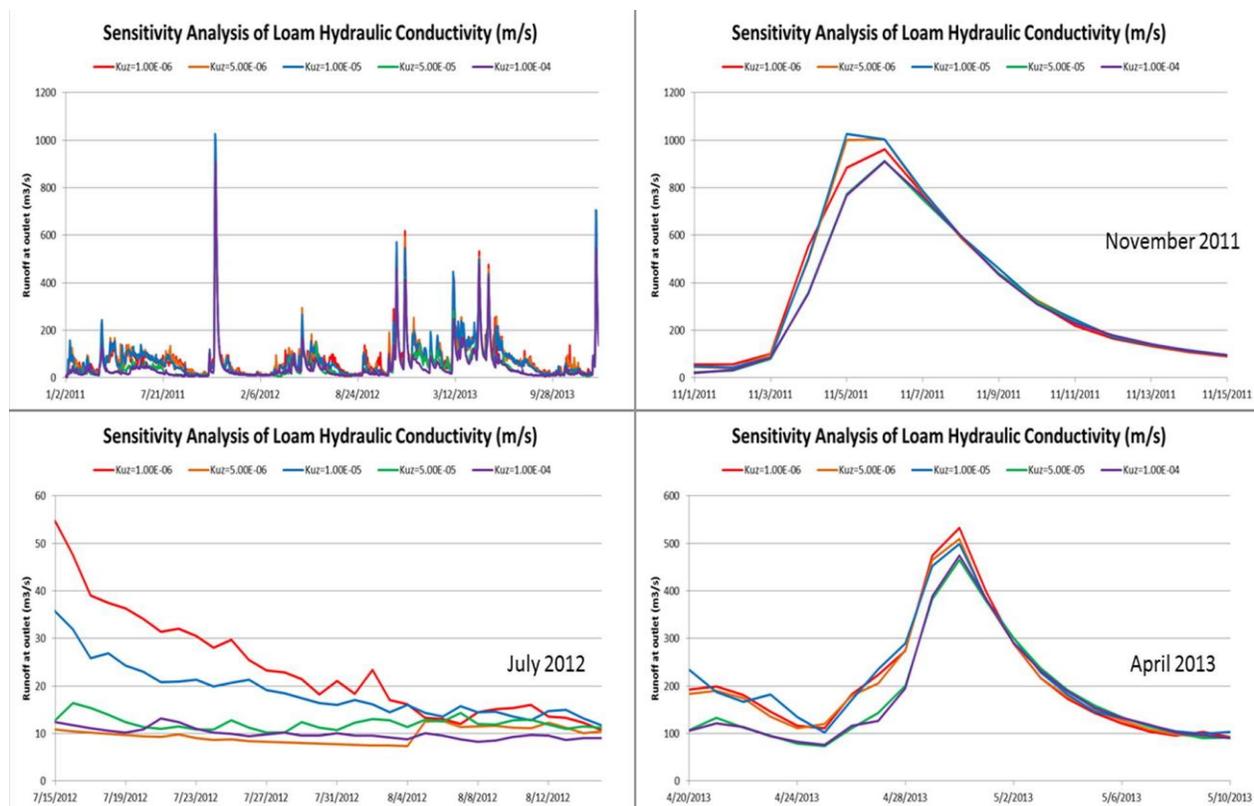


Figure 104: Sensitivity analysis of saturated hydraulic conductivity of Loam.

However, there was no clear changing trend detected with increasing the saturated hydraulic conductivity from $1.00\text{E-}06\text{m/s}$ up to $1.00\text{E-}04\text{m/s}$. When its value increased from $1.00\text{E-}06\text{m/s}$ up to $5.00\text{E-}06\text{m/s}$, the peak flow discharge caused by high intensity rainfall (November 2011) was increased from $960.88\text{m}^3/\text{s}$ up to $1002.08\text{m}^3/\text{s}$. But at same time, the both the discharges of peak flow in spring flood and low flow in drought period were decreased by 4.54% and 58.63%. It is reasonable to catch more significant impacts on the lower flow during dryer period, as the infiltration process was expected to play more important role of recharging the groundwater by taking the water from overland and channels.

Moreover, for the higher intensity rainfall flood, kept increasing the hydraulic conductivity up to $1.00\text{E-}05\text{m/s}$, there was no significant increase of discharge ($+1.45\text{m}^3/\text{s}$) at the previous peak flow day (6th November 2011). But the peak discharge simulated with $1.00\text{E-}05\text{m/s}$ hydraulic conductivity of Loam was shifted one day earlier (5th November) with higher value of discharge ($1027.20\text{m}^3/\text{s}$). Subsequently, this changing trend was not observed anymore after continuously increasing the hydraulic conductivity up to $1.00\text{E-}05\text{m/s}$. In case of changing the Loam hydraulic conductivity from $1.00\text{E-}05\text{m/s}$ up to $5.00\text{E-}05\text{m/s}$, its simulated hydrography in flood November 2011 showed obvious reduction. The peak time came back to 6th of November and its peak discharge was reduced to $912.35\text{m}^3/\text{s}$. Furthermore, there were no more significant impacts of increasing this parameter until $1.00\text{E-}04\text{m/s}$.

Besides, the impacts of Loam saturated hydraulic conductivity on peak flow and low flow in spring flood and summer dryer period with less rainfall landed in the catchment also showed similar fluctuating changing trend. Consequently, it was really difficult to evaluate the effects of hydraulic conductivity in unsaturated zone in Var. One possible reason could be because of the soil depth defined in the catchment was estimated by the surface, then in some place like the place which contain both flat and steep area, the soil water may be blocked at that place as the soil depth in the flat area was assumed much deeper than in the steep slope area. In this case, even in theory, the increasing saturated hydraulic conductivity in the unsaturated zone supposes to lead to the raise of soil infiltration capacity and enhance the low flow and reduce the flood discharge. But due to the difference of soil water level between flat and steep area is highly affected by the soil depth, the simulation responses may opposite to our expectation.

In addition, the ET surface depth which involved in the calculation of soil evaporation had more clear effect in the model simulation (Figure 105). When the soil was saturated during the flood event, with the increasing of the ET surface depth, less discharge values were observed at the peak time of the flood disasters. However, when the soil was unsaturated during the dryer period, its impacts were very limited.

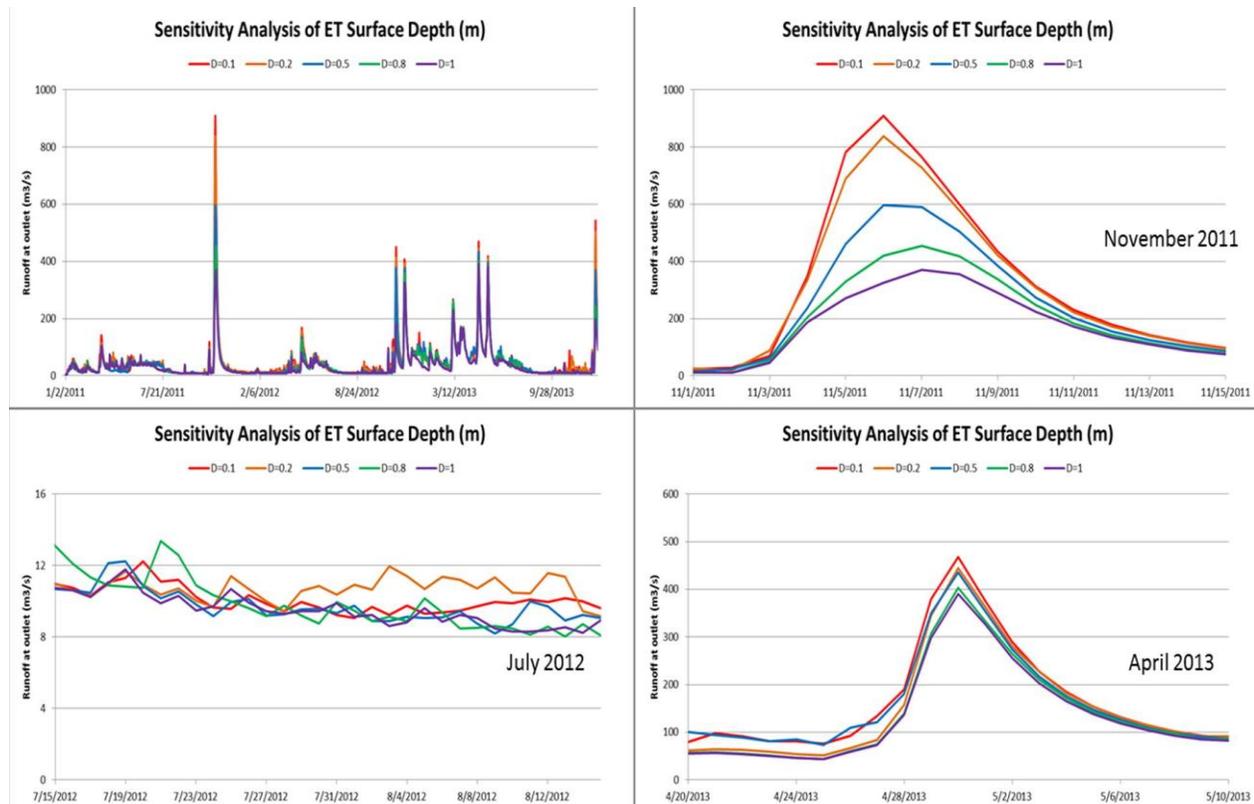


Figure 105: Sensitivity analysis of ET surface depth.

5.1.6. Assessment of flow in saturated zone

In MIKE SHE model, the flow through saturated zone plays a crucial role in the simulation of hydrological behavior in the catchment. Especially in the Var catchment, due to its special hydrogeological characteristics, the exchange process between surface and groundwater occurred very frequently in the catchment. From the study of Todd (1980), the values of $H_{c\ vertical}/H_{c\ Horizontal}$ are ranging between 0.1 and 0.5, thus the horizontal hydraulic conductivity was selected in this sensitivity assessment of saturated zone parameters.

In Figure 106, it was clearly represented the significant impacts of saturated zone horizontal hydraulic conductivity on stream flow simulation in Var. For instance, during the flood event simulated in the beginning of November 2011, with the increase of horizontal hydraulic conductivity, the stream peak flow value had been seriously increased after achieving a certain threshold value (e.g. $5.00E-03\text{m/s}$). When the values of horizontal conductivity changed from $1.00E-05\text{m/s}$ up to $5.00E-04\text{m/s}$, there were no significant improvements on its simulated stream flow. The peak time was held at 4th November 2011 which is nearly two days earlier than the recorded peak time. Besides, all these simulated values were relatively lower (around $200\text{m}^3/\text{s}$). Then continuously raise up this value up to $1.00E-03\text{m/s}$, the simulated hydrograph had obvious changes at both peak time and values. Subsequently, when its value achieved $5.00E-03\text{m/s}$, the peak time was closed to the reality (6th November 2011) and its peak value was more reasonable (around $700\text{m}^3/\text{s}$).

For the drought event with less rainfall landed in the catchment, it was interesting to notice that, the simulated stream flow with lowest value of horizontal hydraulic conductivity ($1.00E-05\text{m/s}$) had negligible simulated flow in the channels (less than $1\text{m}^3/\text{s}$), the discharge at the outlet of the catchment (red line) was around $7.5\text{m}^3/\text{s}$ which is closed to the total boundaries discharge we added in the model. Moreover, with the increase of its value, the simulated discharge showed fluctuating changing trend with highest values simulated with $1.00E-03\text{m/s}$ and lowest values simulated with $5.00E-03\text{m/s}$.

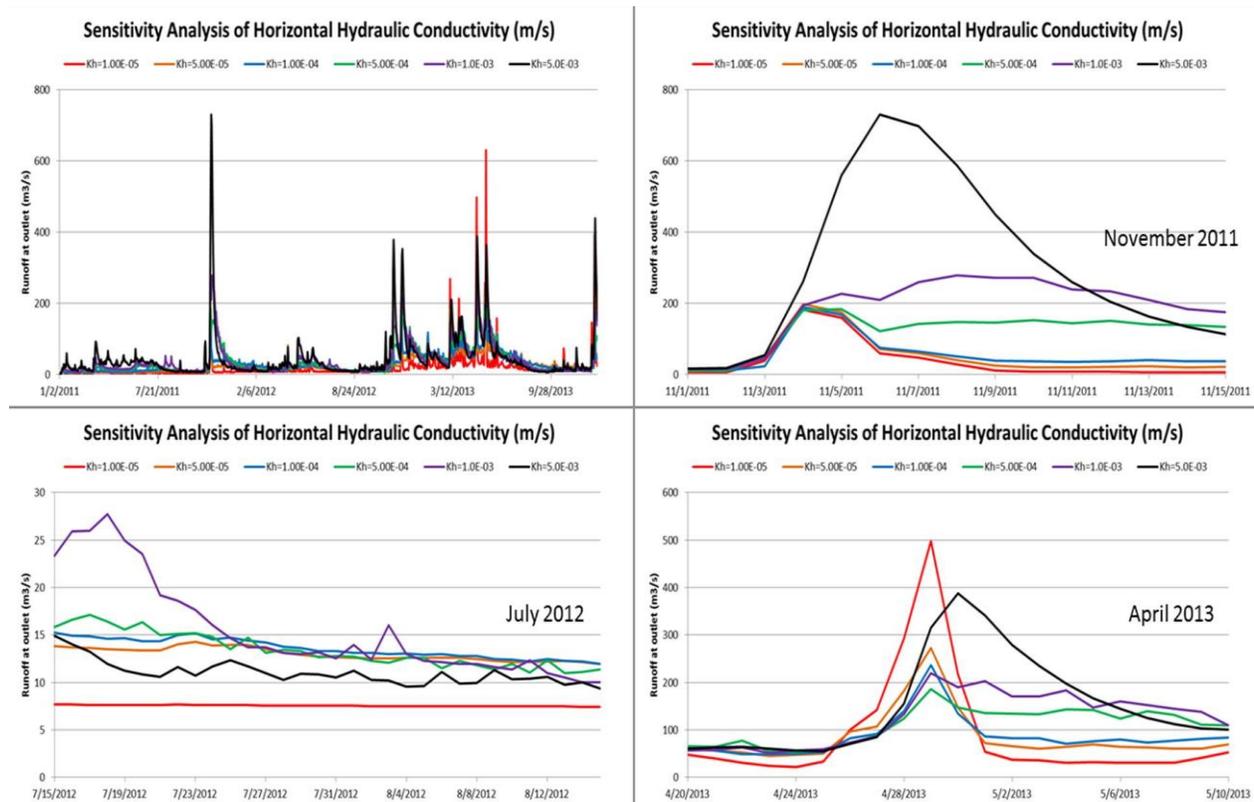


Figure 106: Sensitivity analysis of horizontal hydraulic conductivity in saturated zone.

Moreover, for the spring flood not caused by high intensity rainfall, the changing trend of the response discharge at the outlet of the catchment was the same as the drought simulation with fluctuating variation. The highest peak value was simulated by lowest horizontal hydraulic conductivity ($1.00E-05\text{m/s}$) at 29th April 2013 with nearly $500\text{m}^3/\text{s}$. Then with the increasing of the horizontal conductivity, the peak values had been obviously reduced, and its discharge after the peak, was grown up which let the simulated hydrograph looked more flat. However, after achieving a certain threshold, its hydrograph had been strongly improved which shifted the peak time one day after and kept the peak value around $400\text{m}^3/\text{s}$.

The results of sensitivity analysis in MIKE SHE simulation in Var catchment presented higher sensitivity of the hydraulic conductivity in saturated zone with almost randomness changing impacts. It seems there was one threshold value existing in the simulation, when the parameter value of horizontal conductivity achieved it, the simulation could become more reasonable. However, this threshold could be affected by other input factors such as the soil depth, which instead of directly measuring from the field survey, defined by the modelers based on the

distribution of surface slope and the soil parameters defined in the unsaturated zone. Therefore, in the calibration process, this parameter should be considered with other parameters and listed at the end of the calibration process when other parameters were almost calibrated.

5.1.7. Assessment of sensitivity rate (SR)

As we introduced before, the sensitivity rate (SR) was introduced in the sensitivity assessment of MIKE SHE simulation in Var catchment for identifying the importance of the parameters in the model simulation. In Figure 107, it was clearly indicated that for all three simulated flow discharges, the parameters related to the groundwater flow and the exchange flow between underground and channels showed relatively higher sensitivity in the simulation of MIKE SHE in Var. The horizontal hydraulic conductivity in the saturated zone was considered as the most sensitive parameters in this simulation case study. In theory, increasing its value is considered as enhancing of both infiltration ability of the soil and transmission speed of either groundwater flow or the exchange flow between surface and underground. Consequently, it was logical to get these sensitivity results of horizontal hydraulic conductivity appeared with positive impacts on the flood peak discharge, which let more soil flow recharging the channel and negative impacts on lower flow simulation which caused more stream water infiltrated into the saturated zone. Besides, as the stream discharge was considered as the criteria to evaluate the sensitivity of the parameters, the leakage coefficient of the channel significantly affected the exchange flow between channel and saturated zone had been identified as the second sensitive parameter in the simulation mainly due to its less impact area only limited for the channels. Its impact trends of peak and low flow discharges were the same as the horizontal hydraulic conductivity in the saturated zone, which responded to our conclusions of hydrological assessments in Var flood, which highly affected by both the rainfall intensity and saturated condition of the soil and the recharge flow from soil to the channel during the flood event contributed a part of the peak discharge.

Based on the limited information of snow melting process, we could not quantify the amount of the water from snow melting. However, from the sensitivity analysis of MIKE SHE simulation in Var catchment, we could have some hints about this process in Var. The coefficient controlled the melting and freezing speed in MIKE SHE showed positive impacts on the spring peak flow and negative impacts on both winter flood peak and drought event low flow. It could be explained with our assessment of flood characteristics in Var catchment. In spring flood event, a part of the flood discharge was contributed by the snow melting process, and in winter time due to the lower air temperature, a part of rainfall landed on the catchment could be frozen and stored as the snow cover on the ground. For the low flow simulation, actually there was less snow cover still existing at this time, instead of effecting the melting speed during the event period, the impacts of this coefficient was mainly on the amount of snow remained at this moment.

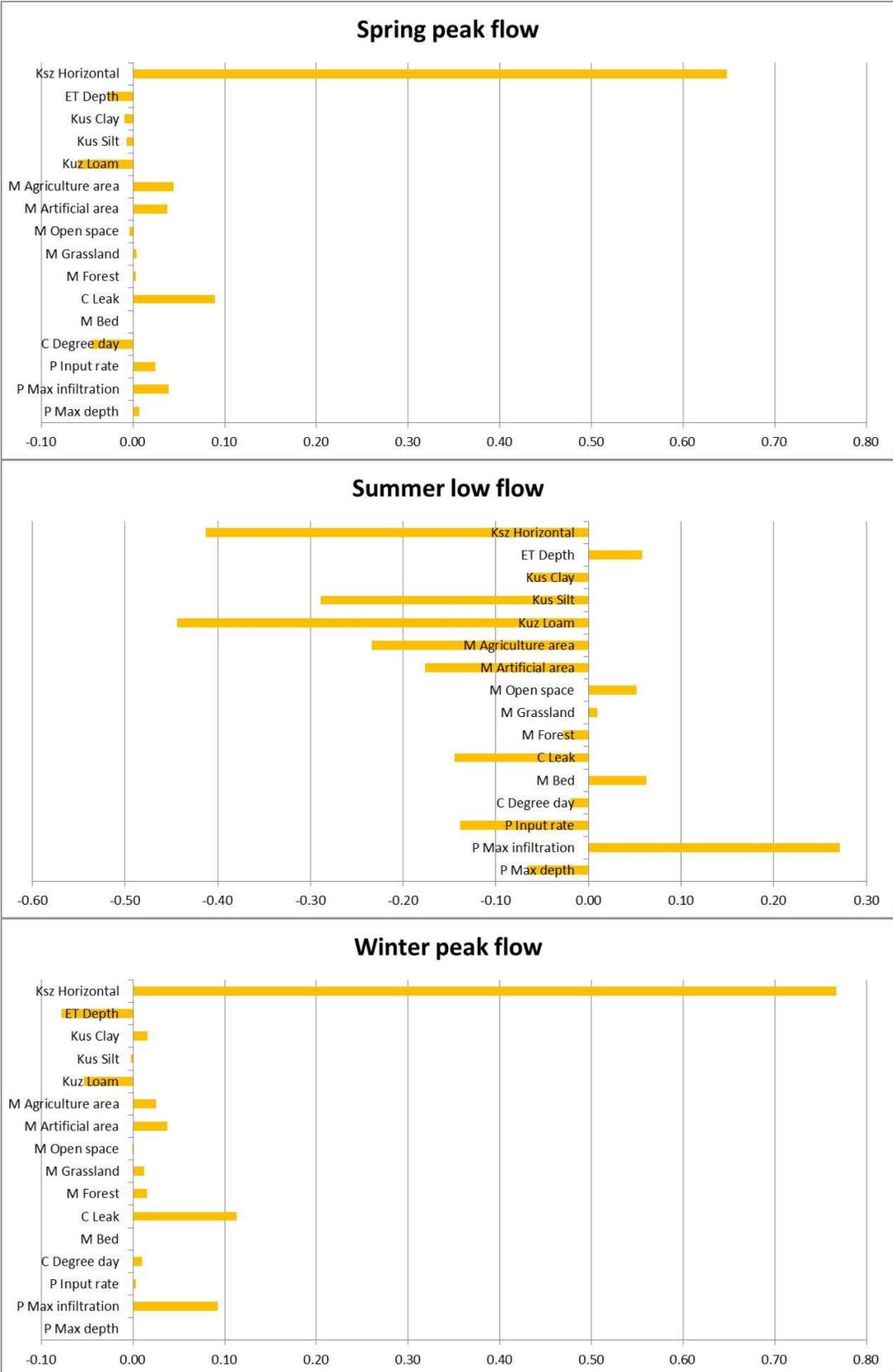


Figure 107: Sensitivity rate of all the tested parameters for peak flow of spring and winter floods and low flow in dry period

In the unsaturated zone, the hydraulic conductivity of the soil was considered as the maximum infiltration rate in the calculation. With higher value of this parameter, more water could be infiltrated into the soil and the stream and surface flow supposed to be reduced with certain amount of rainfall landed on the catchment. The results showed in the figure was clearly represented this expectation. The soil which has bigger area in the catchment showed higher sensitivity in the model simulation (Table). One point we would like to highlight here was the positive impacts of the Clay hydraulic conductivity on peak flow of winter flood.

Table 30: Sensitivity rate of unsaturated zone parameters.

Factors	Loam	Silt Loam	Clay Loam
Area (km2)	1752.14	587.47	414.16
Percentage (%)	62.93	21.10	14.88
SR peak winter	-0.0536	-0.0021	0.0158
SR low summer	-0.4440	-0.2893	-0.0637
SR peak spring	-0.0608	-0.0069	-0.0095

When we went back to check the distributions of Clay in Var catchment, we found that there are 41.26% Clay located at Tinée sub-catchment, which has biggest steep slope area in Var. Based on our soil depth assumption, with higher surface slope, its depth of the soil should be lower. Thus, in Tinée sub-catchment, the average soil depth should be lower than other catchments and the thick soil layers may be more concentrated at the channel area, which compared to the steep land surface was showed with slightly flat condition. Therefore, by increasing the hydraulic conductivity of Clay in unsaturated zone, it might let the soil at the channel area be saturated sooner. And at the peak time, less channel flow would recharge to the soil. In contrast, more soil flow could contribute to the stream peak discharge.

In principle, the Manning coefficient is supposed to have significant impacts on both surface flow and channel flow simulations. But in this case of Var catchment, due to the high steep slope distributed in the catchment, it did not show higher sensitivity in flood simulation. There was almost no impacts of bed Manning variation on the stream flow during flood simulations mainly due to the mountainous stream often appeared with steeper slope. Moreover, among all the surface Manning values, the Manning of Agriculture and Artificial area showed higher sensitivity than the other three. However, considered the land use area, the agriculture and artificial land use had lower control area in Var catchment (2.37% and 1.37%), one of the main reasons for them to produce the higher sensitivity in the simulation could be because of the distribution of those land uses were more concentrated at the downstream of the catchment where closer to the discharge evaluation point at the outlet of Var.

Among all three numerical parameters, the parameter of “Max infiltration amount per time step” showed higher sensitivity and positive impacts on the flow simulated in Var catchment, especially during the summer time with less overland flow in the catchment. However, one part of its sensitivity could be traced to the numerical instability of the calculation when there is shallow water existing in this steeper area.

5.2. Model Calibration and Validation

5.2.1 Discussion about statistic coefficients for modelling evaluation

In theory, if all the inputs data in the deterministic distributed hydrological model were able to accurately represent the physical characteristics of the catchment, it is not necessary to implement the calibration process of the simulation. However, due to the inputs uncertainties among the measurements, the assumptions applied in the modelling strategy and the coarse resolution defined in the model, it is important to add the calibration process in modelling approach to get the optimized parameter values to produce acceptable results for our modelling purposes. Instead of individually comparing simulated and observed values especially for the long time series simulation, some mathematically related statistic coefficients such as NES or MSE (Mean Squared Error) are commonly applied in calibration process to catch the general view of the simulation performance by implementing simple calculations.

However, based on our modelling experience, and the discussion of evaluating different rainfall interpolation functions in this project, depending on the modelling objectives, the benefits of applying the statistic coefficient to evaluating the simulation performance could be limited. One of the main reasons is pointed to the focusing aspects in formula consideration for calculating those statistic coefficients, which may be not toward to our modelling objectives. Therefore, the selection and application of those statistic coefficients in the modelling calibration process should be more detail discussed to make sure the statistic criteria defined the process is able to response the performance of simulation satisfying our modelling objectives.

In the AquaVar project, main objectives of the hydrological simulation are: on one hand to improve the knowledge and understanding of the hydrogeological characteristics of Var catchment and producing the boundary information for downstream hydraulic and groundwater models, on another hand to be able to run in real time and generate reasonable forecast results of flood and drought disasters to support the decision making process. To achieve the first objective, the simulation results should be able to catch the observed hydrograph in the catchment, which is the general simulation objective of all the modelling applications. But for the other one, it requires the MIKE SHE simulation in Var catchment to have good modelling performance on more specific aspects such as better representation of the peak time and values in the flood simulation and lower flow discharge at the drought event. Moreover, to ensure the decision made by the simulation results could be more effective, it is better to produce worse situation in the simulation to be clear that most of the potential risks had been taken into account.

The Nash-Sutcliffe efficiency (NSE) and Mean Squared Error (MSE) are the two criteria most widely used for calibration and evaluation of hydrological model with observed data. The value of MSE depends on the units of simulated variables on the interval from 0 to infinity. And for the NSE, which is dimensionless, its interval is from negative infinity up to 1.

$$MSE = \frac{1}{n} \sum_{t=1}^n (x_{s,t} - x_{o,t})^2 \quad \text{Equation 32}$$

$$NSE = 1 - \frac{\sum_{t=1}^n (x_{s,t} - x_{o,t})^2}{\sum_{t=1}^n (x_{o,t} - \mu_o)^2} = 1 - \frac{MSE}{\sigma_o^2} \quad \text{Equation 33}$$

where n is the total number of time steps, $x_{s,t}$ and $x_{o,t}$ are the simulated and observed value at time step t . μ_o and σ_o are the mean and standard deviation of the observed values. Clearly, the optimization of MSE is subject to be minimized to 0 and NES is subject to be maximized to 1.

From the studies of [Murphy](#) (1988) and [Weglarczyk](#) (1998), three distinctive components could be decomposed in the equation of NSE including the considerations of correlation, conditional bias and unconditional bias:

$$NSE = r^2 - [r - (\sigma_s/\sigma_o)]^2 - [(\mu_s - \mu_o)/\sigma_o]^2 = 2 \cdot \alpha \cdot \beta_n - \alpha^2 - \beta_n^2 \quad \text{Equation 34}$$

with

$$\alpha = \sigma_s/\sigma_o$$

$$\beta_n = (\mu_s - \mu_o)/\sigma_o$$

where r is the linear correlation coefficient between x_s and x_o . The quantity α is a measure of relative variability in the simulated and observed values, and β_n is the bias normalized by the standard deviation in the observed values. The “ideal” values of those three components among r , α and β are $r = 1$, $\alpha = 1$ and $\beta = 0$. It is clear that optimizing NSE aims to find the balance among three components to let the value of NES to be maximized.

However, two facts of applying the NSE in model evaluation must be concerned:

- The bias $\mu_s - \mu_o$ appears in a normalized form, scaled by the standard deviation in the observed flows. Thus, in the catchment which has higher runoff variability, this component will tend to have smaller contribution in the computation and optimization of NSE. It may lead to the simulated results having large volume balance errors.
- With respect to α that maximum value of NSE is obtained when $\alpha = r$. And since r is always smaller than unity which indicates that to maximize the NSE, we need to select a value of α underestimates the variability in the flows which often appeared with underestimation of peak flow and overestimation of lower flow.

Unfortunately, these two facts are exactly against our expectations of MIKE SHE simulation in Var catchment, which supposed to produce good forecasts of flood and droughts disasters.

Moreover, in the variability of stream discharge in Var catchment is also considerable which could be raised up from around 25m³/s up to 910m³/s in less than 1 days (November 2011). Therefore, instead of evaluating the simulation performance only based on the NSE, one more statistic coefficient of KGE was selected in the MIKE SHE calibration to help us improve our knowledge about the simulation quality evaluation. The KGE statistic coefficient could be considered as the improvement of NSE which equally assesses those three components of correlation, bias and variability measures. It may help to improve the bias and variability and slightly decreasing the correlation (Gupta et al., 2009).

$$KGE = 1 - ED \quad \text{Equation 35}$$

with

$$ED = \sqrt{(\gamma - 1)^2 + (\alpha - 1)^2 + (\beta - 1)^2}$$

$$\beta = \mu_s / \mu_o$$

where ED is Euclidian Distance from the ideal point, β is the ration between the mean simulated and mean observed values (μ_s and μ_o). The KGE optimization tends to decrease the recession parameters of surface flow and base flow to simulate a flashier hydrograph and improve the value of variability measure. However, even in the KGE evaluation system, the correlation, bias and variability have equal weight in the consideration. It still has the insufficient of evaluating the peak and low values in the simulation.

Besides the statistic coefficients applied in the model evaluation, the regression lines were also commonly used for assessing the correlation between simulated and observed values. However, depends on which values are selected to be regressing against with, the plotted regression lines may present with different interpretations (Figure 108).

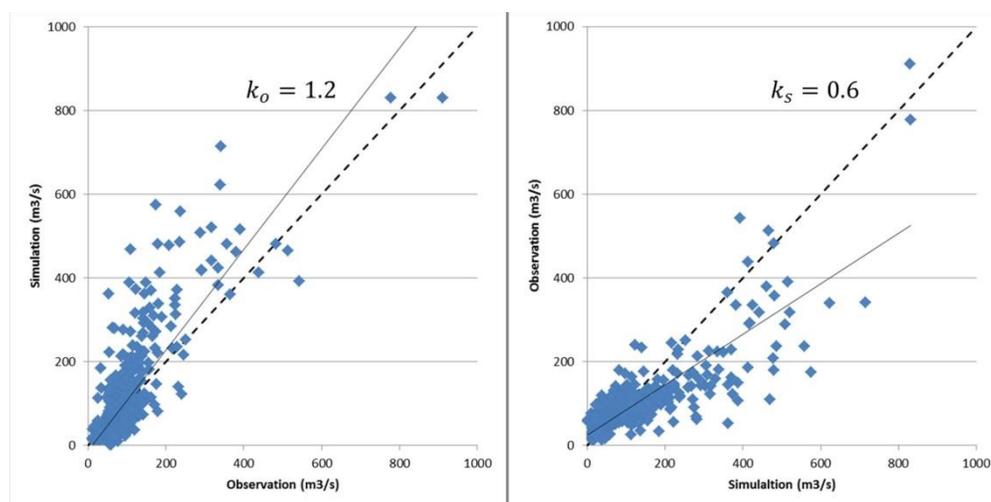


Figure 108: Regression lines produced in different cases.

In the figure above, the values of k_s and k_o are the trend line slopes and their values more closed to 1 will indicate better simulation performance. Clearly, both tow plots were valid but focused on different aspects. k_s is more commonly applied for evaluating the simulation of “normal” condition when the observation values are relatively lower. k_o is more focused on the assessment of model representing “unusual” situation when the observation has bigger values, in our case could be considered as the floods.

Integrated consider the benefits and limitations of different statistic coefficients, the strategy for calibrating the MIKE SHE simulation in Var catchment was designed as a multi-objective calibration process. Instead of changing the parameters to optimize the statistics coefficient for whole simulated time series, the calibration process could more focused on simulation representation of special events occurred in Var. And try to produce the “worse” phenomenon of the natural disasters which could be benefits for the decision makers to implemented related measures.

Due to the data limitation of rainfall records, the time period from 2008 to 2014 was selected as the simulation period of MIKE SHE in Var catchment, which has more gauging stations worked in Var. Then, as results of the topography data was measured at 2009, the period from 2008 to 2011 was designed as the calibration which contained one extreme flood event occurred at November 2011. And the period from 2011 to 2014 was defined as the validation period with one winter flood (November 2011), one summer drought (July 2012) and one spring flood (April 2013) inside. The reasons of reconsidered the year of 2011 in the validation process are

- Due to the missing information of the initial condition in the model, the simulation needs some water events to fulfill the blanks of conditions among ground surface (lakes), channels and soil.
- Moreover, we would like to have the test related to the flood simulation to identify if how long time in advance of the flood event required for the model to be warmed up.

In the calibration process of MIKE SHE simulation in Var catchment, besides all the parameters assessed in the sensitivity analysis, the depth of the soil, which is often defined as the physical inputs of the model, was also considered in the assessment. It made the calibration process become more complex as every time when you changed the depth of soil, all the other parameters should be recalibrated again. Moreover, based on our modelling proposes, two criteria was claimed in the simulation evaluation which the statistic coefficient calculated for the simulation results show the performance level as higher as possible, meanwhile, the simulation should able to catch the “unusual” situation in the catchment such as the flood and drought disasters.

To make sure we had good guideline of the calibration process, some assessment about the application of some statistic coefficients and physical factors including (NSE, KGE, total discharge and peak discharge) in Var catchment simulation was implemented at beginning of the calibration process. The year of 2011 was selected as the tested year even through the calibration was run for 4 years from 2008 to 2011. Main references supporting our selection were:

- There is one extreme flood event appear at the end of this year with around 900 m³/s daily peak discharge.
- Expect in the flood event, at most of the time in this year, the stream flow was more stable (Figure 109), which is perfect for applying the statistic assessment with NSE and KGE.

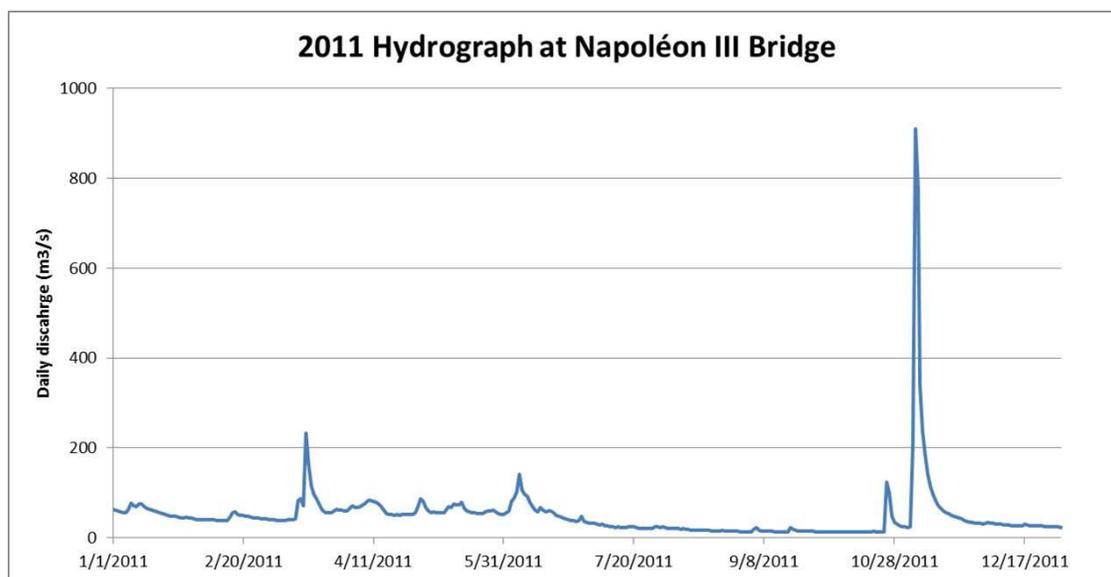


Figure 109: Hydrograph at Napoléon III Bridge 2011.

Therefore, we would like to assess the simulation in year 2011 to see with the sudden raising of the discharge at end of the year, are the statistic coefficients still able to indicate the simulation performance with their criteria.

Moreover, due to the data limitation with many discharge gauging stations in Var catchment have missing records, the stream runoff measured at the outlet of the catchment (Napoléon III Bridge) was selected as the reference of observation to calibrate the model.

Assessment of NSE in MIKE SHE simulation in Var catchment

Among more than 100 calibration cases, the NSE values calculated at the outlet of the catchment in year 2011 was varied in range from -3.13 to 0.70. Based on the statistic criteria, higher value of NSE will indicate better simulation performance. However, among all the simulated time series, there were two cases had same NSE value equal to 0.7. And when we plotted their hydrographs with the observations, different simulation performances was showed in Figure 110. Clearly, except the flood period in November 2011, for all the other parts of the year, the hydrograph produced by case 2 was more closed to reality. However, in the flood period, the peak flow between those two cases was around 120m³/s. And in case 2, its peak time had been slightly shifted one day delay. Moreover, after the flood peak represented in Var catchment, the changing trend of the hydrograph simulated by case 1 showed with sharper shape than the other simulation results which was more similar as the observation. Therefore, the assessment of comparing those two simulation results with same NSE value proved that besides the statistical evaluation of the simulation, it is still necessary and meaningful to implement more detail

assessment of the simulation hydrograph to double check if its simulation performance satisfied the modelling objectives.

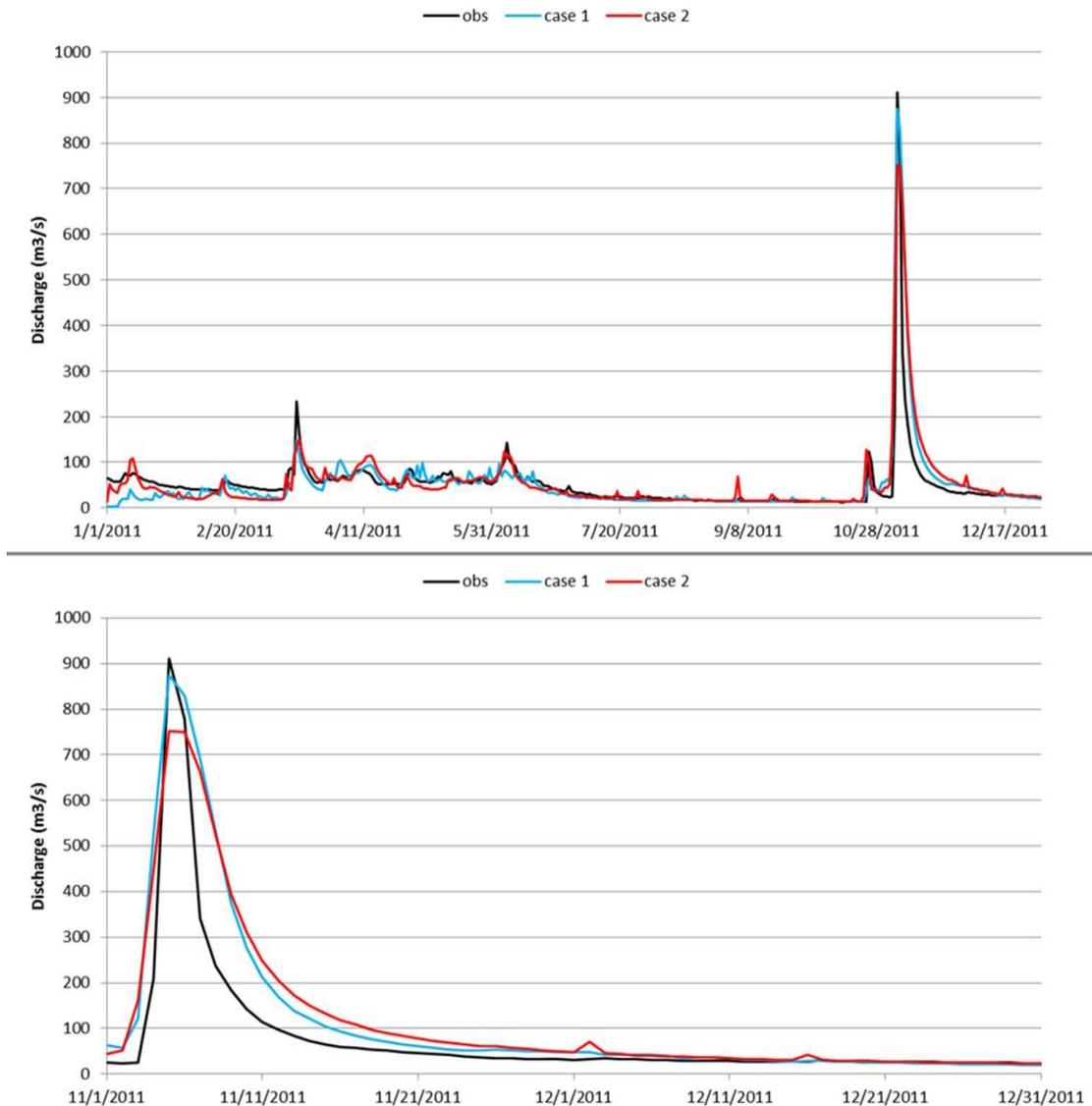


Figure 110: Comparison between the hydrographs with NSE =0.7.

For the same NSE value, the simulation results had the possibility to present different situations. Then the next question could be is the NSE statistic really working as they our expected which the higher NSE will directly indicate the better simulation results. Consequently, the hydrographs of simulated discharge with their NSE values equal to 0.7 and 0.32 (almost the half) were plotted in Figure 111. Clearly, the simulation results with lower NSE value showed strong overestimation of the discharge in the flood events appeared in 2011 which could be considered as the main contributions for reducing its statistic performance. However, when we zoomed to our interesting part which located at November 2011, the higher NSE simulation could not satisfy our modelling objective as neither its simulated peak value nor its peak time were not caught to observations. However, the simulation with lower NSE showed better performance in this case with similar hydrograph shape and caught peak time. Compared to the observation, its peak

discharge was strongly overestimated but in case of flood forecasting, this simulation could be considered as acceptable with worse situation estimated in the model which could be meaningful for the decision makers to consider the worse situation in the flood and make sure their measures could be effective during the event. Consequently, comparison between the high and low NSE hydrograph, in our case, the simulation results with lower NSE was more closed to our expectation of the modelling effects.

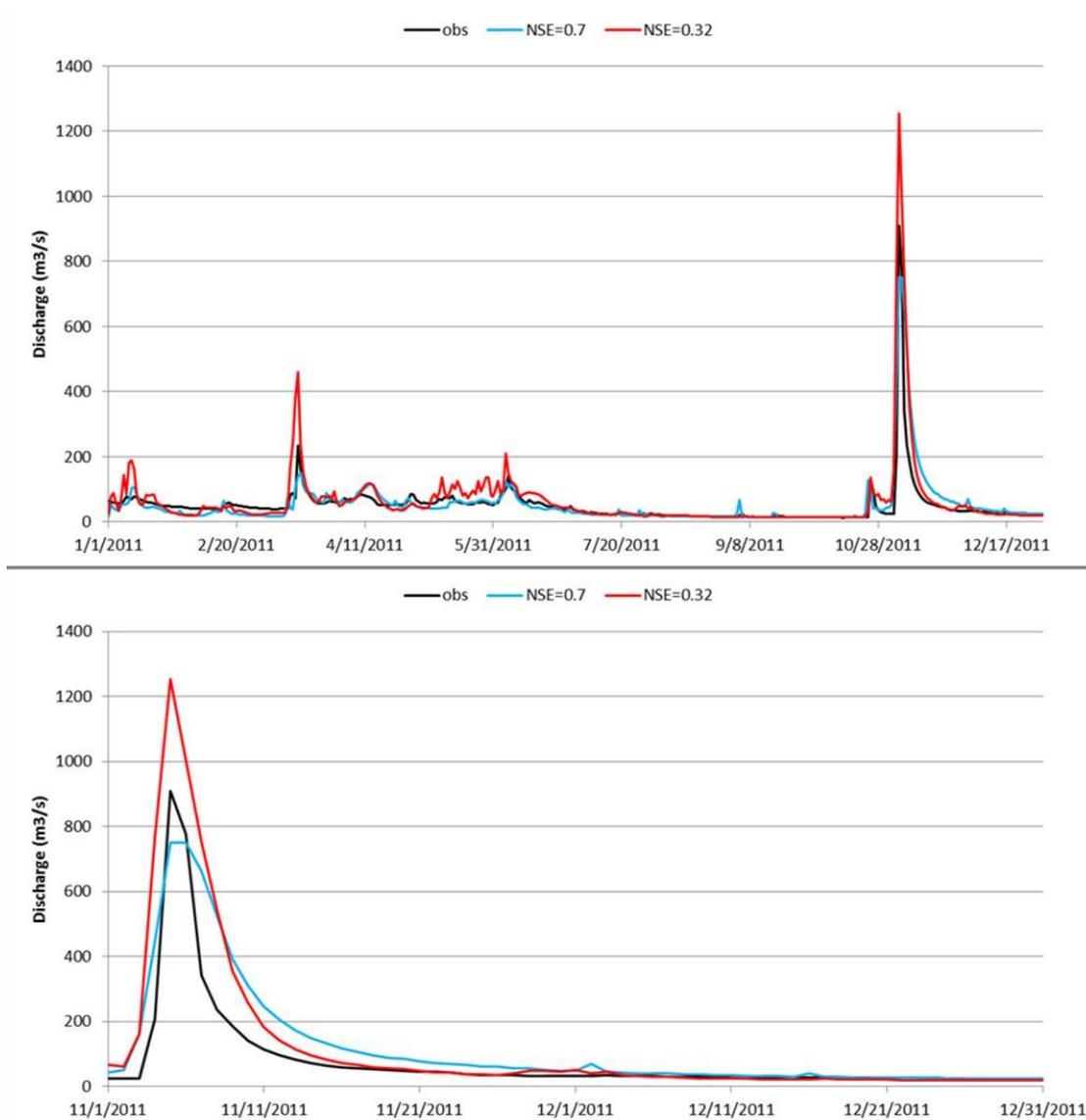


Figure 111: Comparison between the hydrographs with NSE =0.7 and NSE =0.32.

Assessment of KGE in MIKE SHE simulation in Var catchment

As the factors related to the correlation, variability and bias involved in the equation of KGE were considered with equal weights, in general, with same simulation performance, its value will be slightly higher than the NSE. In the calibration process of MIKE SHE in Var catchment, among numerous cases, their KGE values of simulation in 2011 were located in range between -

1.03 to 0.83. Similar as the NSE, the higher value of KGE is expected to indicate better performance of the simulation. Therefore, the hydrographs with highest KGE value of 0.8 and a lower KGE which only half of the previous one (0.43) were plotted with the observation in Figure 112 to check the effects of KGE in our modelling evaluation process. As same as the NSE assessment, even though the higher KGE hydrograph could catch the discharge variation in most time of the year, its representation of the flood disaster could not be accepted for decision maker who in charge of managing the flood risks in Var catchment with obvious underestimation of peak discharge. However, we also noticed that, the hydrograph with highest KGE showed a slightly different situation comparing with the higher NSE, which at least the peak time was caught in the high KGE hydrograph. It was proved that in the consideration of KGE calculation, the impacts of the correlation between simulation and observation play roles in this statistic evaluation.

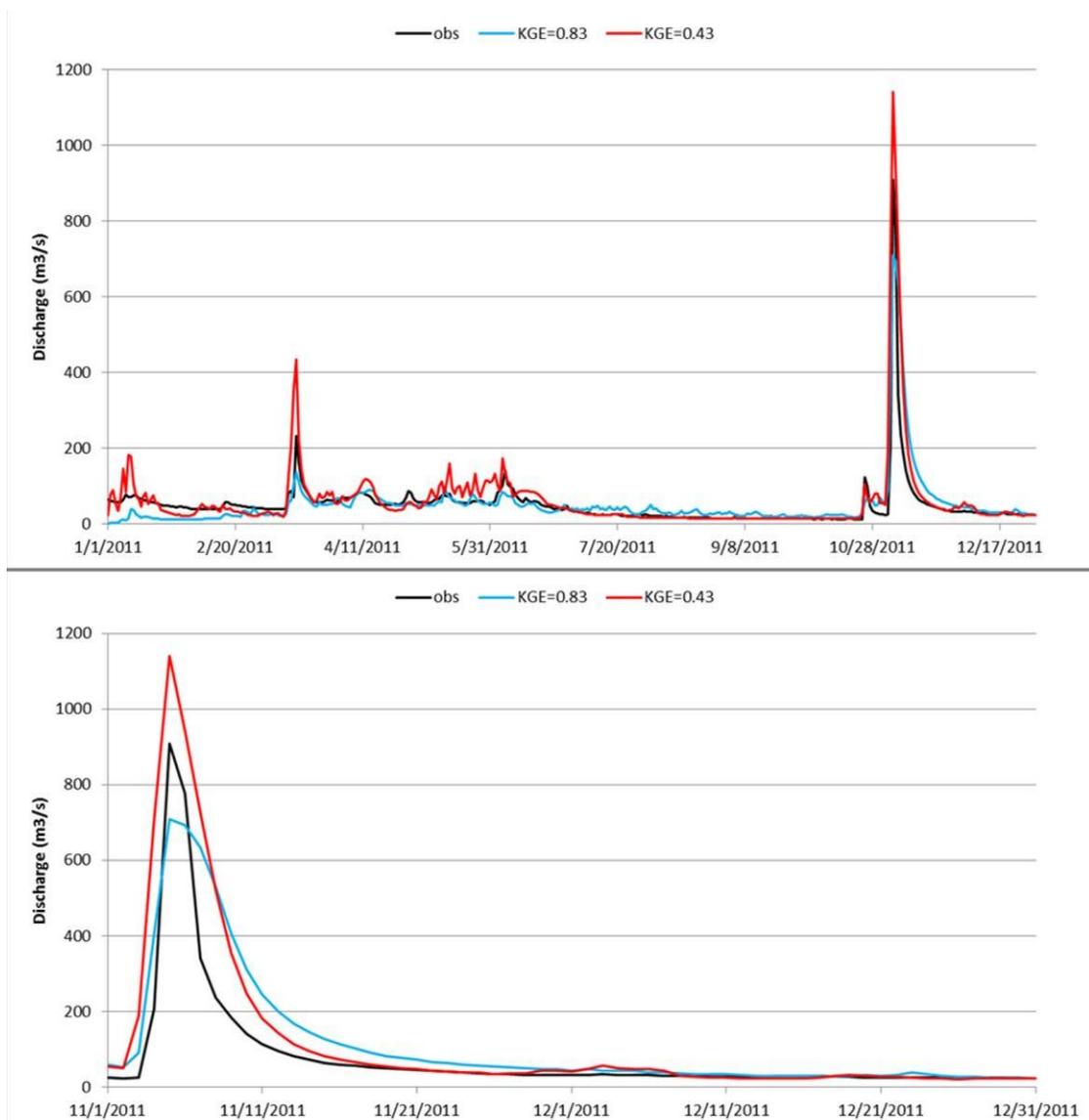


Figure 112: Comparison between the hydrographs with KGE =0.83 and NSE =0.43.

Furthermore, with same KGE values of 0.74, two hydrographs were plotted with the observation in Figure 113. If we only evaluated their simulation performance with the KGE assessment, those two modelling results were expected to have similar hydrograph during the evaluation period. However, it was not the case showed in the figure. Clearly, the simulation of case 2 showed with better performance with more accurate representations among spring and winter flood and snow melting process in year 2011. But of the rest parts of the year especially at beginning of the year and snow melting period, its simulated discharge showed much stronger fluctuation than the case 2 which could not represent well the flood situation in November 2011 (peak discharge underestimated and peak time one day delay). Therefore, the explanation of those two simulations showed with different hydrographs but had same statistic performance could be traced to the statistic factors involved in the KGE calculation. In case 1, even though its plotted hydrograph did not present good performance visually, due to its calculated factors of $\alpha = 1.06$, $\beta = 0.8$ and $r = 0.85$, its statistic performance could be still very high.

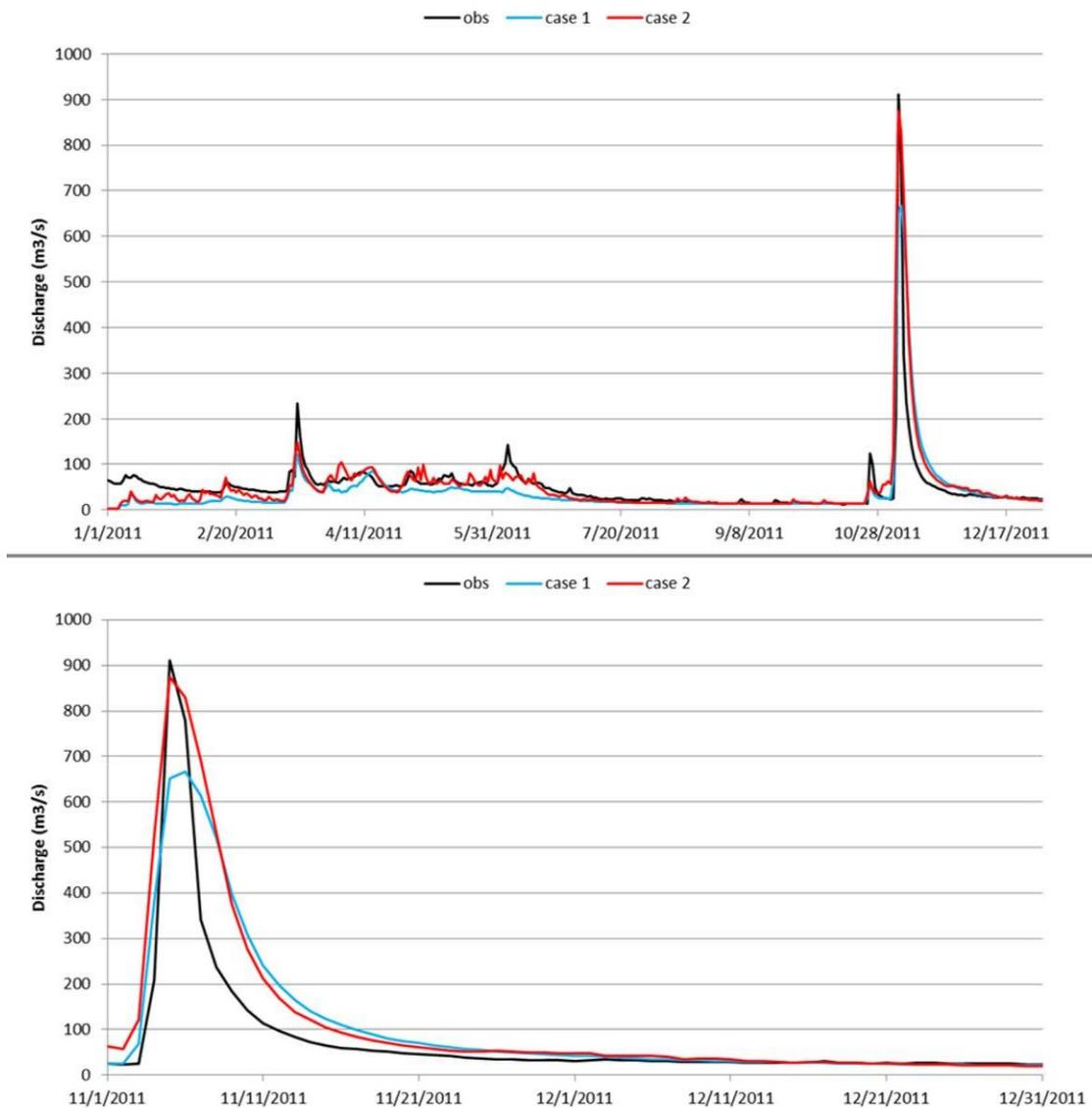


Figure 113: Comparison between the hydrographs with KGE =0.74.

Assessment of physical factors in MIKE SHE simulation in Var

Besides the statistic parameters applied for evaluating the model performance, some physical factors were also necessary to be checked in the calibration process of MIEK SHE in Var catchment such as the simulated total discharge and peak flow value. From the observation time series, the total discharge at Napoléon III Bridge in 2011 is 18238.5m^3 . And its peak flow is occurred at 5th November 2011 with $910\text{m}^3/\text{s}$. Thus the simulated hydrographs of total discharge equaled 18270.16m^3 and 18244.55m^3 were plotted in Figure 114 showed similar performance in most parts of the year. However, more obvious difference between those two simulations was observed in their peak flow representation. The hydrograph of higher total discharge presented with lower peak flow and the other showed opposite situation. Thus it was logical to get that the simulation with higher total discharge may have overestimation in other parts of the year such as the snow melting period showed in the figure.

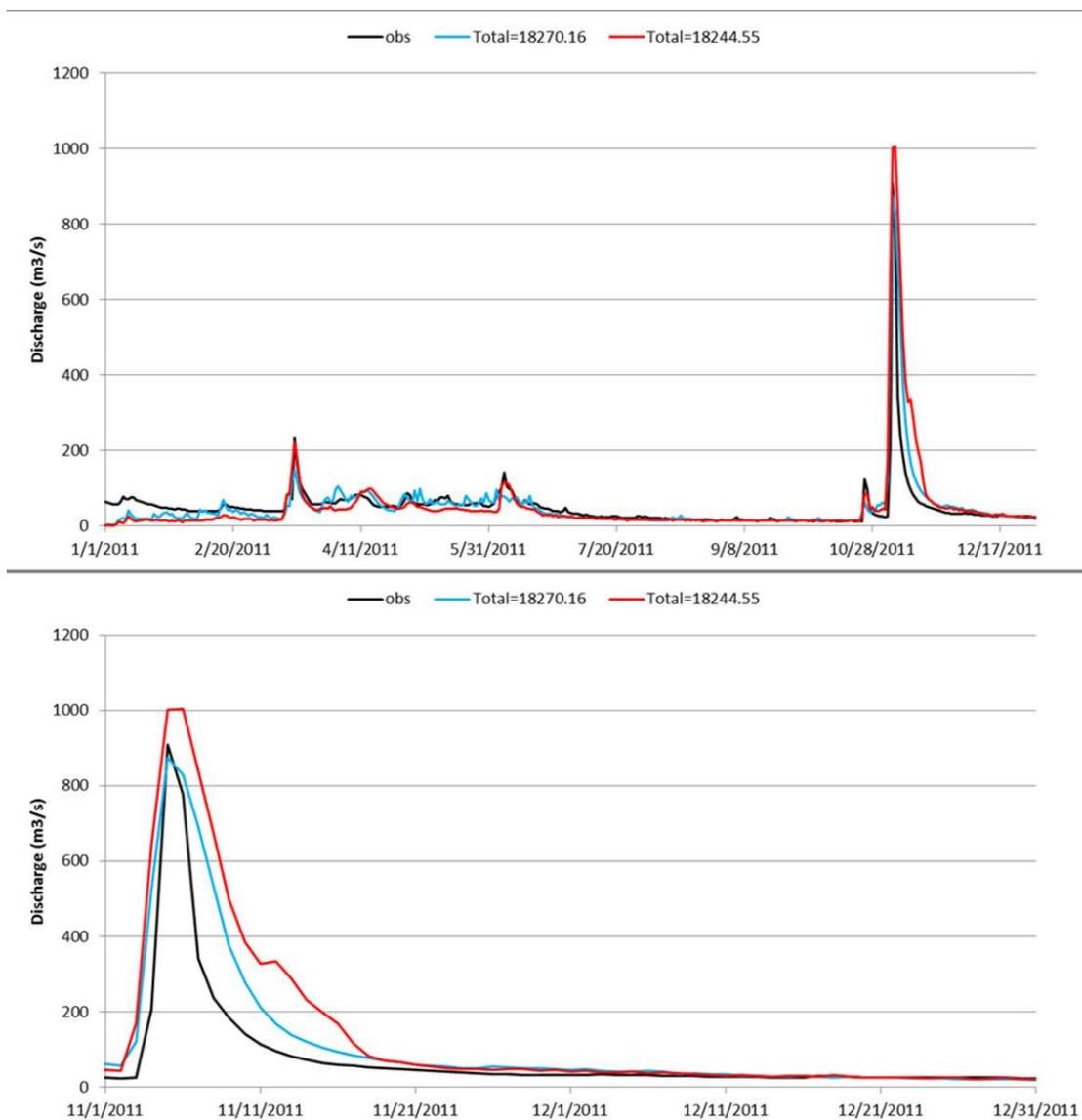


Figure 114: Comparison between the hydrographs with Total discharge = 18270.16m^3 and Total discharge = 18244.55m^3 .

Moreover, for the peak simulation, the hydrograph with peak flow simulated with $897.43\text{m}^3/\text{s}$ and $919.96\text{m}^3/\text{s}$ were plotted in Figure 115. It was clearly indicated that if we only focused on the value of simulated discharge at the peak time, which is defined by the observation, there is high possibilities for us to ignore the correlation between the simulation and observation such as the hydrographs showed in the figure with 1 day delay of the flood peak.

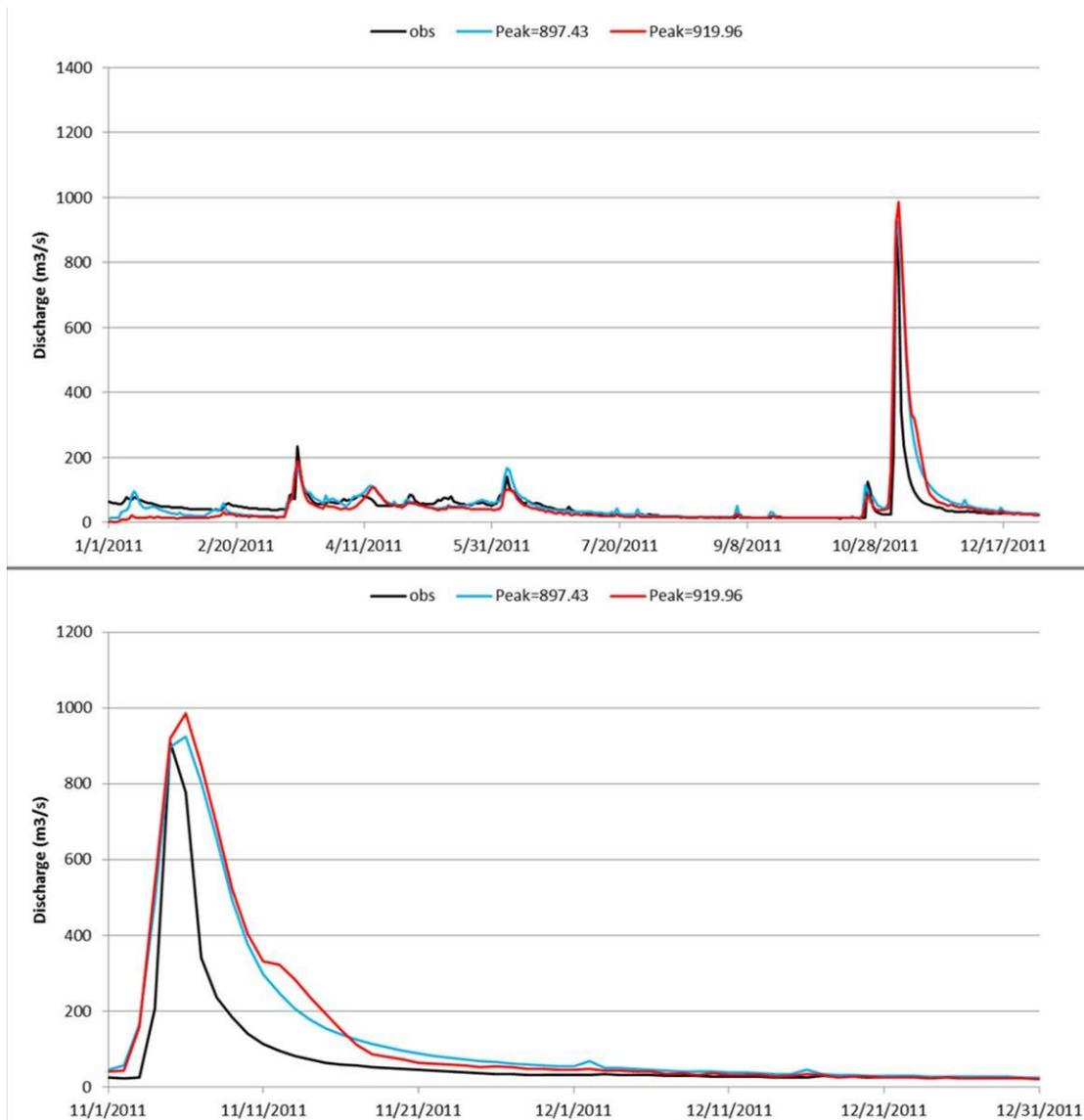


Figure 115: Comparison between the hydrographs with peak flow = $897.43\text{m}^3/\text{s}$ and peak flow = $919.96\text{m}^3/\text{s}$.

Conclusion of defining the calibration strategy in AquaVar project

From the assessment among different factors including statistic coefficients of NSE and KGE and physical factors of total discharge and peak flow values, none of them could work independently to accurately evaluate the simulation performance satisfied our modelling expectations. In some cases, even the statistic coefficients could let us be more confused and make the calibration

process become more complicated. Thus, the calibration process of MIKE SHE in Var catchment required one suitable calibration strategy which expected to be able to integrated consider all the factors mentioned above and clearly present their benefits and limitations linking with our modelling objectives.

As we understood that the statistic coefficients have obvious advantages of representing the simulation performance on “usual” situation. But for the “unusual” scenarios such as flood disaster which have obvious higher values comparing to the average flow during long time series, the higher values of NSE and KGE might lead to the strong underestimation of the simulated discharge which could be less benefit to the decision maker use supposed to use the simulation for considering the worse situation in the disaster. However, if we are more focusing on this “unusual” section, in most part of the simulation period, its results might not be acceptable for the user who wants to have a general view of the hydrogeological characteristics of the catchment. Consequently, we planned to designed one calibration strategy with two step evaluation processes, which at first spending more attention on the statistic performance until its value achieved a certain level, and then in the second step, turning our interests on the evaluation of other physical factors to find the optimization among all the assessment factors.

Here we would like to emphasize our objectives of MIKE SHE simulation in Var, which is supposed to represent the hydrogeological characteristic of Var and forecast the flood and drought events in the catchment. To satisfy the first requirement, the model should have reasonable long time period simulation results. And for the second one it is better to have overestimation of the flood peak and less total discharge during the simulation period which indicates the worse situation during the flood and drought events. Therefore, we would like to define our evaluation rule during the calibration process as follow: due to the performance level of NSE and KGE is defined with their value of 0.5 as the threshold which if the values of NSE and KGE of the simulation lower than 0.5, there is no sense to use simulation results to replace the observations in the hydrological assessment in the catchment. We would like to follow this rule and defined our criteria with values of statistic coefficients above 0.55. Thus, when the values of NSE and KGE of simulation achieved this threshold, more physical factors will start to be considered in the evaluation process. The accepted simulation should be first satisfied with its NSE and KGE higher than 0.55, then result with higher peak flow and lower total discharge will be selected as the reasonable representation made by MIKE SHE model in Var.

5.2.2 Calibration and validation of daily hydrological simulation in Var catchment

Following the calibration strategy we defined above, the deterministic distributed hydrological model MIKE SHE in Var catchment was first calibrated with daily calculation time step from 2008 to 2011. Due to the data limitation at some gauging stations in Var catchment, only the stream discharge observed at outlet of the catchment was selected as the main reference to evaluate the simulation performance. The calibrated model parameters should be firstly satisfied with its statistic performance reach at least “fair” level with its NSE and KGE values both higher than 0.55. Then its peak and total discharge would be checked carefully to let their values more closed to our expectations.

Through that working process, all the parameters were calibrated in the model simulation and their optimized values were listed in Table a and b.

Table 31a: Optimized parameters in daily MIKESHE simulation in Var catchment.

Functions	Parameters		Units	Optimized Value	
Time Step Control	Max precipitation depth per time step	$P_{\text{Max depth}}$	mm	50	
	Max infiltration amount per time step	$P_{\text{Max infiltration}}$	mm	50	
	Input precipitation rate requiring its own time step	$P_{\text{Input rate}}$	mm/hour	5	
Climate	Degree-day coefficient	$C_{\text{Degree day}}$	Flat	mm/°C/day	2
			Northwards		1
			Southwards		2
Rivers and Lakes	Bed resistance	M_{Bed}	Estéron Branches	$m^{1/3}/s$	20
			UpVar Branches		25
			Tinée Branches		27
			Vésubie Branches		27
			Upper part of LowVar Branches		27
			Lower part of LowVar Branches		25
	Leakage coefficient	C_{Leak}	Estéron Branches	/s	7.50E-05
			UpVar Branches		Aquifer only
			Tinée Branches		Aquifer only
			Vésubie Branches		Aquifer only
LowVar Branches	7.50E-05				
Overland Flow	Surface Manning	M_{Forest}	$m^{1/3}/s$	4	
		M_{Grass}		5	
		$M_{\text{Open space}}$		10	
		$M_{\text{Artificial}}$		25	
		$M_{\text{Agriculture}}$		20	

Table 31b: Optimized parameters in daily MIKESHE simulation in Var catchment.

Functions	Parameters		Units	Optimized Value	
Unsaturated Zone	Loam	Water content at saturation	-	0.48	
		Water content at field capacity	-	0.28	
		Water content at wilting point	-	0.14	
		Saturated hydraulic conductivity	m/s	6.00E-05	
	Silt	Water content at saturation	-	0.51	
		Water content at field capacity	-	0.31	
		Water content at wilting point	-	0.11	
		Saturated hydraulic conductivity	m/s	8.00E-06	
	Clay	Water content at saturation	-	0.56	
		Water content at field capacity	-	0.36	
		Water content at wilting point	-	0.22	
		Saturated hydraulic conductivity	m/s	4.00E-06	
	Sand	Water content at saturation	-	0.38	
		Water content at field capacity	-	0.18	
		Water content at wilting point	-	0.08	
		Saturated hydraulic conductivity	m/s	1.00E-03	
ET Surface Depth	ET _{Depth}	m	0.1		
Saturated Zone	Horizontal hydraulic conductivity	K _{sz} Horizontal	m/s	6.50E-03	
	Vertical hydraulic conductivity	K _{sz} Vertical	m/s	6.05E-04	
	Specific Yield	S _y	-	0.20	
	Soil depth	Response Surface slope (°)	0-10	m	-12
			10-20		-5
			20-30		-5
			30-40		-5
			40-50		0
50-60			0		
60-90			0		

For the calibrated model parameters from 2008 to 2011, its evaluation was showed in Table .

Table 32: Evaluation of the calibrated hydrographs at Napoléon III Bridge.

Periods	Statistic coefficients		Physical factors		Observations	
	NSE	KGE	Q _{total} (m ³)	Q _{peak 2011} (m ³ /s)	Q _{total} (m ³)	Q _{peak 2011} (m ³ /s)
2008-2011	0.55	0.70	83989.46	925.87	79851.93	910.00
2008	0.56	0.68	21370.37	-	19418.70	
2009	0.62	0.80	19676.42	-	21711.10	
2010	0.34	0.65	24373.96	-	20483.63	
2011	0.61	0.62	18568.71	-	18238.50	

In the table above, the NSE and KGE values of calibrated results from 2008 to 2011 were all achieved our acceptable statistic criteria of 0.55 (NSE = 0.55, KGE = 0.70). However, if we analysis its statistic performance by individual years, except the simulation of year 2010, all the simulated discharge showed higher statistic performance to the observations. However, when we went back to check the data quality of the observation we found that the data producers already mentioned that the observation data at this station in 2010 was “validés douteux” which indicated some uncertainty existed in this observation. Thus, it was difficult for us to further evaluate the simulation quality and assess the causes of the difference between our simulation and observation for year 2010. Consequently, even the statistics performance of the simulation results in this year was very low (NSE =0.34, KGE =0.65), the simulation of MIKE SHE in Var catchment from 2008 to 2011 was still considered as acceptable. And further analysis might be more focused on the simulation results in year 2008, 2009 and 2011.

Among those three years simulations (2008, 2009 and 2011), year 2009 showed highest statistic performance with NES equaled to 0.62 and KGE equaled to 0.8. We could expect the good simulation in this year mainly due to the topography input applied in the model was at same period which indicated that the inputs condition in 2009 was more closed to the reality and of course, it is logical to have better simulation results produced by this deterministic distributed model whose simulation quality highly depends on the quality of its inputs data. However, if we shifted our focused points from checking the statistic performance to check the physical characteristics represented by the model simulation, we find that the simulated total discharge in 2011 (18568.71m³) was more closed to the observation (18238.50m³). Besides, the simulated peak flow discharge during the extreme flood event in 2011 was almost as same as the observation (925.87m³/s), thus, it further proved that our calibration results of MIKE SHE in Var catchment was acceptable.

The hydrographs of calibrated simulation results and observation were plotted in Figure 116 which clearly presented the accuracy of our simulation. First of all, the variation of the stream discharge at the outlet of the catchment was caught by our simulation with same peak times during the simulation period from 2008 to 2011. Secondly, in most of the cases, the peak values of the winter flood were overestimated by our simulation which responded to our modelling objectives of producing more serious disaster phenomenon for the decision makers to consider more potential risks. Thirdly, during the dryer period, our simulation was slightly underestimated which could be assessed as same as for the flood representation for generating worse conditions

for the potential drought event. Meanwhile, the gap between the simulated and observed stream flow discharge during snow melting period could not be ignored. But it could be explained as the model limitation caused by the hypothesized applied in the model set up for filling the missing blank in representation of the snow and soil conditions in Var.

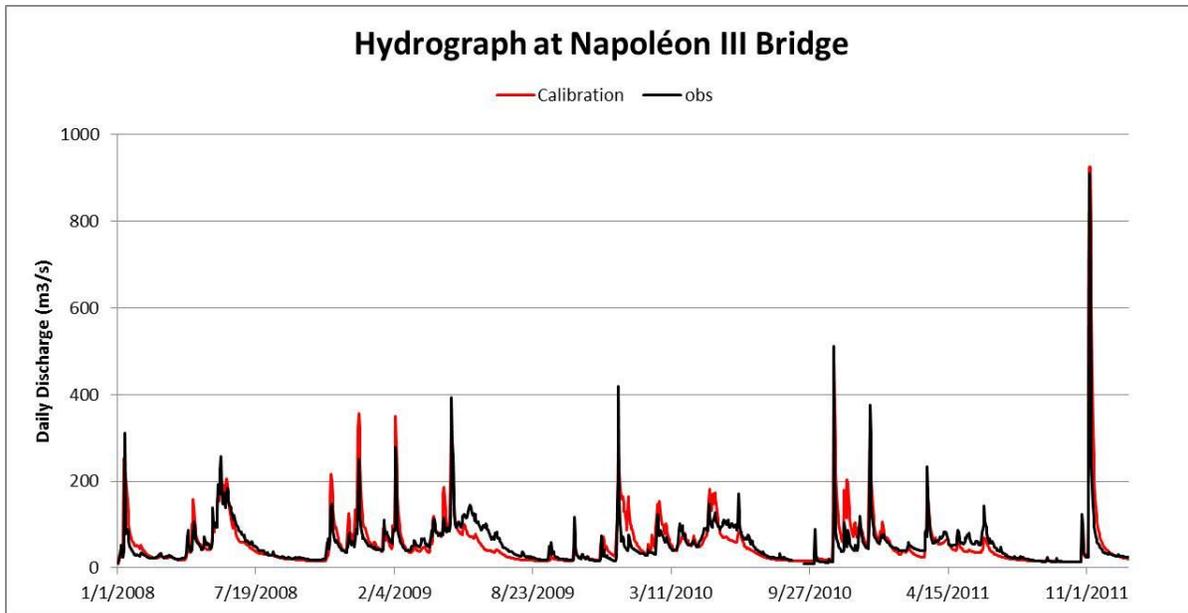


Figure 116: Comparison between daily calibration and observation at Napoléon III Bridge.

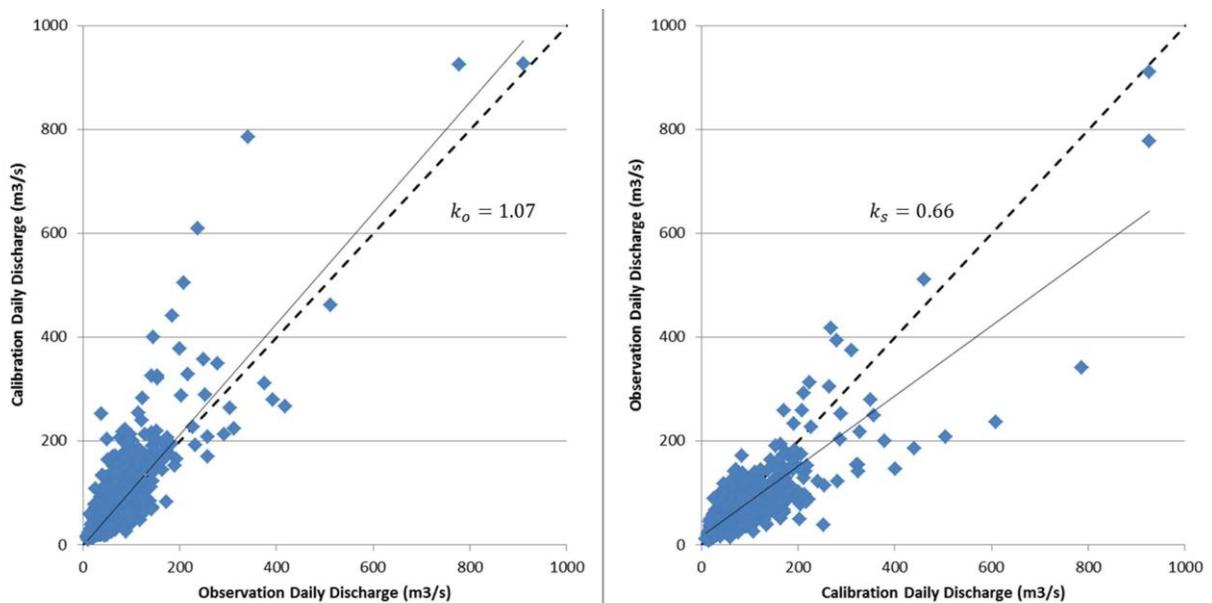


Figure 117: Regression analysis of the calibration results.

Moreover, in Figure 117, by plotting the regression line of simulated and observed values, the calibration results showed better performance of representing the lower stream discharges with k_o value more closed to 1 (compared to the values of $k_s = 0.66$). However, for the higher stream discharge caused by spring and winter floods, the simulation results did not show with better

performance ($k_s = 0.66$) mainly due to the underestimated flow during snow melting process, for the flood which has less impacts from snow process like winter flood, the accuracy of the simulation was quite high.

Subsequently, the calibrated model parameters were applied for the simulation from 2011 to 2014 to validate our MIKE SHE application in Var. The evaluation factors and their values were showed in Table .

Table 33: Evaluation of the validated hydrographs at Napoléon III Bridge.

Periods	Statistic coefficients		Physical factors		Observations	
	NSE	KGE	Q_{total} (m ³)	$Q_{peak\ 2011}$ (m ³ /s)	Q_{total} (m ³)	$Q_{peak\ 2011}$ (m ³ /s)
2011-2014	0.42	0.57	83410.38	834.30	86897.20	910.00
2011	0.62	0.68	14709.50	-	18238.50	
2012	0.61	0.76	15062.36	-	15464.30	
2013	0.63	0.67	23627.06	-	24567.50	
2014	-0.50	0.08	30011.46	-	28626.90	

Compared to the calibration, the statistic performance of validation from 2011 to 2014 was logical to be slightly reduced (NSE = 0.42 AND KGE = 0.57). Among all four years simulations, the model results in 2014 showed with worst statistic performance of NSE = -0.5 and KGE =0.08.

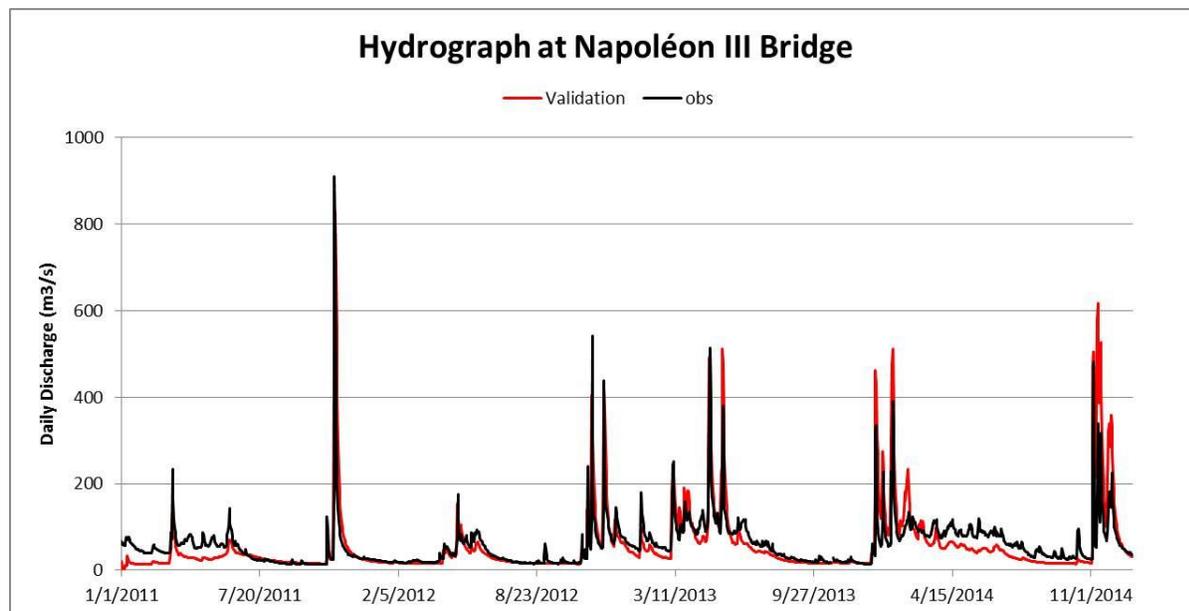


Figure 118: Comparison between daily validation and observation at Napoléon III Bridge

When we plotted the simulated hydrograph with observation (Figure 118), the main problem lead to the lower statistic performance could be traced to the underestimation of stream flow during “snow melting” period and the flow fluctuation in both simulation and observation at the winter flood period in year of 2014. Beside this year, all the other three year showed good statistic performance and their values of physical factors were closed to the reality.

One point we would like to highlight was the underestimated peak flow discharge in November 2011 from the validation. Compared to the calibration, the gap between simulated and observed discharge in the validation was increased from around $16\text{m}^3/\text{s}$ overestimation to nearly $75\text{m}^3/\text{s}$ underestimation. This could be explained by the warming up process of the model simulation. As the initial condition was not available to be collected by the field survey, the simulation started with the “empty” condition of no water accumulated on the ground surface and stored in the soil. Consequently, it needs time and input water for the model to fill the blanks caused by those missing initial condition. In our case to fill all the blanks inside the model, the simulation needs one year to achieve the good initial condition for the further calculation.

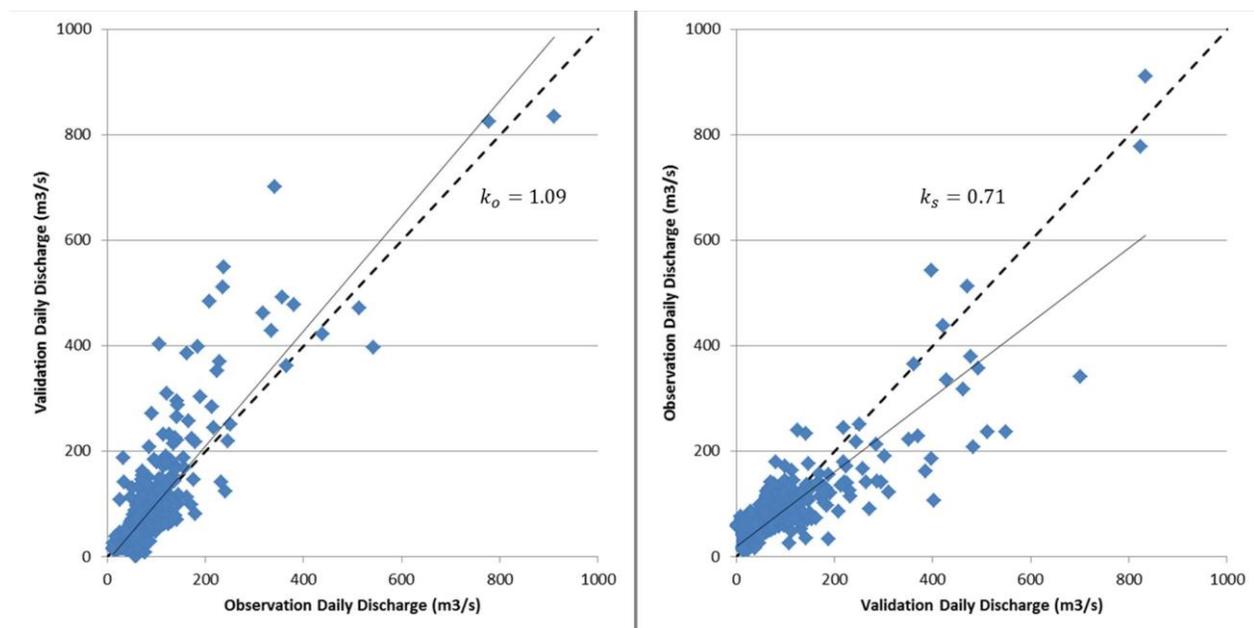


Figure 119: Regression analysis of the calibration results.

In addition, in Figure 119, the regression assessment among the simulation stream flow from 2011 to 2013 was clearly showed that the validation results were able to describe the general hydrogeological characteristics of the catchment and produce reasonable forecast for the coming flood disasters.

5.2.3 Calibration and validation of hourly hydrological simulation in Var catchment

Due to the longer computation time for hourly simulation, its MIKE SHE simulation was calibrated based on the parameters results calibrated in daily simulation. The optimized values of the parameters applied in the hourly simulation were slightly different to the daily simulation (Table 30a and b).

Table 30a: Optimized parameters in hourly MIKESHE simulation in Var catchment.

Functions	Parameters		Units	Optimized Value	
Time Step Control	Max precipitation depth per time step	$P_{\text{Max depth}}$	mm	50	
	Max infiltration amount per time step	$P_{\text{Max infiltration}}$	mm	50	
	Input precipitation rate requiring its own time step	$P_{\text{Input rate}}$	mm/hour	5	
Climate	Degree-day coefficient	$C_{\text{Degree day}}$	Flat	4	
			Northwards	mm/°C/day	2
			Southwards	4	
Rivers and Lakes	Bed resistance	M_{Bed}	Estéron Branches	$m^{1/3}/s$	20
			UpVar Branches		25
			Tinée Branches		25
			Vésubie Branches		27
			LowVar Branches		25
	Leakage coefficient	C_{Leak}	/s	7.50E-05	
Overland Flow	Surface Manning	M_{Forest}		$m^{1/3}/s$	8
		M_{Grass}			10
		$M_{\text{Open space}}$			15
		$M_{\text{Artificial}}$			25
		$M_{\text{Agriculture}}$			20

Table 34b: Optimized parameters in hourly MIKESHE simulation in Var catchment.

Functions	Parameters		Units	Optimized Value
Unsaturated Zone	Loam	Water content at saturation	-	0.48
		Water content at field capacity	-	0.28
		Water content at wilting point	-	0.14
		Saturated hydraulic conductivity	m/s	6.00E-06
	Silt	Water content at saturation	-	0.51
		Water content at field capacity	-	0.31
		Water content at wilting point	-	0.11
		Saturated hydraulic conductivity	m/s	2.00E-05
	Clay	Water content at saturation	-	0.56
		Water content at field capacity	-	0.36
		Water content at wilting point	-	0.22
		Saturated hydraulic conductivity	m/s	5.00E-06
	Sand	Water content at saturation	-	0.38
		Water content at field capacity	-	0.18
		Water content at wilting point	-	0.08
		Saturated hydraulic conductivity	m/s	1.00E-03
ET Surface Depth	ET _{Depth}	m	0.1	
Saturated Zone	Horizontal hydraulic conductivity	K _{sz} Horizontal	m/s	5.50E-03
	Vertical hydraulic conductivity	K _{sz} Vertical	m/s	5.50E-04
	Specific Yield	S _y	-	0.2
	Soil depth	Response Surface slope (°)	0-10	m
10-40			-4	
40-90			0	

Due to the uncertainty in both input data and observations, we could not expect the simulation showed with higher statistic performance. Instead of comparing the lower values of statistic coefficients, we directly went to check the hydrographs produced by the simulation with long time series and short time period for special event representation.

The hydrographs of calibration and validation were showed in Figure 120 and Figure 121, which indicated that the MIKE SHE model was kind of over sensitive to the sudden rainfall event in Var. However, it could be considered as one mode limitation, which is due to the missing data of the soil depth, there was high uncertainty caused by our assumption in the soil description in the model which may not have enough storage for the water infiltrated from surface to underground. Moreover, the uncertainty of the input data from distribution could also not be ignored which in the hourly time step, the impacts of the small regional rainfall could be enlarged by the interpolation method applied in this project.

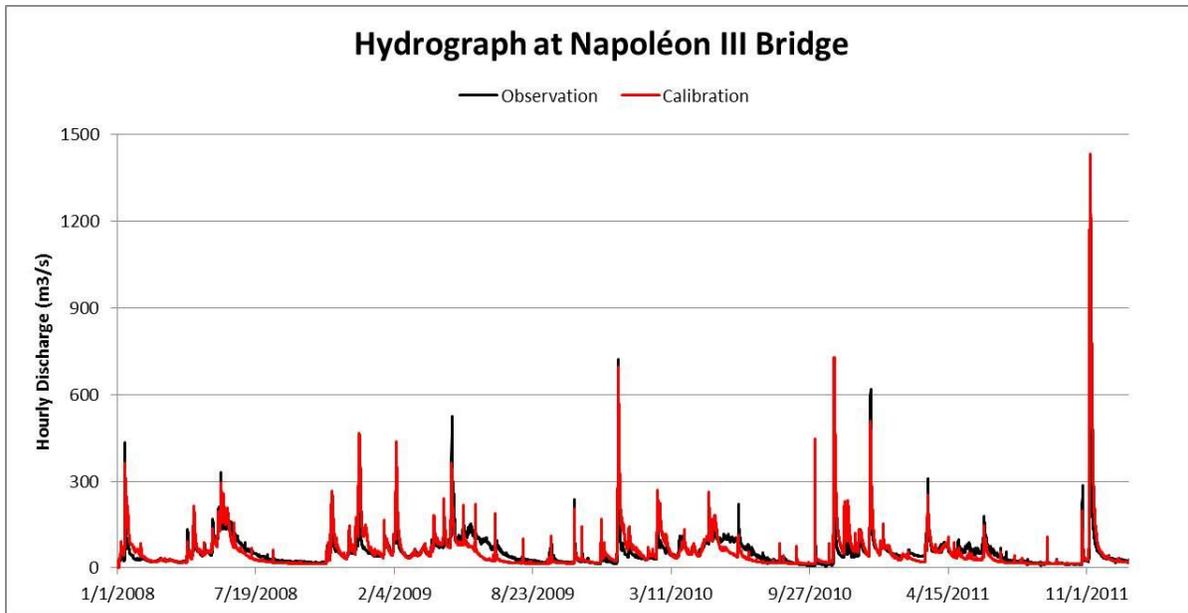


Figure 120: Comparison between hourly calibration and observation at Napoléon III Bridge

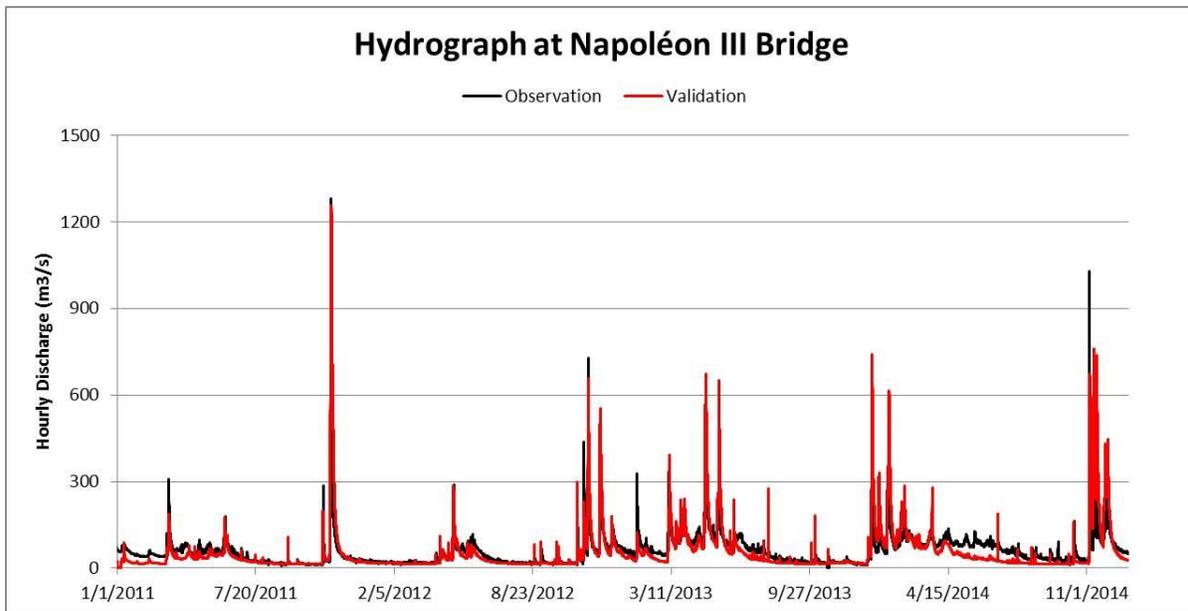


Figure 121: Comparison between hourly validation and observation at Napoléon III Bridge

In the design of the AquaVar EDSS, the hourly simulation of MIKE SHE will mainly applied for forecasting the coming disasters in Var. Therefore, the hourly simulated hydrographs for the 2011 November flood, 2012 summer drought and 2013 spring flood were plotted in Figure 122 to further evaluate our hourly simulation results:

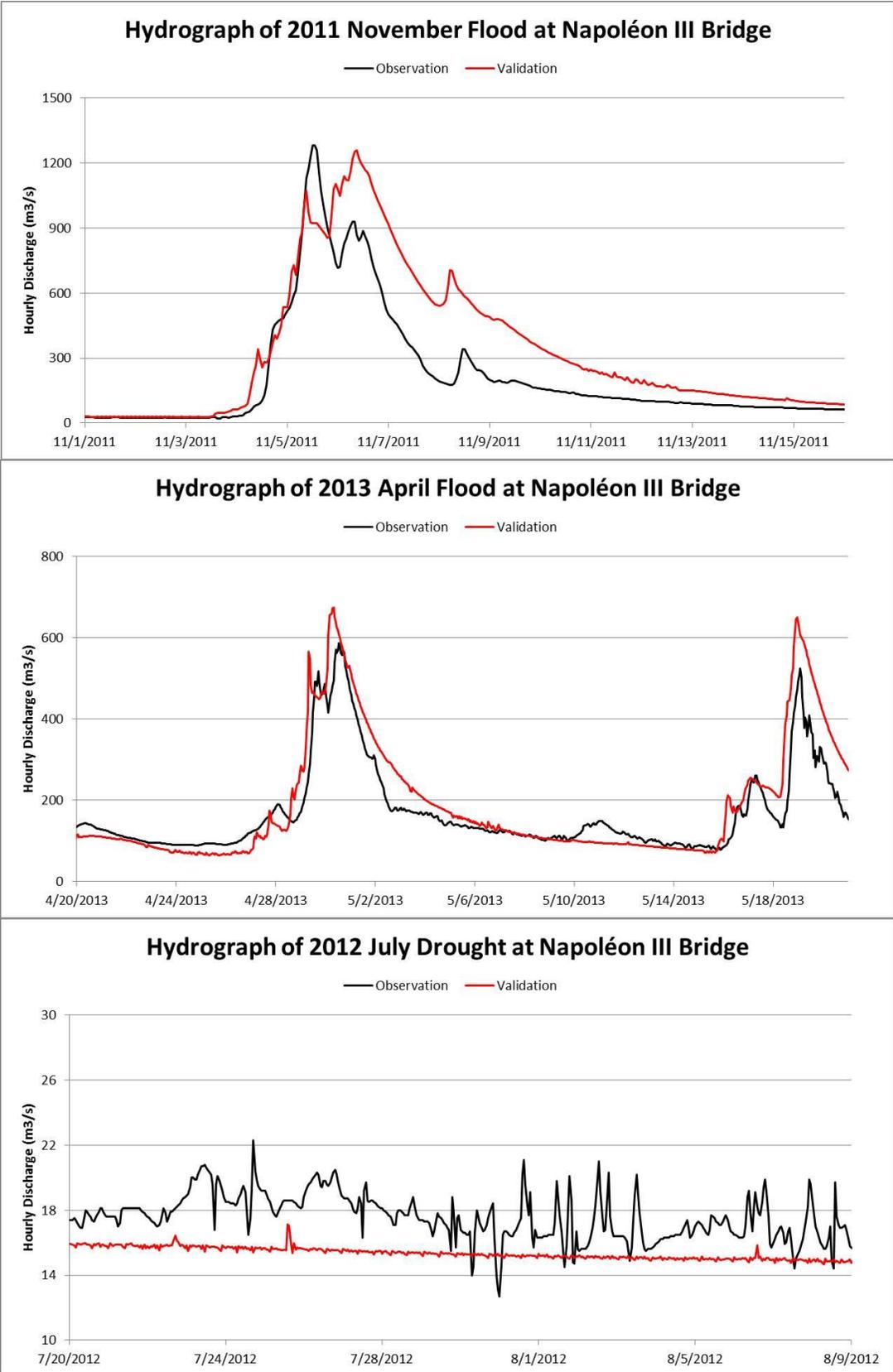


Figure 122: Hydrographs of flood November 2011, April 2013 and drought July 2012 at Napoléon III Bridge.

- For the flood simulated in Var catchment, for the flash flood occurred at November 2011, the shape of the observation hydrograph was almost caught by the simulation with obvious overestimation after the peak flow appeared in Var. The peak flow simulated in the MIKE SHE simulation was similar as the observation but with less than 1 day delay of the peak time. For the spring flood recorded in April 2013, both the shape and the peak time were well represented by the simulation with slightly higher discharge.
- For the drought event at July 2012, firstly, the hydrography plotted by the hourly observation showed strong flow fluctuation in range from $12.7\text{m}^3/\text{s}$ to $22\text{m}^3/\text{s}$. With no obvious rainfall landed in Var catchment, this flow variation seems not reasonable especially at some time step the difference of observation during one hour reached $6\text{m}^3/\text{s}$. However, the discharge produced by MIKE SHE showed a decreasing trend with less variation, if we considered it as the worse situation of drought disaster, the simulation results could be benefits for the decision maker to implement some relevant measures.

5.3. Uncertainty Analysis and Discussion of Simulation Limitations

After the calibration and validation process, the MIKE SHE simulation in Var catchment was able to generally represent the hydrogeological characteristics of Var catchment and be applied in the AquaVar EDSS to generate reasonable boundary information for downstream models and forecast the potential natural disasters such as flood and drought events in the region. However, due to the missing information about several physical factors required by the model set up, many hypotheses were conceived and applied in the simulation in Var catchment, which has high possibility to cause the uncertainties in the model simulation. Moreover, the uncertainty existing in the observation should also be taken into account of the simulation. For instance, the daily simulation showed “bad” performance in the year of 2014, when we plotted the simulated hydrographs with the observation at stations of La Clave” where located at the outlet of the Estéron sub-catchment, something weird was detected in the data time series (Figure 123).

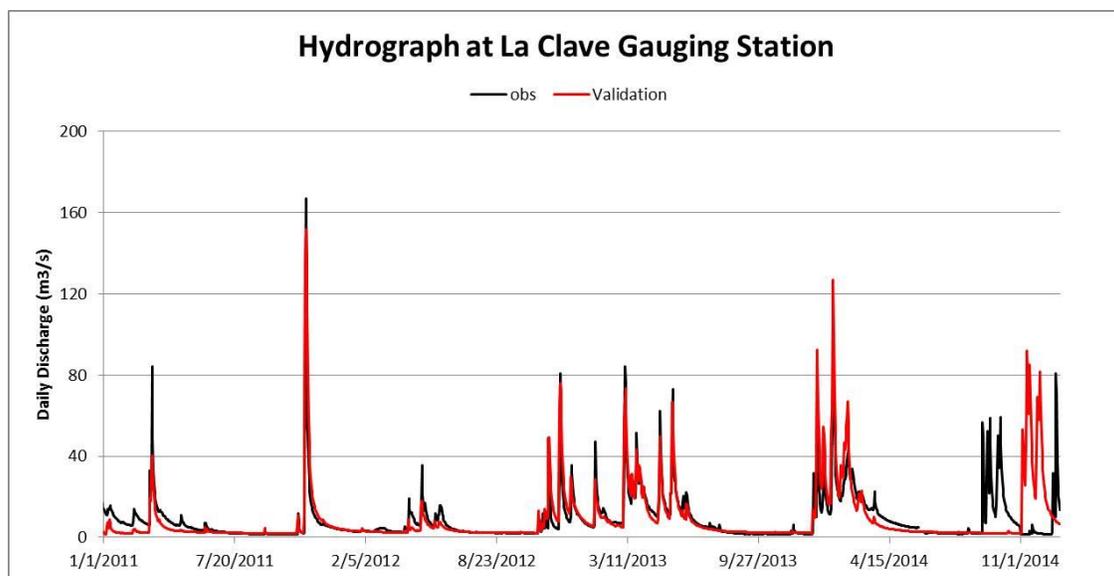


Figure 123: Hydrograph of daily validation and observation at stations of La Clave.

Compared the simulation and observation, in most part of the hydrograph, the simulated results showed higher performance to the observation; however, there was clearly a weird flood events recorded at September could not be caught by the simulation with around 50 m³/s discharge during one month. Then, when we compared the daily and hourly hydrographs taken from this station with our daily simulation (Figure 124), clearly our simulation results almost caught the shape of the hourly hydrograph and it indicated that there were some errors in the data of the observation, and imaged that if we calibration the model with those weird data, we could never achieve our modelling objectives.

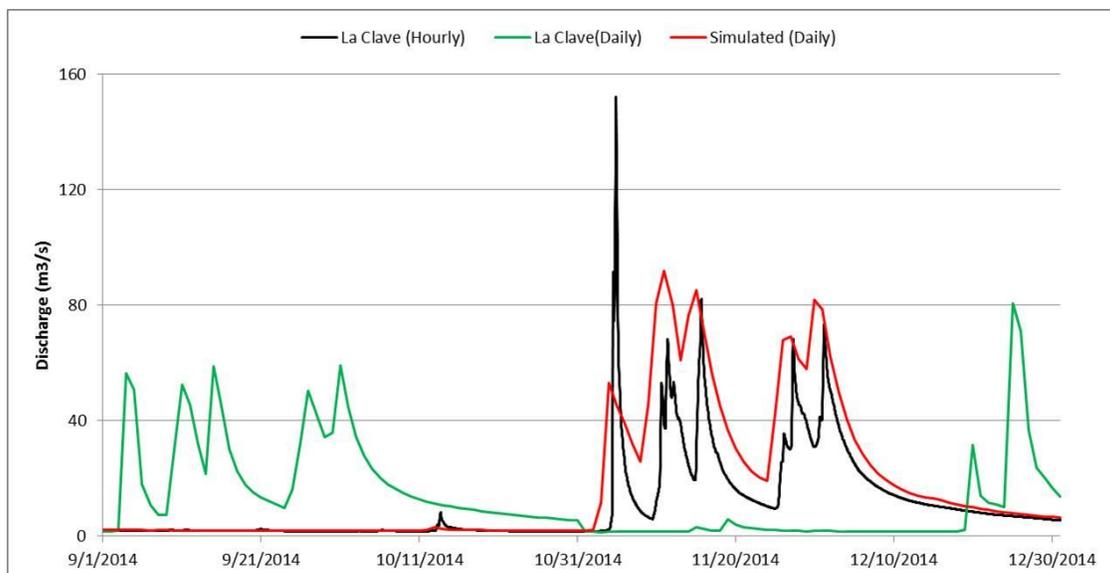


Figure 124: Comparison among daily and hourly observation with daily simulation at stations of La Clave.

Besides those “uncertainty” in the observation, in the model itself, the “uncertainty” or so called model limitations caused by the assumptions applied for filling the missing data gaps in the simulation were also considerable in the modelling process of MIKE SHE in Var. It was mainly appeared in two aspects consisted with the descriptions of snow and soil conditions in the Var.

Based on the hydrological assessment and few field measurements, the snow melting and freezing process in the Var catchment is not only affected by the variation of air temperature, but also influenced by the sun intensity and duration. In our case, we assumed the value of the “Degree-day coefficient” in a spatial distributed format lead to the improvement of snow melting and freezing process at the flat and southwards places. But during the whole simulation period, the value in different places was temporal constant, which indicates the temporal variation of snow melting and freezing process was not well represented in the model simulation. Besides, another impact factor of this process was the air temperature which in our case collected in daily time interval could not represent the mountainous temperature variation during one day. Therefore, in the simulation of MIKE SHE in Var catchment, the amount of the snow stored in the winter time was strongly underestimated due to the higher daily air temperature input in the model, which could be considered as the main cause of the underestimated stream flow at the snow melting period. In Figure 125, it was clearly represented the impacts caused by this limitation on the stream flow simulation.

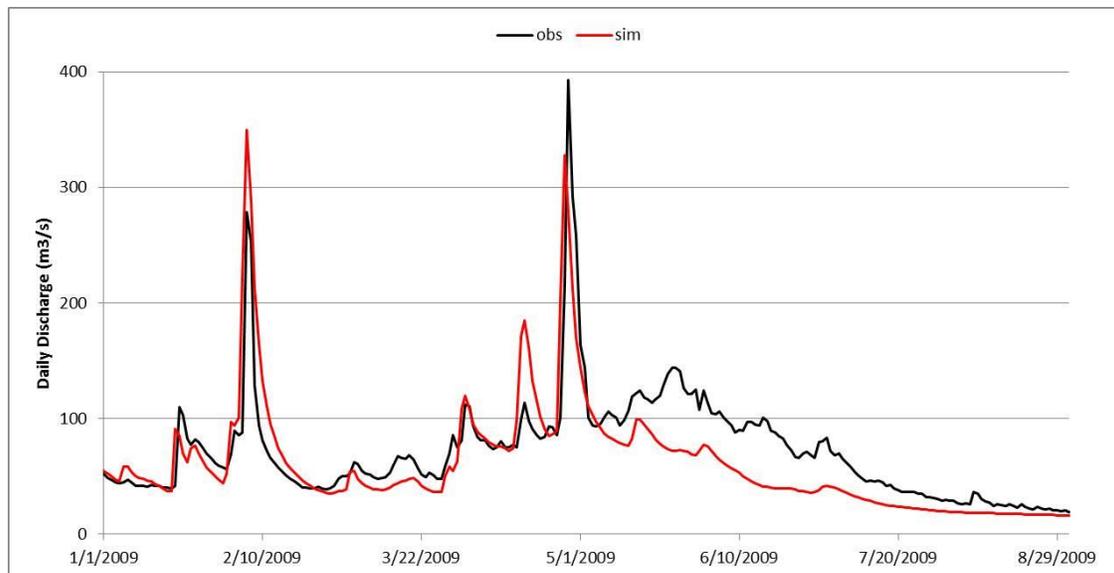


Figure 125: Underestimation of snow storage in winter time caused the underestimation of stream flow during snow melting period.

Moreover, due to the limitation of geological information over Var catchment, the MIKE SHE simulation in Var catchment could not be set up as the typical groundwater model which contained several geological layers to describe the underground conditions in the catchment. There is only one layer added in the saturated zone simulation in MIKE SHE and its lower boundary (depth) was defined by its assumed relationship with surface slope. It could cause the strong underestimation of the soil storage capacity as there was only the top soil taken into account in the simulation. Therefore, during the flood representation, after the flood peak appeared in the catchment, the channel discharge simulated by MIKE SHE was often higher than the observation. This is mainly because of in the simulation with shallow soil depth, the soil was still saturated even after the flood and compared to the reality, and less amount of water could be stored in the soil, infiltrated into the deeper layer, and released after the flood. In Figure 126, it presented that the overestimation of the stream flow during flood event and then after, the underestimation of the channel discharges was mainly caused by less water released from the soil to the streams.

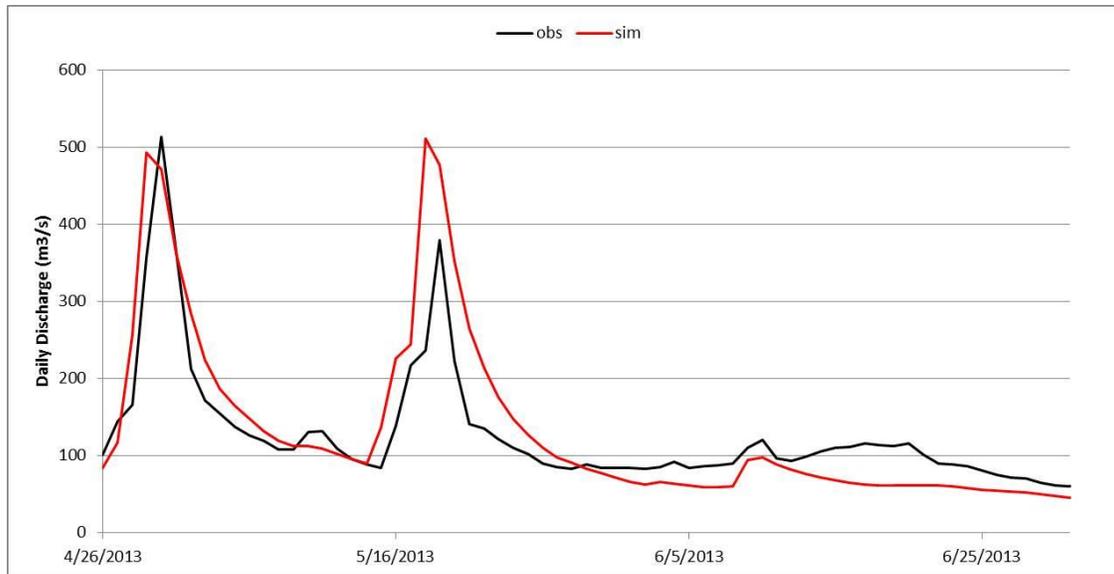


Figure 126: Underestimation of soil water storage during floods caused the overestimation of stream flow after the peak time and underestimation after the flood.

Beside the modelling limitation caused by those hypotheses applied in the model set up, the uncertainty of the simulation also came from distributed rainfall input in the simulation. As we understand that the hourly rainfall could be characterized with high regional and randomness characteristics. Therefore, by applying the IDW interpolation method which estimated the rainfall based on the distance between interpolated points and gauging reference, the rainfall impacts area was often enlarged and the amount of the rainfall at this time step was overestimated. Then combined with the shallow soil depth assumed in the model, in the hourly simulation, some “sudden” flow raises were appeared when there is nothing recorded in the observation (Figure 127).

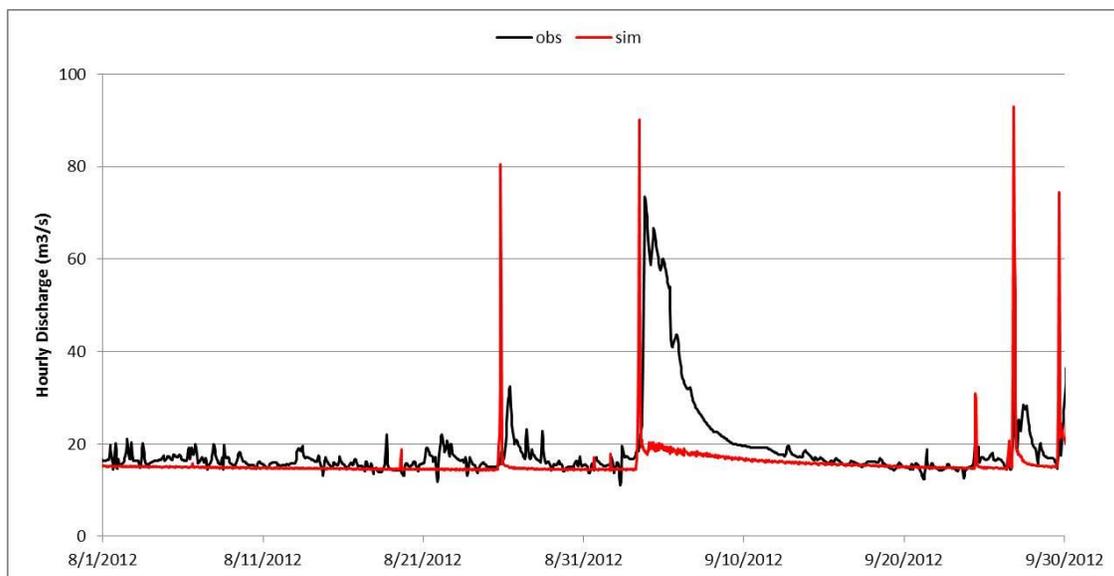


Figure 127: The “sudden” flood raise in the hourly MIKE SHE simulation in Var.

GENERAL CONCLUSION AND PERSPECTIVES

The main objective of AquaVar project is to develop a real time decision support system consisting with several deterministic distributed models to integrated assess the hydrogeological characteristics of Var, the river-aquifer exchanges in the lower Var valley and forecast the natural disasters in the catchment for supporting decision making process in regional water resource management.

In this study, it was started from the discussion about the design of the EDSS architecture. By reviewing the progress of EDSS, a multi-layered structure was defined in this study, which was expected to have obvious advantages in managing the information transmission started from data collection in the field through modelling assessment and ended at visualization for different user groups. The efficient data transmission process and optimized EDSS structure defined in this study have the ability to achieve the main objective of AquaVar, which is to support the real time decision making process for the local managers. Then, among three modelling parts, in this study, the deterministic distributed hydrological model MIKE SHE was built in the Var catchment under serious missing data conditions.

Three deterministic distributed models were designed as the core of the AquaVar EDSS, which supposed to represent the hydrological phenomenon, surface flow movement, groundwater movement and water exchanges between river-aquifer respectively. This Ph.d study as one part of the AquaVar project was mainly focusing on the simulation of deterministic distributed hydrological model (MIKE SHE) in Var catchment. Compared to other type of hydrological models like conceptual model, the deterministic distributed hydrological model has advantage of detail and accurately representing the multi-hydrological processes in the catchment. At same time, it high data requirement in the modelling set up process often limits it application in the ungauged or poor gauged catchment with less field data available. Thus, followed the modelling strategy we defined in this study, many hypothesize were conceived during the modelling set up process to fill the gap between model requirements and field data collection:

- The soil depth distributed in Var is strongly affected by the surface slope.
- There is less groundwater water entered the catchment from outside.
- The snow melting process is highly impacted by the air temperature and sunshine duration in Var catchment.

The reasonable modelling results proved that for representing the complex catchment hydrological system like Var catchment, the minimum modelling requirement could be more concentrated on the data collection among topography, precipitation and air temperature which linked with the most effective hydrological processes in the catchment: rainfall-runoff process. For other factors such as snow storage, evapotranspiration and soil conditions, higher data quality could continuously improve the accuracy of simulation. But in case of Var catchment, when few field survey were available in the basin, with their estimated relationship linked with surface slope, all other information could be described in the model to produce reasonable results generally representing the hydrogeological characteristics of the catchment and forecast the

coming natural disasters. Moreover, in the modelling part of this study, an integrated evaluation strategy was conceived to calibrate the model for satisfying our modelling objectives. Compared with some studies only evaluated by statistic performance, introducing more physical factors and event assessments in the calibration process has benefits to helping the modeler improving their modelling accuracy. In the hydrological modelling assessment in Var catchment with around 2800 km² control area and serious missing data problem, one threshold values of the statistic coefficient was redefined in the model evaluation process (e.g. NSE above 0.5). Then when this criterion was satisfied, the focusing point in the model evaluation process was shifted to assess the physical phenomenon described in the model simulation (e.g. total discharge and peak flow). However, in the section of uncertainty and limitations discussion, some improvements could also be expected in the further work in this catchment with more detail field data survey implemented in the catchment to well describe the soil and snow conditions.

For the AquaVar project, the perspectives of the MIKE SHE application are promising to play significant role in the modelling system among three deterministic models (MIKE SHE, MIKE 21FM and FeFlow) in AuqaVar EDSS (Figure 128). The AquaVar EDSS is expected to have the meteorological forecast information from other institutes such as Météo-France. And then through data transformation processes in the system, the forecast data will be converted to the standard input data format of MIKE SHE to run in real time. The MIKE SHE model will produce the boundary conditions for the other two models MIKE 21FM and FeFlow model, which more focused on the lower Var valley parts of the catchment. All the modelling assessment results will be organized and pass to the “Operations Center” to support the decision making process.

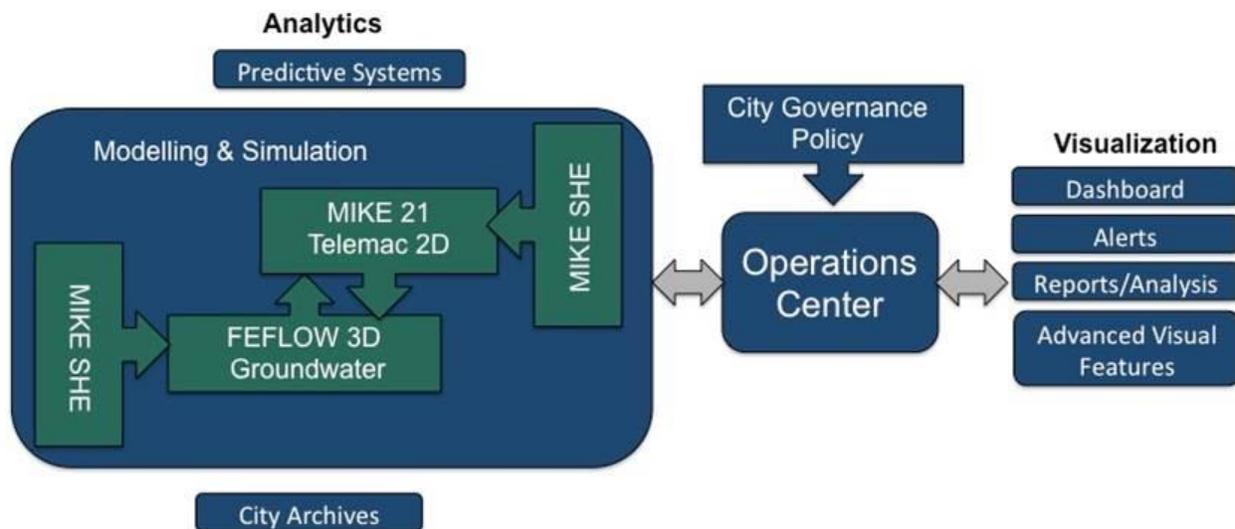


Figure 128: Modelling system of AquaVar EDSS.

REFERENCES

- [1] Abbott, M.B., Bathurst, J.C., Cunge, J.A., O'connell, P.E. and Rasmussen, J., 1986. An introduction to European Hydrological System-Ststeme Hydrologique Europeen, "SHE", 2: Structure of physically-based, distributed modelling system, *Journal of Hydrology*, 87(1), 61-77.
- [2] Abimbola, O.P., Wenninger, J., Venneker, R. and Mittelstet, A.R., 2017. The assessment of water resources in ungauged catchment in Rwanda, *Journal of Hydrology: Regional Studies* 13 (2017) 274-289.
- [3] Allamano, P., Claps, P., Laio, F., and Thea, C., 2009. A data-based assessment of the dependence of short-duration precipitation on elevation, *Physics and Chemistry of the Earth, Parts A/B/C*, 34(10), 635-641.
- [4] Al-Ahmadi, K., and Al-Ahmadi, S., 2013. Rainfall-altitude relationship in Saudi Arabia, *Advances in Meteorology*, 2013.
- [5] Al-Sabhan, W., Mulligan, M. and Blackburn, G. A., 2003. A real-time hydrological model for flood prediction using GIS and the WWW, *Computers, Environment and Urban Systems* 27 (2003) 9-32.
- [6] Arnaud, P., Bouvier, C., Cisneros, L., and Dominguez, R., 2002. Influence of rainfall spatial variability on flood prediction, *Journal of Hydrology*, 260 (1), 216 -230.
- [7] Andersen, J., Refsgaard, J.C. and Jensen, K.H., 2001. Distributed hydrological modelling of Senegal River Basin – model construction and validation. *Journal of Hydrology*, 247(3), 200-214.
- [8] Anthony, R.N., 1965. *Planning and Control Systems: A Framework for Analysis*, Harvard University Graduate School of Business Administration, Cambridge, MA, 1965.
- [9] Arnold, J. G. and Fohrer, N., 2005. SWAT2000: current capabilities and research opportunities in applied watershed modelling, *Hydrol. Process.*, 19, 563–572, 2005.
- [10] Arnott, D. and Pervan, G., 2008. Eight key issues for the decision support systems discipline, *Decision Support Systems* 44 (2008) 657-672.
- [11] Bárdossy, A., 2007. Calibration of hydrological model parameters for ungauged catchments, *Hydrol. Earth Syst. Sci.* 11 (2), 703–710.
- [12] Basist, A., Bell, G.D., and Meenterneyer, V., 1994. Statistical relationships between topography and precipitation patterns, *Journal of Climate*, 7(9), 1305-1315.

- [13] Berlekamp, J., Lautenbach, S., Graf, N., Reimer, S., and Matthies, M., 2007. Integration of MONERIS and GREAT-ER in the decision support system for the German Elbe river basin, *Environ. Modell Softw.*, 22, 239–247, 2007.
- [14] Beven, K. J., 1996. A discussion of distributed hydrological modelling. Springer.
- [15] Beven, K.J., 1997. TOPMODEL: a critique. *Hydrological Processes* 11, 1069–1085.
- [16] Beven, K.J., 2012. *Rainfall-Runoff Modelling – The Primer*. Wiley and Sons, Chichester.
- [17] Beven, K., and Freer, J., 2001. Equifinality, data assimilation, and uncertainty estimation in mechanistic modeling of complex environmental systems using the GLUE methodology, *J. Hydrol.* 249, 11–29.
- [18] Beven, K. J., and Hornberger, G. M., 1982. ASSESSING THE EFFECT OF SPATIAL PATTERN OF PRECIPITATION IN MODELING STREAM FLOW HYDROGRAPHS1. Wiley Online Library.
- [19] Bhargava, H.K., Krishnan, R. and Müller, R., 1997. Decision support on demand: emerging electronic markets for decision technologies, *Decision Support Systems* 19 (1997) 193-214.
- [20] Blöschl, G., Sivapalan, M., 1995. Scale issue in hydrological modelling – a review. *Hydrological Processes* 9, 251-290.
- [21] Blöschl, G., Sivapalan, M., Wagener, T., Viglione, A. and Savenije, H., 2013. *Runoff Prediction in Ungauged Basins: Synthesis Across Processes, Places and Scales*. Cambridge University Press, UK, pp. 252.
- [22] Booker, D.J., Snelder, T.H., 2012. Comparing methods for estimating flow duration curves at ungauged sites, *Journal of Hydrology* 434-435, 78-94.
- [23] Booker, D.J. Woods, R.A., 2014. Comparing and combining physically-based and empirically-based approaches for estimating the hydrology of ungauged catchments, *Journal of Hydrology* 508 (2014) 227-239.
- [24] Bosson, E., Sabel, U., Gustafsson, L., Sassner, M. and Destouni, G., 2012. Influences of shifts in climate, landscape and permafrost on terrestrial hydrology, *Journal of Geophysical Research: Atmospheres* (1984-2012), 117 (D5).
- [25] Bostan, P. A., and Akyürek, Z., 2009. Spatio-Temporal Analysis of Precipitation and Temperature Distribution over Turkey, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 38(Part II).
- [26] Brooks, K. N., Folliott, P. F., and Magner, J. A., 2013. *Hydrology and the Management of Watersheds* (4th ed.). John Wiley & Sons, Inc.

- [27] Brown, L., 2001. How water scarcity will shape the new century, *Water Science and Technology* 43 (4), 17-22.
- [28] Brunson, C., McClatchey, J., and Unwin, D. J., 2001. Spatial variations in the average rainfall-altitude relationship in Great Britain: an approach using geographically weighted regression, *International Journal of Climatology*, 21(4), 455-466.
- [29] Brutsaert, W., 2005. *Hydrology: an introduction*. Cambridge University Press.
- [30] Butts, M.B., Payne, J.T., Kristensen, M. and Madsen, H., 2004. An evaluation of the impact of model structure on hydrological modelling uncertainty for streamflow simulation, *Journal of Hydrology*, 298(1), 242-266.
- [31] Bui, T.X., 1997. Decision support in the future tense, *Decision Support Systems* 19 (3) (1997 (March)) 149-150.
- [32] Chaubey, I., Haan, C. T., Grunwald, S., and Salisbury, J. M., 1999. Uncertainty in the model parameters due to spatial variability of rainfall, *Journal of Hydrology*, 220(1), 48-61.
- [33] Chow, V., 1972. Hydrologic modelling. *Journal of the Boston Society of Civil Engineering*, 60(1-27).
- [34] Christiaens, K. and Feyen, J., 2001. Analysis of uncertainties associated with different methods to determine soil hydraulic properties and their propagation in the distributed hydrological MIKE SHE model, *Journal of Hydrology*, 246(1) 63-81.
- [35] Chu, H., 2012. Assessing the relationships between elevation and extreme precipitation with various durations in southern Taiwan using spatial regression models, *Hydrological Processes*, 26(21), 3174-3181.
- [36] Clark, M.P., Woods, R.A., Zheng, X., Ibbitt, R.P., Slater, A.G., Rupp, D.E., Schmidt, J., Uddstrom, M.J., 2008. Hydrological data assimilation with the Ensemble Kalman Filter: use of streamflow observations to update states in a distributed hydrological model, *Advances in Water Resources* 31, 1309-1324.
- [37] Codd, E.F., 1970. A relational model for large shared data banks, *Communications of the ACM* 13 (6) (1970) 370-387.
- [38] Codd, E.F. and Associates, 1993. "Providing OLAP (On-line Analytical Processing) to User-Analysts: An IT Mandate," a white paper, commissioned by Arbor Software (now Hyperion Solutions) 1993.
- [39] Cortés, U., Sánchez-Marrè, M., Ceccaroni, L., R-Roda, I., Poch, M., 2000. Artificial intelligence and environmental decision support systems, *Applied Intelligence* 13 (1), 77-91.

- [40] Crawford, N.H. and Linsley, R.K., 1966. Digital Simulation in Hydrology, Stanford Watershed Model 4.
- [41] Cunderlik, J., 2003. Hydrologic model selection for the CFCAS project: Assessment of Water Resources Risk and Vulnerability to Changing Climatic Conditions. Department of Civil and Environmental Engineering, The University of Western Ontario.
- [42] Cunge, J., 2003. Of data and models, *Journal of Hydroinformatics*, 5, 75-98.
- [43] Dadiyorto, W., Shie-Yui, L., Yabin, S., and Chi, D. D., 2015. An innovative approach to improve SRTM DEM using multispectral imagery and artificial neural network, *Journal of Advances in Modeling Earth Systems*
- [44] Denzer, F., 2005. Generic integration of environmental decision support systems: –state-of-the-art, *Environmental Modelling & Software* 20 (2005) 1217-1223
- [45] Demetriou, C. and Punthakey, J.F., 1998. Evaluating sustainable groundwater management options using the MIKE SHE integrated hydrological modelling package, *Environmental Modelling & Software*, 14(2), 129-140.
- [46] DHI, 2012. MIKE ZERO User's Manual. (Mike by DHI, Ed.).
- [47] Diersch, H. J., Kolditz, O., 1998. Coupled groundwater flow and transport: 2. Thermohaline and 3D convection systems. *Advances in water resources*, 21(5): 401-425.
- [48] Dingman, S. L., 1994. *Physical hydrology* (Vol. 575). Prentice Hall Englewood Cliffs, NJ.
- [49] Dingman, S. L., 2002. *Physical hydrology*.
- [50] Du, M., Zattero, E., Ma, Q., Delestre, O., Gourbesville, P., Fouché, O., 2016b. 3d hydraulic modeling of a complex alluvial aquifer for groundwater resource management, *Procedia engineering*, special issue of the 12th international conference on hydroinformatics, 154: 340-347.
- [51] Edelstein, H., 1996. Mining data warehouses, *Information Week*, January 8, 1996, <http://www.informationweek.com/561/61oldat.htm>.
- [52] Emily, A. Tennevin, G., Mangan, C., 2010. Etude hydrogéologique des nappes profondes de la basse-vallée du Var (Alpes-Maritimes), Technical report, H2EA Consulting firm and Mangan Consulting firm, Nice, France, 101 pages.
- [53] Engeland, K., Hisdal, H., 2009. A comparison of low flow estimates in ungauged catchments using regional regression and the HBV-model, *Water Resources Management* 23, 2567-2586.r, pp. 1-17.
- [54] Ewen, J., Parkin, G. and O'connell, P.E., 2000. SHETRAN: distributed river basin flow and transport modelling system, *Journal of Hydrologic Engineering*, 5(3), 250-258.

- [55] FAO, 2008. Rainwater Harvesting Potential for Food Security, First African Water Week, Accelerating Water Security for Socio-economic Development of Africa, Tunis, Tunisia, 26-28th, March 2008.
- [56] Fenicia, F., McDonnell, J.J., Savenije, H.H.G., 2008. Learning from model improvement: on the contribution of complementary data to process understanding, *Water Resources Research* 44, W06419. <http://dx.doi.org/10.1029/2007WR006386>.
- [57] Fotheringham, A. S., Brunson, C., and Charlton, M., 2003. Geographically weighted regression: the analysis of spatially varying relationships, John Wiley & Sons.
- [58] Freeze, R.A. and Harlan, R.L., 1969. Blueprint for a physically-based, digitally-simulated hydrologic response model, *Journal of Hydrology*, 9(3), 1547-1578.
- [59] Gelfan, A., 2010. Extreme snowmelt floods: frequency assessment and analysis of genesis on the basis of the dynamic-stochastic approach, *Journal of Hydrology*, 388(1), 85-99.
- [60] Goovaerts, P., 1997. Geostatistics for natural resources evaluation, Oxford university press.
- [61] Goovaerts, P., 1998. Ordinary cokriging revisited, *Mathematical Geology*, 30(1), 21-42.
- [62] Goovaerts, P., 2000. Geostatistical approaches for incorporating elevation into the spatial interpolation of rainfall, *Journal of Hydrology*, 228(1), 113-129.
- [63] Gorry, G.A. and Scott Morton, M.S., 1989. A framework for management information systems, *Sloan Management Review* 13 (1) 1971 50-70.
- [64] Gouvas, M., Sakellariou, N., and Xystrakis, F., 2009. The relationship between altitude of meteorological stations and average monthly and annual precipitation, *Studia Geophysica et Geodaetica*, 53(4), 557-570.
- [65] Graham, D.N. and Butts, M.B., 2005. Flexible, integrated watershed modelling with MIKE SHE, *Watershed Models*, 849336090, 245-272.
- [66] Gregg, D.G., Goul, M. and Philippakis, A., 2002. Distributing decision support systems on the WWW: the verification of a DSS metadata model, *Decision Support Systems* 32 (2002) 233-245.
- [67] Guariso, G., Rinaldi, S. and Soncini-Sessa, R., 1986. The management of Lake Como: A Multiobjective Analysis, *Water Resources Research*, Vol. 22, No.2, page109-120.
- [68] Guglielmi, Y., 1993. Hydrogéologie des aquifères Plio-Quaternaires de la basse vallée du Var, PhD thesis, Université d'Avignon et des Pays du Vaucluse, France, 200 pages.

- [69] Guglielmi, Y., Reynaud, A., 1997. Etude de la variation piézométrique de la nappe du Bec de l'Estéron en vue de la réalisation d'une zone d'activité. Technical report, Laboratoire de Géologie Appliquée, Besançon, 9 pages.
- [70] Guinot, V. and Gourbesville, P., 2003. Calibration of physically based models: back to basics? *Journal of Hydroinformatics*, 05.4, 2003.
- [71] Gupta, H.V., Beven, K.J., Wagener, T., 2006. Model calibration and uncertainty estimation encyclopedia of hydrological sciences, In: Anderson, M.G. (Ed.), *Encyclopedia of Hydrological Sciences*. John Wiley & Sons Ltd, Chichester, pp. 1-17
- [72] Gupta, H.V, Kling, H., Yilmaz, K.K, and Martinez, G.F., 2009. Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling, *Journal of Hydrology*.
- [73] Gurtz, J., Baltensweiler, A., and Lang, H., 1999. Spatially distributed hydrotopo-based modelling of evapotranspiration and runoff in mountainous basins, *Hydrological Processes*, 13, 2751-2768.
- [74] Haastrup, H., Maniezzo, V., Marrarelli, M., Mazzeo, R. F., Mendes, I., Paruccini, M., 1998. A decision support system for urban waste management, *European Journal of Operational Research* 109 (1998) 330-341.
- [75] Haberlandt, U., Krysanova, V., Klöcking, B., Becker, A. and Bárdossy, A., 2001. Development of a metamodel for large-scale assessment of water and nutrient fluxes-first components and initial tests for the Elbe River Basin, *IAHS Publication*, 268, 263-269, 2001.
- [76] Haberlandt, U., 2010. From hydrological modelling to decision support, *Advances in Geosciences*, 27, 11-19. 2010.
- [77] Haklay, M., and Tobón, C., 2003. Usability evaluation and PPGIS: towards a user-centred design approach, *International Journal of Geographical Information Science*, 17(6), 577-592.
- [78] Handmer, J., 2001. Improving flood warnings in Europe: a research and policy agenda, *Environmental Hazards* 3 (2001) 19-28.
- [79] Harlin, J., 1991. Development of a process oriented calibration scheme for the HBV hydrological model, *Nordic Hydrol.* 22, 15-36.
- [80] Harun, S., Jajarmizadeh, M. and Salarpour, M., 2012. A review on theoretical consideration and types of models in hydrology. *Journal of Environmental Science and Technology*, 5(5), 249–261.

- [81] Hashemi, F. and Decker, W., 1969. Using climatic information and weather forecast for decisions in economizing irrigation water. *Agricultural Meteorology* 6 (4), 245-257.
- [82] He, Y., Bardossy, A. and Zehe, E., 2011. A review of regionalization for continuous streamflow simulation. *Hydrol. Earth Syst. Sci.* 15, 3539-3553.
<http://dx.doi.org/10.5194/hess-15-3539-2011>.
- [83] Hrachowitz, M., Savenije, H.H.G., Blöschl, G., McDonnell, J.J., Sivapalan, M., Pomeroy, J.W., Arheimer, B., Blume, T., Clark, M.P., Ehret, U., Fenicia, F., Freer, J.E., Gelfan, A., Gupta, H.V., Hughes, D.A., Hut, R.W., Montanari, A., Pande, S., Tetzlaff, D., Troch, P.A., Uhlenbrook, S., Wagener, T., Winsemius, H.C., Woods, R.A., Zehe, E., Cudennec, C., 2013. A decade of predictions in ungauged basins (PUB): a review. *Hydrol. Sci. J.* 58, 1198–1255. <https://doi.org/10.1080/02626667.2013.803183>.
- [84] Hundecha, Y., Zehe, E. and Bárdossy, A., 2002. Regional parameter estimation from catchment properties for the prediction of ungauged basins, In *Proceedings of the PUB Kick-off meeting* (pp. 20-22).
- [85] IBM, *Intelligent Operations Center for Smarter Cities Administration Guide*, (November, 2012).
- [86] *ICT as an enable for Smart Water Management*. ITU-T Technology Watch Report (October 2010).
- [87] Infanger, G., 1994. *Planning Under Uncertainty: Solving Large-scale Stochastic Linear Programming*, Boyd & Fraser Publishing Company, Danvers, MA.
- [88] Inmon, W.H., 1992. *Building the Data Warehouse*, QED Information Sciences, Wellesley, MA, 1992.
- [89] INSEE, 2008. *Résultats du recensement de la population de 2008 – Aire urbaine de Nice*, INSEE, 2008.
- [90] Jakeman, A.J., Hornberger, G.M., 1993. How much complexity is warranted in a rainfall-runoff model? *Water Resources Research* 29, 2637-2649.
- [91] Johansson, B., and Chen, D., 2003. The influence of wind and topography on precipitation distribution in Sweden: Statistical analysis and modelling, *International Journal of Climatology*, 23(12), 1523-1535.
- [92] Johnes, P. J., 1996. Evaluation and management of the impact of land use change on the nitrogen and phosphorus load delivered to surface waters: the export coefficient modelling approach, *J. Hydrol.*, 183, 323–349, 1996.
- [93] Jones, J. A. A., 1997. *Global hydrology*. Essex, UK: Longman.

- [94] Johnson, G. L., and Hanson, C. L., 1995. Topographic and atmospheric influences on precipitation variability over a mountainous watershed, *Journal of Applied Meteorology*, 34(1), 68-87.
- [95] Juston, J., Seibert, J., Johansson, P.O., 2009. Temporal sampling strategies and uncertainty in calibrating a conceptual hydrological model for a small boreal catchment, *Hydrol. Process.* 23, 3093-3109. <https://doi.org/10.1002/hyp.7421>.
- [96] Kahila, M., and Kytta, M., 2009. SoftGIS as a bridge-builder in collaborative urban planning, In *Planning support systems best practice and new methods* (pp. 389-411). Springer.
- [97] Kall, P., Wallace, S.W., 1994. *Stochastic Programming*, John Wiley and Sons, New York.
- [98] Keen, P., 1987. Decision support systems: the next decade, *Decision Support Systems* 3 (3) (1987) 253-265.
- [99] Kimball, R., 1996. *The Data Warehouse Toolkit*, John Wiley & Sons, New York, NY, 1996.
- [100] Kitchin, R., 2014. The real-time city? Big data and smart urbanism, *GeoJournal*, 79(1), 1-14.
- [101] Kitchin, R., Lauriault, T. P., and McArdle, G., 2015. Knowing and governing cities through urban indicators, city benchmarking and real-time dashboards. *Regional Studies, Regional Science*, 2(1), 6-28.
- [102] Kokkonen, T.S., Jakeman, A.J., Young, P.C., Koivusalo, H.J., 2003. Predicting daily flows in ungauged catchments: model regionalization from catchment descriptors at the Coweeta Hydrologic Laboratory, North Carolina. *Hydrol. Process.* 17, 2219–2238.
- [103] Konz, M., Seibert, J., 2010. On the value of glacier mass balances for hydrological model calibration, *J. Hydrol.* 385, 238-246. <https://doi.org/10.1016/j.jhydrol.2010.02.025>.
- [104] Koutsoyiannis, D., Karavokiros, G., Efstratiadis, A., Mamassis, N., Koukouvinos, A., Christofides, A., 2003. A decision support system for the management of the water resource system of Athens, *Physics and Chemistry of the Earth* 28 (2003) 599-609.
- [105] Kristensen, K. and Jensen, S., 1975. A model for estimating actual evapotranspiration from potential evapotranspiration, *Nordic Hydrology*, 6(3), 170-188.
- [106] Krysanova, V., Müller-Wohlfeil, D. I., and Becker, A.: Development and test of a spatially distributed hydrological/water quality model for mesoscale watersheds, *Ecol. Model.*, 106, 261–289, 1998.
- [107] Kuczka, G., 1992. Network linear programming codes for water supply head-works modelling. *Journal of Water Resources Planning and Management* 3, 412-417.

- [108] Kumar, R. and Khepar, S.D., 1980. Decision models for optimal cropping patterns in irrigations based on crop water production functions, *Agricultural Water Management* 3 (1), 65-76.
- [109] Kunkel, R. and Wendland, F., 2002. The GROWA98 model for water balance analysis in large river basins – the river Elbe case study, *J. Hydrol.*, 259, 152–162, 2002.
- [110] Lam, D. and Swayne, D.A., 2001. Issues of EIS software design: some lessons learnt in the past decade. *Environmental Modelling and Software*, vol. 16(5). Elsevier Science, pp. 419–425.
- [111] Lee, D., Felix, J. R. A., He, S., Offenhuber, D., Ratti, C., 2015. CityEye: Real-time Visual Dashboard for Managing Urban Services and Citizen Feedback Loops, CUPUM 2015 368-Paper.
- [112] Lewarne, M., 2009. Setting up ArcSWAT hydrological model for the Verlorenvlei catchment. Stellenbosch: University of Stellenbosch.
- [113] Li, M., Shao, Q.X., Zhang, L., Chiew, F.H.S., 2010. A new regionalization approach and its application to predict flow duration curve in ungauged basins. *J. Hydrol.* 389 (1-2), 137–145.
- [114] Linsley, R. K., Kohler, M. A., and Paulhus, J. L. H., 1949. *Applied hydrology*. McGraw-Hill New York.
- [115] Liu, H.L., Chen, X., Bao, A.M. and Wang, L., 2007. Investigation of groundwater response to overland flow and topography using a coupling MIKE SHE/MIKE 11 modelling system for an arid watershed, *Journal of Hydrology*, 347 (3), 448-459.
- [116] Lloyd, C. D., 2005. Assessing the effect of integrating elevation data into the estimation of monthly precipitation in Great Britain, *Journal of Hydrology*, 308(1), 128-150.
- [117] Loucks, D.P., Stedinger, J.R., Haith, D.A., 1981. *Water Resource Systems Planning and Analysis*, Prentice Hall, Englewood Cliffs, NJ.
- [118] Ma, Y., Huang, Y., Chen, X., Li, Y. and Bao, A., 2013. Modelling snowmelt runoff under climate change scenarios in an ungauged mountainous watershed, Northwest China, *Mathematical Problems in Engineering*, 2013.
- [119] Madsen, H., 2003. Parameter estimation in distributed hydrological catchment modelling using automatic calibration with multiple objectives. *Advances in Water Resources*, 26(2), 205–216.
- [120] Maidment, D.R., and Hoogerwerf, T.N., 2002. *Parameter Sensitivity in Hydrologic Modelling*.

- [121] Mair, A., and Fares, A., 2010. Comparison of rainfall interpolation methods in a mountainous region of tropical island, *Journal of Hydrologic Engineering*, 16(4), 371-383.
- [122] Mishra, S., 2009. Uncertainty and sensitivity analysis techniques for hydrologic modeling, *Journal of Hydroinformatics*, 11(3-4), 282-296.
- [123] Mbilinyi, B.P., Tumbo, S.D., Mahoo, H.F., Mkiramwinyi, F.O., 2007. GIS-based decision support system for identifying potential sites for rainwater harvesting, *Physics and Chemistry of the Earth* 32 (2007) 1074-1081
- [124] McDonald, M. G., Harbaugh, A. W., 1984. A modular three-dimensional finite-difference ground-water flow model. R83-875. Technical report, U.S. Geological Survey. 528 pages.
- [125] McIntyre, N.R., Wheater, H.S., 2004. Calibration of an in-river phosphorus model: prior evaluation of data needs and model uncertainty, *J. Hydrol.* 290, 100–116.
<https://doi.org/10.1016/j.jhydrol.2003.12.003>.
- [126] McIntyre, N., Lee, H., Wheater, H., Young, A., Wagener, T., 2005. Ensemble predictions of runoff in ungauged catchments. *Water Resour. Res.* 41 (12), W12434.
<http://dx.doi.org/10.1029/2005wr004289>.
- [127] McMichael, C.E., Hope, A.S. and Loaiciga, H.A, 2006. Distributed hydrological modelling in California semi-arid shrublands: MIKE SHE model calibration and uncertainty estimation, *Journal of Hydrology*, 317(3-4), 307-324.
- [128] McMillan, H.K., Hreinsson, E.O., Clark, M.P., Singh, S.K., Zammit, C., Uddstrom, M.J., 2013. Operational hydrological data assimilation with the recursive ensemble Kalman filter, *Hydrology and Earth System Sciences* 17, 21-38.
- [129] McNurlin, B.C. and Sprague, R.H., 2004. *Information Systems Management in Practice*, 6th Ed., Prentice Hall, Englewood Cliffs, NJ, 2004.
- [130] Melsen, L.A., Teuling, A.J., Berkum, S.W., Torfs, P.J.J.F., Uijlenhoet, R., 2014. Catchments as simple dynamical systems: a case study on methods and data requirements for parameter identification, *Water Resour. Res.* 50, 5577-5596.
<https://doi.org/10.1002/2013WR014720>.
- [131] Mernild, S.H. Hasholt, B. and Liston, G.E., 2008. Climatic control on river discharge simulations, Zackenberg River drainage basin, northeast Greenland, *Hydrological Processes*, 22(12), 1932-1948.
- [132] Merz, R., Blöschl, G., 2004. Regionalisation of catchment model parameters, *J. Hydrol.* 287 (1–4), 95–123. <http://dx.doi.org/10.1016/j.jhydrol.2003.09.028>.
- [133] Merz, R., Blöschl, G., 2005. Flood frequency regionalisation – spatial proximity vs. catchment attributes, *Journal of Hydrology* 302, 283-306.

- [134] Moore, R. J., Bell, V. A. and Jones, D. A., 2004. Forecasting for flood warning, *C. R. Geoscience* 337 (2005) 203-217.
- [135] Muleta, M.K., and Nicklow, J.W., 2005. Sensitivity and uncertainty analysis coupled with automatic calibration for a distributed watershed model, *Journal of Hydrology*, 306(1), 127-145.
- [136] Murphy, A., 1988. Skill scores based on the mean square error and their relationships to the correlation coefficient, *Monthly Weather Review* 116, 2417–2424.
- [137] Mwenge Kahinda, J., Taigbenu, A.E., Sejamoholo, B.B.P., Lillie E.S.B., Boroto R.J., 2009. A GIS-based decision support system for rainwater harvesting (RHADESS), *Physics and Chemistry of the Earth* 34 (2009) 767-775.
- [138] National Oceanic and Atmospheric Administration (NOAA), 2000. “NOAA reports record warmth for January–March 2000, FEMA reports presidentially declared disasters have nearly doubled and costs have skyrocketed.” NOAA News, <http://www.noaanews.noaa.gov/stories/s412.htm>.
- [139] Ng, H. Y. F. and Marsalek, J., 1992. Sensitivity of streamflow simulation to changes in climatic inputs. *Nordic Hydrology*, 23(4), 257–272.
- [140] Nicótina, L., Alessi Celegon, E., Rinaldo, A., and Marani, M., 2008. On the impact of rainfall patterns on the hydrologic response, *Water Resources Research*, 44(12).
- [141] Obled, C., Wendling, J., and Beven, K., 1994. The sensitivity of hydrological models to spatial rainfall patterns: an evaluation using observed data. *Journal of Hydrology*, 159(1), 305-333.
- [142] OLAP Council, 1997. Definitions, <http://www.dssresources.com/glossary/olaptrms.html>.
- [143] Oudin, L., Andréassian, V., Perrin, C., Michel, C., Le Moine, N., 2008. Spatial proximity, physical similarity, regression and ungauged catchments: a comparison of regionalization approaches based on 913 French catchments. *Water Resour. Res.* 44 (3), W03413. <http://dx.doi.org/10.1029/2007wr006240>.
- [144] Oudin, L., Kay, A., Andréassian, V., Perrin, C., 2010. Are seemingly physically similar catchments truly hydrologically similar? *Water Resour. Res.* 46, W11558. <http://dx.doi.org/10.1029/2009WR008887>.
- [145] Oogathoo, S., 2006 Runoff simulation in the canagagigue Greek watershed using the MIKE SHE model, Citeseer.
- [146] Pallottino, S., Sechi, G. M. and Zuddas P., 2005. A DSS for water resources management under uncertainty by scenario analysis, *Environment Modelling & Software* 20(2005)1031-1042

- [147] Parajka, J., Merz, R., Blöschl, G., 2005. A comparison of regionalisation methods for catchment model parameters, *Hydrology and Earth System Sciences* 9, 157-171. <http://dx.doi.org/10.5194/hess-9-157-2005>.
- [148] Parajka, J., Viglione, A., Rogger, M., Salinas, J.L., Sivapalan, M., Bloeschl, G., 2013. Comparative assessment of predictions in ungauged basins – part 1: runoffhydrograph studies. *Hydrol. Earth Syst. Sci.* 17 (5), 1783-1795.
- [149] Perrin, C., Oudin, L., Andreassian, V., Rojas-Serna, C., Michel, C., Mathevet, T., 2007. Impact of limited streamflow data on the efficiency and the parameters of rainfall-runoff models, *Hydrol. Sci. J.* 52, 131-151. <https://doi.org/10.1623/hysj.52.1.131>.
- [150] Pielke, R. A. Jr. and Downton, M. W., 1999. U.S. trends in streamflow and precipitation: Using societal impact data to address an apparent paradox. *Bull. Am. Meteorological Soc.*, 80, 1435-1436.
- [151] Pielke, R. A. Jr. and Downton, M. W., 2000. Precipitation and damaging floods: Trends in the United States, 1932-1997. *J. Climate*, 13(20), 3625-3637.
- [152] Plate, E. J., 2009. HESS Opinions“ Classification of hydrological models for flood management.” *Hydrology and Earth System Sciences*, 13(10), 1939–1951.
- [153] Pomareda, C., 1977. Economic analysis of irrigation production functions --an application of linear-programming, Unpublished paper, World Bank, Washington, DC, pp. 1-11.
- [154] Potot, C., 2011. Etude hydrochimique du système aquifère de la basse vallée du Var, apport des éléments traces et des isotopes (Sr, Pb, $\delta^{18}O$, ^{226}Ra , ^{228}Ra). PhD thesis. Université Nice Sophia Antipolis, France, 240 pages.
- [155] Potot, C., Féraud G., Schärer U., Barats A., Durrieu G., Le Poupon C., Travi Y., Simler R., 2012. Groundwater and river baseline quality using major, trace elements, organic carbon and Sr–Pb–O isotopes in a Mediterranean catchment: The case of the Lower Var Valley (south-eastern France), *Journal of Hydrology*, 472: 126–147.
- [156] Power ,D.J., 1999. Decision Support Systems Glossary, DSS Resources, World Wide Web, <http://www.DSSResources.COM/glossary/>.
- [157] Power, D.J., 2002. *Decision Support Systems: Concepts and Resources for Managers*, Greenwood/Quorum Books, Westport, CT, 2002.
- [158] Power, D.J. and Sharda, R., 2007. Model-driven decision support systems: Concepts and research directions, *Decision Support Systems* 43 (2007) 1044-1061.
- [159] Quinn, P. F., Hewett, C. J. M. and Dayawansa, N. D. K., 2008. TOPCATNP: a minimum information requirement model for simulation of flow and nutrient transport from agricultural systems, *Hydrol. Process.*, 22, 2565-2580, 2008.

- [160] Raghunath, H. M., 2006. Hydrology: principles, analysis and design. New Age International.
- [161] Razavi, T., Coulibaly, P., 2012. Streamflow prediction in ungauged basins: review of regionalization methods, J. Hydrol. Eng. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0000690](https://doi.org/10.1061/(ASCE)HE.1943-5584.0000690).
- [162] Refsgaard, J. C., 1997. Parameterisation, calibration and validation of distributed hydrological models. Journal of Hydrology, 198(1-4), 69–97.
- [163] Refsgaard, J.C., Storm, B., and Singh, V.P., 1995. MIKE SHE, Computer Models of Watershed Hydrology, 809-846.
- [164] Rizzoli, A.E. and Young, W.J., 1997. Delivering environmental decision support systems: software tools and techniques, Environmental Modelling and Software 12, 237-249.
- [165] Rochester, R. E. L., 2010. Uncertainty in hydrological modelling: a case study in the Tern catchment, Shropshire, UK. UCL (University College London).
- [166] Ruszczyński, A., 1997. Decomposition methods in stochastic programming, Mathematical Programming 79, 333-353.
- [167] Sahoo, G.B., Ray, C. and De Carlo, E.H., 2006. Calibration and validation of a physically distributed hydrological model, MIKE SHE, to predict streamflow at high frequency in a flashy mountainous Hawaii stream, Journal of Hydrology, 327(1-2), 94-109.
- [168] Salewicz, K. A. and Nakayama, M., 2004. Development of a web-based decision support system (DSS) for managing large international rivers, Global Environmental Change 14 (2004) 25-37.
- [169] Sandra, P., Daniel, V., Jan, S., 2017. Prediction of hydrographs and flow-duration curves in almost ungauged catchments: Chich runoff measurements are most informative for model calibration? Journal of Hydrology 554 (2017) 613-622
- [170] Santoro, F., Tonino, M., Torresan, S., Critto, A., Marcomini, A., 2013. Involve to improve: A participatory approach for a Decision Support System for coastal climate change impacts assessment. The North Adriatic case, Ocean & Coastal Management 78 (2013) 101-111.
- [171] Schlossberg, M., & Shuford, E. (2005). Delineating“ public” and“ participation” in PPGIS. Retrieved from <https://scholarsbank.uoregon.edu/xmlui/han-dle/1794/1343>
- [172] Sechi, G.M., Zuddas, P., 1998. Structure oriented approaches for water system optimization, Conference on Coping with Water Scarcity, Hurgada, Egypt, September 1998.

- [173] Sechi, G.M., Zuddas, P., 2000. WARGI: water resources system optimisation aided by graphical interface, In: Blain, W.R., Brebbia, C.A. (Eds.), *Hydraulic Engineering Software*. WITPRESS, pp. 109-120.
- [174] Segond, M.-L., Wheater, H.S., and Onof, C., 2007. The significance of spatial rainfall representation for flood runoff estimation: A numerical evaluation based on the Lee catchment, UK, *Journal of Hydrology*, 347(1), 116-131.
- [175] Seibert, J., Beven, K.J., 2009. Gauging the ungauged basin: How many discharge measurements are needed? *Hydrol. Earth Syst. Sci.* 13, 883-892. <https://doi.org/10.5194/hess-13-883-2009>.
- [176] Seibert, J., McDonnell, J.J., 2013. Gauging the ungauged basin: relative value of soft and hard data, *J. Hydrol. Eng.* 20, A4014004. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0000861](https://doi.org/10.1061/(ASCE)HE.1943-5584.0000861).
- [177] Sempere-Payá, V., Todolí-Ferrandis, D. and Santonja-Climent, S., 2013. ICT as an Enabler to Smart Water Management, S.C. Mukhopadhyay & A. Mason (Eds.): *Real-Time Water Quality Monitoring*, SSMI 4, pp. 239-258.
- [178] Sen, A.K. and Niedzielski, T., 2010. Statistical characteristics of riverflow variability in the Odra River Basin, Southwestern Poland, *Polish Journal of Environmental Studies*, 19(2), 387-397.
- [179] Shaw, M., Deline, R., Klein, D.V., Ross, T.L., Young, D.M., Zelesnik G., 1996. Abstractions for software architecture and tools to support them, *IEEE Transactions on Software Engineering* 21 (4) (1995 (Apr.)) 1996 (Apr.).
- [180] Shim, J.P., Warkentin, M., Courtney, J.F., Power, D.J., Sharda, R. and Carlsson, C., 2002. Past, present, and future of decision support technology, *Decision Support Systems* 33 (2002) 111-126
- [181] Shrestha, R. R., Bardossy, A. and Rode, M., 2007. A hybrid deterministic-fuzzy rule based model for catchment scale nitrate dynamics, *J. Hydrol.*, 342, 143-156, 2007.
- [182] Shuttleworth, W. J. and Wallace, J.S., 1985. Evaporation from sparse crops-an energy combination theory. *Quarterly Journal of the Royal Meteorological Society*, 111(469), 839-855.
- [183] Simon, H. A., 1960. *The New Science of Management Decision*, Harper Brothers, New York, 1960.
- [184] Singh, R., Archfield, S.A. and Wagener, T., 2014. Identifying dominant controls on hydrologic parameter transfer from gauged to ungauged catchments – A comparative hydrology approach, *Journal of Hydrology* 517 (2014) 985-996.

- [185] Singh, S.K., Bárdossy, A., 2012. Calibration of hydrological models on hydrologically unusual events, *Adv. Water Resour.* 38, 81–91.
<https://doi.org/10.1016/j.advwatres.2011.12.006>.
- [186] Singh, V. P., 1988. *Hydrologic systems. Volume I: Rainfall-runoff modeling*. Prentice Hall, Englewood Cliffs New Jersey. 1988. 480.
- [187] Singh, V.P., 1995. Watershed modelling. In: Singh, V.P. (Ed.), *Computer Models of Watershed Hydrology*, Water Resources Publications, Highlands Ranch, Colorado, pp. 1-22.
- [188] Singh, V.P., Frevert, D., 2006. *Watershed Models*, Taylor & Francis, Boca Raton.
- [189] Sivapalan, M., Beven, K., and Wood, E.F., 1987. On hydrologic similarity: 2. A scaled model of storm runoff production, *Water Resources Research*, 23(12), 2266-2278.
- [190] Sivapalan, M., Takeuchi, K., Franks, S., Gupta, V., Karambiri, H., Lakshmi, V., Liang, X., Mcdonnell, J., Mendiondo, E., O'connell, P., Oki, T., Pomeroy, J., Schertzer, D., Uhlenbrook, S., Zehe, E., 2003. IAHS decade on predictions in Ungauged Basins (PUB), 2003-2012: shaping an exciting future for the hydrological sciences. *Hydrolog. Sci. J.* 48 (6), 857-880. <http://dx.doi.org/10.1623/Hysj.48.6.857.51421>.
- [191] Smits, P., Annoni, A., Craglia, M., 2009. One Information Space, Billions of Sensors, Technologies for Information Management. ICT FP7 Call 5 Intelligent Information Management, 11-12, May 2009.
- [192] Smarter cities software, 2015, <http://www-03.ibm.com/software/products/nl/intelligent-operations-center>
- [193] Soncini-Sessa, R., Castelletti, A. and Weber, E., 2003. A DSS for planning and managing water reservoir systems, *Environmental Modelling & Software* 18 (2003) 395-404.
- [194] Souriguère, K., 2003. *Etat des lieux-diagnostic, SAGE nappe et basse vallee du var*. Syndicat mixte d'études de la basse vallée du Var. Carros, France.
- [195] Sun, W., Wang, Y., Wang, G., Cui, X., Yu, J., Zuo, D., Xu, Z., 2017. Physically based distributed hydrological model calibration based on a short period of streamflow data: case studies in four Chinese basins, *Hydrol. Earth Syst. Sci.* 21, 251-265.
<https://doi.org/10.5194/hess-21-251-2017>.
- [196] Tao, T., 2009. Uncertainty Analysis of Interpolation Method in Rainfall Spatial Distribution – A Case of Small Catchment in Lyon, *Journal of Water Resource and Protection*, 01 (02), 1363-144.
- [197] Taylor, K., Cameron, M., & Haines, J., 1998. An integrated information system on the web for watershed management. *ACM GIS'98*, November 1998, Washington, DC, USA.

- [198] Thompson, J.R., Sørensen, H.R., Gavin, H. and Refsgaard, A., 2004. Application of the coupled MIKE SHE/MIKE11 modelling system to a lowland wet grassland in southeast England, *Journal of Hydrology*, 242(3), 210-227.
- [199] Tian, J., Wang, Y. L., Li, H. Z., Li, L., Wang, K.L., 2005. DSS development and applications in China, *Decision Support Systems* 42 (2007) 2060-2077.
- [200] Tobin, C., Nicótina, L., Parlange, M.B., Beme, A., and Rinaldo, A., 2011. Improved interpolation of meteorological forcings for hydrologic applications in a Swiss Alpine region, *Journal of Hydrology*, 401(1), 77-89.
- [201] Todd, D.K., 1980. *Groundwater Hydrology*, 2nd ed., John Wiley & Sons, New York, 535p.
- [202] United Kingdom Climate Impacts Programme, 2001. Available from: <http://www.ukcip.org.uk> (consulted 8 August 2001).
- [203] United Nations Educational, Scientific and Cultural Organization, 2006. *Water a Shared Responsibility: the United Nations World Water Development Report 2*, 7, place de Fontenoy, 75007 Paris, France.
- [204] Van, Asselt, M. B. A., Mellors, J., Rijkens-Klomp, N., Greeuw, S. C. H., Molendijk, K. G. P., Beers, P. J., van Notten, P., 2001. Building blocks for participation in integrated assessment: A review of participatory methods, ICIS Working Paper I01-E003. ICIS, Maastricht, The Netherlands.
- [205] Vansteenkiste, T., Tavakoli, M., Van Steenberghe, N., De Smedt, F., Batelaan, O., Pereira, F., & Willems, P., 2014. Intercomparison of five lumped and distributed models for catchment runoff and extreme flow simulation. *Journal of Hydrology*, 511, 335–349.
- [206] Vázquez, R.F., Feyen, L., Feyen, J. and Refsgaard, J.C., 2002. Effect of grid size on effective parameters and model performance of the MIKE SHE code, *Hydrological Processes*, 16(2), 355-372.
- [207] Verruijt, A., 1970. *Theory of groundwater flow*. Macmillan Education UK (Ed.), 182 pages.
- [208] Vo, N.D., 2015. *Deterministic hydrological modelling for flood risk assessment and climate change in large catchment, Application to Vu Gia Thu Bon catchment, Vietnam*, HAL Id: tel-01245061, version 1
- [209] Vrugt, J.A., Gupta, H.V., Dekker, S.C., Sorooshian, S., Wagener, T., Bouten, W., 2006. Application of stochastic parameter optimization to the Sacramento soil moisture accounting model, *J. Hydrol.* 325, 288–307. <https://doi.org/10.1016/j.jhydrol.2005.10.041>.
- [210] Vu, V., Do, D. and Dang, T., 2008. Potential evapotranspiration estimation and its effect on hydrological model response at the Nong Son Basin, 24, 213-223.

- [211] Wade, S., Hossell, J., Hough, M., Fenn, C. (Eds.), 1999. The impacts of climate change in the South East. Epsom: WS Atkins (Technical report).
- [212] Wagener, T., Montanari, A., 2011. Convergence of approaches toward reducing uncertainty in predictions in ungauged basins, *Water Resour. Res.* 47, W06301. <http://dx.doi.org/10.1029/2010WR009469>.
- [213] Wang, S., Zhang, Z., Sun, G., Strauss, P., Guo, J., Tang, Y., Yao, A., 2012. Multi-site calibration, validation and sensitivity analysis of the MIKE SHE Model for a large watershed in northern China, *Hydrology and Earth System Sciences*, 16(12), 4621-4632.
- [214] Wang, Y., Dietrich, J., Voss, F., and Pahlow, M., 2007. Identifying and reducing model structure uncertainty based on analysis of parameter interaction. *Advances in Geosciences*, 11, 117-122.
- [215] Weglarczyk, S., 1998. The interdependence and applicability of some statistical quality measures for hydrological models. *Journal of Hydrology* 206, 98–103.
- [216] Willems, P., 2000. Probabilistic modeling of the emission receiving surface waters. Ph. D Thesis, Faculty of Engineering, Katholieke Universiteit, Leuven, Belgium.
- [217] Wijesekara, G. N., Farjad, B., Gupta, A., Qiao, Y., Delaney, P., Marceau, D.J., 2014. A comprehensive land-use/hydrological modelling system for scenario simulations in the Elbow River watershed, Alberta, Canada, *Environmental Management*, 53(2), 357-381.
- [218] Witt, J. L., 1998. “National Press Club luncheon speech, November 10, 1998.” <http://www.fema.gov/library/wittspch11.htm>.
- [219] Xie, Y., Wang, H.W., and Efstathiou, J., 2005. A research framework for Web-based open decision support systems, *Knowledge-Based Systems* 18 (2005) 309-319
- [220] Xu, C., 2002. Hydrologic models. Textbooks of Uppsala University. Department of Earth Sciences Hydrology.
- [221] Yan, J. and Smith, K. R., 1994. Simulation of Integrated Surface Water and Ground Water System-Model Formulation 1. *JAWRA Journal of the American Water Resources Association*, 30(5), 879-890.
- [222] Yeh, W.G., 1985. Reservoir management and operations models: a state-of-the-art review, *Water Resources Research* 25 (12), 1797-1818.
- [223] Zhang, S. and Goddard, S., 2003. 3CoFramework: a component-based framework for distributed applications, *Proc. of the 2003 International Conference on Software Engineering Research and Practice*, 2003 (Jun.), pp. 398-404.
- [224] Zhang, S. and Goddard, S., 2007. A software architecture and framework for Web-based distributed Decision Support Systems, *Decision Support Systems* 43 (2007) 1133-1150

- [225] Zhang, X. D., Huang, G. H., Nie, X. H. and Lin, Q. G., 2011. Model-based decision support system for water quality management under hybrid uncertainty, *Expert Systems with Applications* 38 (2011) 2809-2816.
- [226] Zhang, Y.Q., Chiew, F.H.S., 2009. Relative merits of different methods for runoff predictions in ungauged catchments, *Water Resour. Res.* 45, W07412.
<http://dx.doi.org/10.1029/2008WR007504>.
- [227] Zhang, Z. Q., Wang, S. P., Sun, G., McNulty, S. G. Zhang, H.Y., Li, J.L., Zhang, M.L., Klaghofer E., Strauss P., 2008. Evaluation of the MIKE SHE model for application in the Loess Plateau, China 1. *Journal of American Water Resources Association*, 44(5), 1108-1120.
- [228] Zhao, F., Zhang, L., Chiew, F.H.S., Vaze, J., and Cheng, L., 2013. The effect of spatial rainfall variability on water balance modelling for south eastern Australian catchments, *Journal of Hydrology*, 493, 16-29.

APPENDIX

Appendix 1: Land use Classifications (European Agriculture Centre)

GRID_CODE	LABEL1	LABEL2	LABEL3
1	Artificial surfaces	Urban fabric	Continuous urban fabric
2	Artificial surfaces	Urban fabric	Discontinuous urban fabric
3	Artificial surfaces	Industrial, commercial and transport units	Industrial or commercial units
4	Artificial surfaces	Industrial, commercial and transport units	Road and rail networks and associated land
5	Artificial surfaces	Industrial, commercial and transport units	Port areas
6	Artificial surfaces	Industrial, commercial and transport units	Airports
7	Artificial surfaces	Mine, dump and construction sites	Mineral extraction sites
8	Artificial surfaces	Mine, dump and construction sites	Dump sites
9	Artificial surfaces	Mine, dump and construction sites	Construction sites
10	Artificial surfaces	Artificial, non-agricultural vegetated areas	Green urban areas
11	Artificial surfaces	Artificial, non-agricultural vegetated areas	Sport and leisure facilities
12	Agricultural areas	Arable land	Non-irrigated arable land
13	Agricultural areas	Arable land	Permanently irrigated land
14	Agricultural areas	Arable land	Rice fields
15	Agricultural areas	Permanent crops	Vineyards
16	Agricultural areas	Permanent crops	Fruit trees and berry plantations
17	Agricultural areas	Permanent crops	Olive groves
18	Agricultural areas	Pastures	Pastures
19	Agricultural areas	Heterogeneous agricultural areas	Annual crops associated with permanent crops
20	Agricultural areas	Heterogeneous agricultural areas	Complex cultivation patterns
21	Agricultural areas	Heterogeneous agricultural areas	Land principally occupied by agriculture, with significant areas of natural vegetation
22	Agricultural areas	Heterogeneous agricultural areas	Agro-forestry areas
23	Forest and semi natural areas	Forests	Broad-leaved forest
24	Forest and semi natural areas	Forests	Coniferous forest
25	Forest and semi natural areas	Forests	Mixed forest
26	Forest and semi natural areas	Scrub and/or herbaceous vegetation associations	Natural grasslands
27	Forest and semi natural areas	Scrub and/or herbaceous vegetation associations	Moors and heathland

28	Forest and semi natural areas	Scrub and/or herbaceous vegetation associations	Sclerophyllous vegetation
29	Forest and semi natural areas	Scrub and/or herbaceous vegetation associations	Transitional woodland-shrub
30	Forest and semi natural areas	Open spaces with little or no vegetation	Beaches, dunes, sands
31	Forest and semi natural areas	Open spaces with little or no vegetation	Bare rocks
32	Forest and semi natural areas	Open spaces with little or no vegetation	Sparsely vegetated areas
33	Forest and semi natural areas	Open spaces with little or no vegetation	Burnt areas
34	Forest and semi natural areas	Open spaces with little or no vegetation	Glaciers and perpetual snow
35	Wetlands	Inland wetlands	Inland marshes
36	Wetlands	Inland wetlands	Peat bogs
37	Wetlands	Maritime wetlands	Salt marshes
38	Wetlands	Maritime wetlands	Salines
39	Wetlands	Maritime wetlands	Intertidal flats
40	Water bodies	Inland waters	Water courses
41	Water bodies	Inland waters	Water bodies
42	Water bodies	Marine waters	Coastal lagoons
43	Water bodies	Marine waters	Estuaries
44	Water bodies	Marine waters	Sea and ocean
48	NODATA	NODATA	NODATA
49	UNCLASSIFIED	UNCLASSIFIED LAND SURFACE	UNCLASSIFIED LAND SURFACE
50	UNCLASSIFIED	UNCLASSIFIED WATER BODIES	UNCLASSIFIED WATER BODIES
255	UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED

Appendix 2: Monthly rainfall correlation among different stations.

	4076001	4115001	6005001	6006001	6016001	6033002	6050002	6074005	6077006	6081001	6088001	6094002	6102001	6120004	6125001	6127001
4076001	1.00															
4115001	0.90	1.00														
6005001	0.96	0.90	1.00													
6006001	0.86	0.77	0.88	1.00												
6016001	0.93	0.92	0.94	0.84	1.00											
6033002	0.89	0.81	0.90	0.98	0.86	1.00										
6050002	0.90	0.84	0.94	0.92	0.89	0.94	1.00									
6074005	0.89	0.82	0.89	0.89	0.91	0.93	0.88	1.00								
6077006	0.90	0.81	0.90	0.94	0.90	0.96	0.91	0.96	1.00							
6081001	0.96	0.90	0.96	0.88	0.94	0.90	0.93	0.90	0.90	1.00						
6088001	0.85	0.76	0.87	0.97	0.81	0.97	0.89	0.88	0.91	0.88	1.00					
6094002	0.93	0.91	0.93	0.81	0.97	0.83	0.87	0.88	0.88	0.92	0.78	1.00				
6102001	0.92	0.88	0.92	0.85	0.93	0.87	0.87	0.91	0.91	0.89	0.81	0.93	1.00			
6120004	0.90	0.91	0.91	0.79	0.93	0.82	0.85	0.85	0.85	0.89	0.77	0.92	0.93	1.00		
6125001	0.93	0.93	0.92	0.79	0.94	0.82	0.87	0.84	0.84	0.92	0.76	0.94	0.91	0.95	1.00	
6127001	0.92	0.87	0.91	0.87	0.95	0.90	0.88	0.94	0.94	0.91	0.84	0.93	0.96	0.93	0.91	1.00

Appendix 3: Daily rainfall correlation among different stations.

	4076001	4115001	6005001	6006001	6016001	6033002	6050002	6074005	6077006	6081001	6088001	6094002	6102001	6120004	6125001	6127001
4076001	1.00															
4115001	0.84	1.00														
6005001	0.90	0.80	1.00													
6006001	0.80	0.72	0.82	1.00												
6016001	0.87	0.81	0.86	0.75	1.00											
6033002	0.82	0.74	0.85	0.96	0.78	1.00										
6050002	0.86	0.77	0.90	0.83	0.81	0.86	1.00									
6074005	0.82	0.74	0.83	0.84	0.82	0.87	0.81	1.00								
6077006	0.67	0.61	0.68	0.66	0.66	0.71	0.72	0.72	1.00							
6081001	0.90	0.84	0.90	0.81	0.84	0.84	0.91	0.82	0.68	1.00						
6088001	0.76	0.70	0.80	0.91	0.72	0.90	0.81	0.79	0.61	0.81	1.00					
6094002	0.87	0.84	0.86	0.73	0.94	0.76	0.81	0.80	0.64	0.84	0.71	1.00				
6102001	0.83	0.76	0.85	0.79	0.86	0.81	0.81	0.86	0.71	0.81	0.75	0.85	1.00			
6120004	0.83	0.84	0.84	0.74	0.87	0.77	0.79	0.79	0.68	0.82	0.72	0.88	0.84	1.00		
6125001	0.84	0.88	0.81	0.69	0.86	0.71	0.77	0.73	0.63	0.82	0.67	0.89	0.78	0.88	1.00	
6127001	0.83	0.78	0.82	0.79	0.86	0.82	0.79	0.89	0.70	0.82	0.74	0.85	0.91	0.85	0.80	1.00

Appendix 4: Hourly rainfall correlation among different stations.

	<i>4115001</i>	<i>6005001</i>	<i>6033002</i>	<i>6050002</i>	<i>6074005</i>	<i>6088001</i>	<i>6094002</i>	<i>6102001</i>	<i>6120004</i>	<i>6125001</i>
4115001	1.00									
6005001	0.41	1.00								
6033002	0.32	0.49	1.00							
6050002	0.41	0.63	0.56	1.00						
6074005	0.33	0.49	0.61	0.50	1.00					
6088001	0.29	0.40	0.50	0.45	0.36	1.00				
6094002	0.47	0.56	0.38	0.49	0.42	0.36	1.00			
6102001	0.35	0.50	0.42	0.47	0.51	0.34	0.50	1.00		
6120004	0.48	0.51	0.39	0.48	0.43	0.36	0.56	0.49	1.00	
6125001	0.59	0.48	0.35	0.48	0.38	0.32	0.57	0.45	0.62	1.00

Appendix 5: Sensitivity assessment of overland Manning.

