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# HABILITATION THESIS

## Mathematical modelling in support of Water Management: a Hydroinformatics approach

- contributions of the candidate to Hydroinformatics -

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Motto:

> "*The lecturer pumps laboriously into sieves. The water may be wholesome, but it runs through. A mind must work to grow*."
>
> \- Inaugural address of Charles W. Eliot, Harvard president, 1869 -

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# (A) ABSTRACT

Present habilitation thesis aims at presenting the outcomes in terms of knowledge, understanding and research activities carried out by the candidate in the 16 years following the awarding of the PhD title. The PhD has been defended at "Politehnica" University of Timisoara, within the Faculty of Hydrotechnics, and confirmed by The Ministry of Education (Ministerul Invatamantului), on the basis of the Order no. 3428 from 17 March 1998. The thesis also aims to incorporate the achievements up to date, of more than 23 years, on delivering lectures, exercises and workshops in a university environment.

The background of the candidate is both in Civil Engineering (graduate of 1987) and Mathematics (graduate of 1994). Consequently the scientific, professional and educational activities performed through the years are in the new innovative field of Hydroinformatics that is combining the two backgrounds. Main achievements after the defence of the PhD in 1998, are presented in this habilitation thesis, however the involvement in the field can be tracked back as far as beginning of September 1990. It started at "Politehnica" University of Timisoara, at former Faculty of Hydrotechnics, where the field of modelling and analysis of numerical solution for equations describing physical phenomena started to be intensively looked at in 1990, as computers were more and more available. Faculty of Hydrotechnics, at that time, was challenged to start offering special programmes related to environment and non-structural engineering solutions to problems of flooding. This new perspectives in engineering created opportunities for young scientists to look into emergent fields of study that offered new insights into solutions to problems of aquatic environment. At the beginning of the year 2001, the candidate joined UNESCO-IHE as lecturer, continuing research and teaching career, with new challenges due to the international nature of the student audience and of the research questions needed to be addressed from the perspective of finding solutions to water related problems that would be applicable worldwide.

The subjects of research, after the PhD, consists on theoretical contributions within the field of Hydroinformatics and applications of the developed theories to problems of aquatic environment.

Theoretical contributions, can be summarized as follows:

- Developing flood modelling approaches for decision making during a flood event;
- Defining flood modelling approaches for reservoir driven river systems, as well as for complex network river systems;
- Defining new parameters for fazil ice in ice modells;
- Development of an improved methodology for flood vulnerability index taking into account potential sea level rise due to climate change;
- Developing adapted flood vulnerability indexes for coastal areas;
- Developing algorithms for extracting Xsection data from new types of data (Lidar, DEM, etc) and their use in improving definition of synthetic river Xsections;
- Development of approaches for designing reservoir operation curves, using multi objective optimization;

- Defining general frameworks for decision support systems;

Special applications of the theoretical contributions are:

- Flood inference model between Yellow River reservoir system and flooding of the area downstream of the reservoirs;
- Optimization of reservoir operation strategies; (Yellow River in China, Blue Nile in Sudan, etc);
- Flood vulnerability application to river and coastal areas in complex rivers and deltas of the world (e.g. Mekong, Niger delta, etc) ;
- Use of cloud and cluster computing for flood models;
- Ice flooding on Yellow River;
- Decision support systems for floods with pasive and active involvement of stakeholders;
- Development of educational programmes.

Research results and achievements are presented in detail in section(b-i) (Scientific, professional and academic achievements) based on 10 selected papers published by the candidate in the last five years. The research findings presented in the selected articles are reiterated herein. Section (b-i) of the habilitation thesis is structured in five parts. Section 1 ("Hydroinformatics) presents three of the main thrusts of the Hydroinformatics; mathematical modelling, information flow and information sharing (as decision support systems). The research work and contributions for each of these main thrusts are detailed in the following three sections (Section 2 to Section 4). Modelling, flow of information (as new technologies) and information sharing (as decision support systems) are shown for the particular topics of floods and reservoir operation.

As an academic I have also contributed to academic programs that inspired my teaching of others. Along with my involvement in education, in lecturing several topics (Computational hydraulics, River modelling, Decision support systems, Collaborative Engineering, etc), I have also been active in guiding MSc students, coordinating the specialization of Hydroinformatics (2005-2007), programme coordination of the Water Science and Engineering programme(2010-2011) and PhD supervision. Equally I have been involved in educational research projects varying from testing and implementation of educational paradigms and platforms (www.TENCompetence.org), to organizing educational networks (www.etnet21.net), as well as conferences sessions and workshops. Therefore in Section 5 ("Higher Education in Hydroinformatics") of this thesis the addition in developing educational programmes is presented, because such type of activity is an important part of the promotion and development of a research field.

Plans for future research and development are presented in section (B-ii). All future plans are related to the fields of research presented in part (B-i) of the habilitation thesis.

# (B) ACHIEVEMENTS AND DEVELOPMENT PLANS

## Articles constituting the habilitation thesis

The list of the ten selected published articles based on which the present habilitation thesis is written:

[1.]Castro-Gama, M.E., **Popescu, I.**, Li, S., Mynett, A., van Dam, A. (2014), Flood inference simulation using surrogate modelling for the Yellow River multiple reservoir system, Environmental Modelling and Software, 55, 250-265

[2.] Fu, C., **Popescu, I.**, Wang, C., Mynett, A.E., Zhang, F. (2014), Challenges in modelling river flow and ice regime on the Ningxia-Inner Mongolia reach of the Yellow River, China, Hydrology and Earth System Sciences, 18 (3), 1225-1237

[3.] Balica, S. F., **Popescu, I.**, Beevers, L., Wright, N., G., (2013), Parametric and physically based modelling techniques for flood risk and vulnerability assessment: a comparison; *Journal of Environmental Modelling & Software*, **41** (3), 84-92

[4.] Moya-Gomez, V, **Popescu, I**, Solomatine, D., L. Bociort, (2013), Cloud and cluster computing in uncertainty analysis of integrated flood models, *Journal of Hydroinformatics*, **15**(1), 55-69

[5.] Van, P. D. T., **Popescu, I.**, van Griensven, A., Solomatine, D. P., Trung, N. H., and Green, A., (2012), A study of the climate change impacts on fluvial flood propagation in the Vietnamese Mekong Delta, *Hydrol. Earth Syst. Sci*., 16 (12), 4637-4649

[6.] **Popescu, I**, Jonoski, A, Bhattacharya, B. (2012), Experiences from online and classroom education in Hydroinformatics, *Hydrology and Earth System Sciences*, **16**(11), 3935-3944

[7.] Gichamo Z., G., **Popescu, I**., Jonoski, A., Solomatine D.P. (2012) River Cross Section Extraction from ASTER Global DEM for Flood Modeling, *Journal of Environmental Modelling & Software*, **31**(5), 37-46

[8.] **Popescu, I.,** Jonoski, A., Bociort, L. (2012), Decision Support Systems for flood management in the Timis-Bega catchement, *J. of Environmental Engineering and Management*, **11**(11), 847-953

[9.] Hassaballah, K., Jonoski, A., **Popescu, I.**,Solomatine, D.P, (2012), Model-based optimisation of downstream impact during filling of a new reservoir: case study of Mandaya/Roseires reservoirs on the Blue Nile River, *Water Resources Management*, **26**(2), 273-293

[10.] Hartanto, I.M., Beevers, L., **Popescu, I.**, Wright, N.G., (2011), Application of a coastal modelling code in fluvial environments, *J. of Environmental Modelling and Software*, **26**(12), 1685-1695

Research projects within which the theory and applications presented in the thesis have been developed are:

- ProACC II - Post-graduate Research programme on Adaptation to Climate Change, with special focus on Mekong river basin; DUPC funded project (http://proacc.unesco-ihe.org/about-proacc); 2012-2014; Budget 800.000 €
- ProACC I - Post-Doctoral Research Programme on Adaptation to Climate Change (PRoACC) with Special Focus on the Mekong River Basin, DUPC funded project, (http://proacc.unesco-ihe.org/about-proacc); 2010-2012; Budget 500.000 €
- LENVIS - Localised environmental and health information services. Specific research on development of localised information services (water-related) for water quality on lakes and dissemination through web infrastructure accessible via mobile phone interfaces, EU FP7 funded project; 2008-2011; (www.lenvis.eu); Budget 320.000 €
- EnviroGRIDS - Building Capacity for a Black Sea Catchment Observation and Assessment System supporting Sustainable Development ; EU FP7 funded project (www.envirogrids.net); 2009-2013; Budget 350.000 €
- FloodSITE - Integrated flood risk analysis and management methodologies; EU FP7 funded project (www.floosite.net); 2004-2008; Budget 370.000 €
- DSS-Romania - DSS Flood for Romania: Feasibility study and market analysis of a Decision Support System; Partners for Water funded project; 2006-2007; Budget 120.000 €

Member in Doctoral Examination Committee related to the "Flood modelling for large river systems":

- PhD of L. Shengyang, Thesis: Optimisation of reservoir operation, for flood defence on the lower Yellow River. Delft University of Technology, December 2013;
- PhD of J. Duric, Thesis: Probabilistic design of dams taking into account associated vulnerabilities, Delft University of Technology, December 2014

Mentor in PhD Guidance related to "Flood modelling for large river systems" and "Decision Support Systems for flood management":

- A. Azab, Thesis: Development of a framework fro decision support system for Edko lake in Egypt by integrating GIS techniques and numerical models. (Defended in 2012 at TU Delft)
- A. Almoradie, Thesis: Network Distributed Support System for Collaborative Citizens' and Stakeholders Participation in Management of Water and Environmental Resources. (Defended in 2014 at TU Delft) - in co-supervision
- C. Wang, Thesis: Numerical Modelling of Ice Floods in the Ning-Meng reach of the Yellow River basin. (Scheduled defence 2015 at TU Delft)
- Z. Mousa, Thesis: Living with sea level rise on a subsiding delta: combining impact assessments to develop mitigation and adaptation options for the Niger delta. (Scheduled defence 2016 at TU Delft)

# (B-i) Scientific, professional and academic achievements

## 1. HYDROINFORMATICS

### 1.1. Water and ICT

Developments and population growth of the recent years caused the raising of pressures on the available freshwater resources. These pressures, along with the various complex issues related to environment brought increased relevance to the broad field of water resources management. The complexities of the current problems in water resources (different scales; different water resources functions) need to be considered simultaneously. This requires an approach that uses new sets of support systems and tools, which would improve the decision-making processes, making it better informed (Jonoski and Popescu, 2004).

Throughout time people have been developing and managing water resources in river basins around the world in order to satisfy their demands for water quantity and quality or to cope with extreme events (such as floods or droughts). Consequently there is a lot of knowledge about these issues, from the knowledge of local communities to the modern scientifically developed theories and procedures. As such there are clear demands for changes in the institutional frameworks in order to meet the demands for water resources management, however there is no sufficient direction as to how can this be achieved.

The position advanced in this thesis is that developments of ICT tools and systems are useful in helping these directions as much as they are necessary. The develpments of such systems in the water domain are coined as Hydroinformatics.

The concept of Hydroinformatics as a new and distinct academic discipline were conceived and implemented by Professor Michael B. Abbott (Abbott, 1991, 2001). In the last two decades, Hydroinformatics has been recognized internationally, attracted a successful series of biennial international conferences and has a peer reviewed journal. Broadly, Hydroinformatics can be defined as:

> "*the study of the flow of information and the generation of knowledge related to the dynamics of water in the real world, through the integration of information and communication technologies for data acquisition, modelling and decision support, and to the consequences for the aquatic environment and society and for the management of water based systems*" (Abbott, 1991).

It is important to mention the social context within which Hydroinformatics operates. Jonoski (2002) states: "Because of its reliance on physical science, Hydroinformatics has its strength, because of its employment of ICT it can become powerful, and because of its social awareness its applications provide value". As such it can be used to solve problems of aquatic environment and support decision makers.

In the past 30-40 years engineers, in general, have been sceptical about the value of modelling systems, they prefer to deal with the real world. However, as compared with the past, there was a clear trend towards greater reliance and use of observed and collected data. In general, few decades ago, though the collection of data had its own inherent problems, the trust in collected data was greater than in the models that utilise the collected data. However after all data is available (collected) there is still the need to be analysed, in order to learn from it new information. The process entails looking for patterns and anomalies in the data. Statistical analysis is used to determine particular correlations. As time passed, nowadays a much more trust is given to models because of the possibility to have the so called 'knowledge discovery' from data. As such Hydroinformatics is a path from data to decision making, through models (see Figure 1).

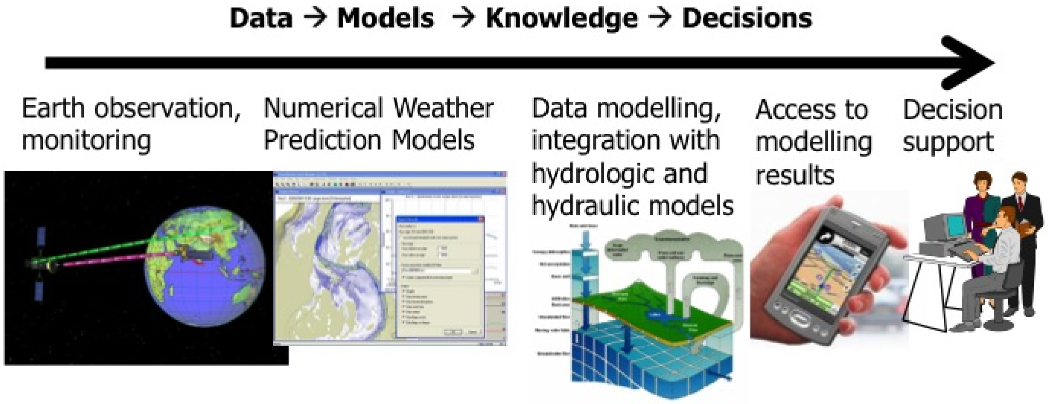


***Figure 1. Hydroinformatics: from data to decision making***

Models are means to an end therefore they are usually incorporated in the decision-making processes. A good example of the latest state in the development of Hydroinformatics is its role in conceiving, designing and implementing the bridge and tunnel connection between Denmark and Sweden. The latest modelling tools were used to predict currents in conjunction with remote sensing and monitoring. A particular communication system was devised to take into account and keep informed a number of active stakeholders in the construction process. Eco-systems were preserved and costs were reduced (Thorkilsen and Dynesen, 2001). Similar developments are taking place in other areas of hydrotechnics.

### 1.2. Modelling and flow of information

Many of the integrated systems that engineers are using have embedded complex interactions that are not immediately apparent. The straightforward approach of trying to understand the complexity is to build a (single, integrated) model of the complex interactions. "What our minds are unable to do because of the complexity and the calculations involved, we give to the computer" is what R. Price (2007) is mentioning. This is important when considering, in hydraulics for example, an unsteady state analysis instead of a steady state analysis.

Simulation modelling has therefore become an important tool in order to understand the behaviour of complex systems and to make predictions while taking into account boundary or internal conditions of the system itself.

The possibility to model and analyse complex water-based systems is possible due to the development of digital technologies: computers and ICT technologies. These have changed the way in which the behaviour of a system can be replicated, especially because of the capability of using graphics to analyse and present data; to track the development of models; and to visualise output. Along with these developments there are interesting consequences for the way in which we relate to the world around us, people's involvement with computers is a commitment to virtual reality, which is in contrast to the 'traditional' rational view (i.e clear separation between society and nature). People's knowledge is the capability with which the resources are managed, however, nowadays people increasingly see themselves as part of the system. All knowledge is situated in a given context and is itself a resource.

The fundamental element that distinguishes Hydroinformatics is the movement from representing knowledge in hydraulics and hydrology by symbols to signs. Symbols are defined to be in the minds of water engineers as descriptors of processes of the real world, while signs point towards these features and processes. The generic knowledge encapsulated in the modelling systems of today is available to a large number of people, not just to developers of systems. This way of using knowledge enables users to learn new knowledge depending on their ability to interpret and assimilate that knowledge. This type of knowledge communication is facilitated by the development of interfaces and supporting tools, as it can be seen that a lot of effort has been lately placed on modelling environments and interfaces rather than computational engines. Abbott (1992, 1993) highlights this view by referring to a model not just as "simplified representation of reality" or a "system for converting inputs into outputs" but "models serve as devices for communicating knowledge".

Modelling is the kernel of Hydroinformatics. The development of software packages for traditional computational hydraulics situations follows a number of well-defined steps (Dee, 1993):

- Represent the (generic) physical laws in terms of mathematical algorithms;
- Transform the resulting (conservation) equations in terms of a digital representation of the algorithms
- Solve the resulting difference equations within particular constraints and boundary conditions
- Design, code and test the numerical procedures
- Design, produce and test the resulting software system that can be linked to other systems such as databases, GIS, CAD, 2D and 3D graphics, and so on.

The resulting software tools are used with a particular set of data to instantiate a water-based system that it will generate a computational model of that particular system. The instantiation of the model is an important process and entails:

- Decision regarding the purpose of the model
- Review of existing available data and collection of other necessary data
- Build model infrastructure and select initial values for parameters
- Carry out consistency tests

- Calibrate parameters and validate the model

The user needs to identify testing scenarios, and then select a preferred scenario to carry out sensitivity tests.

An important remark needs to be mentioned here, models are constructed by conceptualizing the real world system into structural and process objects. Conceptualization is done by developer, from his/her own perspective/perception, and with focus for the class of problems that the software package is supposed to address. However the user of the software might not have the same point of view as the developer. Consequently the user may apply the software package outside the limits for which it was designed, because he/she is the one who will structure his/her model, select data to be used, decide on how to calibrate the model, how to interpret the results, etc. The last level in using a model is the decision maker, who is the third person, more remote from the modelling process, but concerned with what the model produces in terms of data that will assist in the decision making process.

### 1.3. Decision Support Systems and Stakeholder participation

As mentioned in the previous paragraphs Hydronformatics as a field was established during the last decades, originating from the narrower field of computational hydraulics (Abbott 1991, 1999). Initially established as the filed of study of numerical modeling and information flows related to aquatic systems, it has increasingly transformed its focus from developments concerned with improving the numerical modeling tools in their computational speed and accuracy, into developments facilitating wide use of modelling systems by professionals in water areas. A lot of effort has been invested on user interfaces, new types of graphical outputs, parameter controls and structured date-base facilities. As such, Hydroinformatics contributed to the development of generic modeling systems of the so-called fourth generation which enabled the increase of potential users of Hydroinformatics tools from the rather restricted group of numerical modelers to large number of specialists in hydraulics, hydrology and water resources, who became distinct group of model users, as compared to model developers.

Hydroinformatics used the technological developments in instrumentation, real-time data transmissions, data assimilation, remote sensing and GIS interfaces for the purpose of development, improved modeling tools and services. In the same time, taking advantage of ICT developments models became embedded into decision support systems. Traditional understanding of a Decision Support Systems (DSS) is that it is developed by water resources experts for water resources experts. This view is changing, DSSs being viewed as potential platforms for knowledge exchange among experts, involved stakeholders and the decision makers (Ako et al. 2010). As such, in the last 10 years Hydroinformatics has been transformed from a purely technical, into socio-technical discipline. The theoretical background for this transformation lies in the realization that in all water- and environment- related decision making processes the social and the technical are interwoven to such an extent that they need to be approached simultaneously. The existing Hydroinformatics tools and systems can support the emerging paradigms for water management such as IRBM (Jonoski and Popescu, 2004).

IRBM has several challenges that are addressed by Hydroinformatics through analysis, design and development of new systems and environments that enable knowledge sharing among large number (many thousands) of stakeholders, who are coming from diverse backgrounds and are involved in water management activities.

The platforms for development and deployment of these kinds of systems are the electronic networks such as the Internet. These types of platforms are facilitating knowledge circulation and knowledge sharing, attempting to stimulate the emergent processes of public participation and involvement in decision making (Almoradie et al, 2014a,b; Popescu et al, 2012). Internet based environments are developed to act as virtual platforms for gathering knowledge and data about a particular water related problem, then enable all interested parties to analyze and formulate judgments about possible courses of action. Based on the defined actions the platforms eventually facilitate negotiation and collaboration activities among all participating parties (Jonoski, 2002). The systems described above are the Network Distributed Decision Support Systems (NDDSS), which are characterized by three functional components: the fact engine component, the judgment engine component and the platform for collaboration.

The fact engine component is the kernel of a NDDSS. The kernel comprises different models describing the physical system under analysis. On demand the models are instantiated in order to forecast and describe the responses of the physical system under consideration to proposed interventions. These may vary from traditional distributed hydraulic, hydrological or ecological models (which may operate at different temporal and spatial scales), to models describing the socio-economic situation and in particular the water resources utilization at basin–wide level.

The judgment engine is the component available on the Internet. This component allows the participant (stakeholders) to formulate their own judgments about the proposed solutions, according to their own interests. This component poses a lot of challenges in its design and development, as it requires very diverse customization and personalization of the content for the diverse user needs.

The platform for collaboration and negotiation brings together all participants/stakeholders, with the aim to obtain a common agreed opinion on the course of action. The methods of aggregation of judgment data, as well as their incorporation in automated negotiation or collaboration are not easy to be implemented and selected.

These Hydroinformatics systems initially develop as tools for raising awareness within institutions, of stakeholders and the public. Initially they have an educational character. Depending on their successful development and acceptance, later on they may develop into full-fledged systems for, impact assessment, direct participation and decision support.

# 2. APPROACHES TO FLOOD MODELLING

*"The possible ranks higher than the actual"*

-Heidegger, 1927-

## 2.1. Scientific and technical contributions to aspects of flood modelling

The main aim of this chapter is to present the added value of the approach taken by the candidate in modelling river systems. Presented theory and applications are based on articles [1], [2],[3], [4], [5], [7], and [10], of the habilitation thesis (see page 3 of this thesis).

The final goal of modelling floods is to support decision makers in managing them. Floods are inevitable hazards. In order to serve society and environment effectively, decision makers need to understand the vulnerabilities and risks associated with floods, i.e. understand the main processes producing floods (rainfall patterns and flood propagation) and seek for best strategies to reduce their impact. Flood modelling eventually produces flood extent maps that lead to the evaluation of risks and help reduce the impact of floods.

Flood modelling presented herein addresses the following aspects:

- checking the applicability of a numerical solution of the equations of flow by benchmarking a coastal code for the use of river flow (Hartanto et al, 2011); (selected publication [10])
- proposing an new approach in modelling floods during flood events, (Castro Gama et al., 2014a, 2014b; Van et al, 2012); (selected publication [1] and [5])
- modelling ice-triggered floods (Fu et al, 2014); (selected publication [2])
- evaluating vulnerability due to floods, and improving this assessment by comparing parametric and physically based methods, concluding when parametric methods should be used by decision makers (Balica et al, 2013); (selected publication [3])

In parallel with modelling of floods, several other issues emerged during research; such as the complexity of the problem to be solved, which can not always be handled by one PC; or needs for data that is not yet available. Computer power capacity was addressed by studying solution algorithms for cloud and cluster computing (Moya Quiroga Gomez et al,2013; (selected publication [4])), while missing sets of data were determined from DEM, or remote sensing (Gichamo et al, 2012; (selected publication [7])). These kinds of problems are part of the modelling efforts and were addressed as integral part of the research.

Apart from the published papers in peer reviewed journals, research results were disseminated to conferences, such as:

- 11th International Conference on Hydroinformatics, 17-22 August, 2014, HIC 2014, New York, USA

- SimHydro 2014:Modelling of rapid transitory flows, 11-13 June 2014, Sophia Antipolis, France
- Geospatial World Forum, 05-09 May, 2014, Geneva, Switzerland
- 35th International IAHR Congress, 4-11 September, 2013, Chengdu, China
- Seminar on Operational Research for Development, Sustainability and Local Economies, 27-30 January 2013, Champoluc, Italy
- 5th International Yellow River forum, 24-28 September, 2012, Zhengzhou, China
- 10th International Conference on Hydroinformatics, 14-18-July, 2012, HIC 2012, Hamburg, Germany
- BALWOIS, International Conference on water, climate and environment, 28 May – 2 June 2012, Ohrid, Republic of Macedonia
- 34th Interrnational IAHR Congress, June,2011, Brisbane,Australia
- 9th Interrnational Conference on Hydroinformatics 2010 Tianjin, China

### 2.2. Modelling floods

Mathematical models for river flooding are based on equations that describe the physics of the flow phenomena by a combined set of continuity and momentum equations, also known as shallow water equations. These are also known as de Saint Venant equations (Popescu, 2014). They do not have analytical solutions, hence are solved numerically.

In one dimension these two equations are:

- Momentum

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)+gA(\cos\theta\frac{\partial y}{\partial x}-s_0+s_f)=0 \tag{eq. 1}$$

- Continuity

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \tag{eq. 2}$$

(7.2)

where:

| | |
|---|---|
| Q | discharge |
| A | flow area |
| y | depth |
| g | acceleration due to gravity |
| so | bed gradient |
| sf | friction slope |
| t | time |
| x | distance |
| θ | angle made by conduit with horizontal |

Alternatively, $\cos\theta \frac{\partial y}{\partial x} - s_0$ can be written as $\frac{\partial h}{\partial x}$, where h is the stage or water level above datum. The system of equations (1) and (2) require four boundary conditions. If the flow is subcritical (Froude number being less than unity), the boundary conditions include two initial conditions (on h/y/A and Q), one upstream condition (preferably Q), and one downstream condition (either on h or a rating curve as a function of h and Q). If the flow is supercritical (Froude number greater than unity) then no downstream boundary condition is needed two additional conditions must be given at the upstream boundary. The two equations have corresponding versions for 2D. The main aspects of solving 1D equations are presented along with the special issues that needs to be addressed in case that 2D form of the equations is used.

Saint Venant equations are most often solved using finite differences, though other methods such as the finite volume and finite element (especially for 2D) are also used lately.

Implicit iterative methods, like the four point Priessman scheme (Priessman 1962) or the 6-point Abbott-Ionescu scheme (Abbott and Ionescu 1967) are used to solve the Saint Venant equations. An implicit rather than explicit form of solution is preferred for because of stability reasons. The 4-point scheme has the advantage that the space step can be varied arbitrarily (though care is needed to preserve accuracy). The 6 point staggered scheme has the advantage that it fits in better with 2D modelling. In general the implicit schemes have the disadvantage that they create some numerical dispersion due to the choice of weighting parameter for the space derivative. Nowadays such schemes allow for variable time steps to ensure that convergence of the iterative scheme at a given time increment is consistent from time step to time step.

As good and accurate as the implicit scheme is, it has few difficulties when it is implemented in a code. One difficulty is that for small flow depths the solution may become unstable. In that case the modeler needs to give more weight to the conveyance upstream. Another difficulty is the transition between sub- and super-critical flow, when the modeler needs to drop the convection of inertia term as the actual Froude number approaches unity. This approach avoids having to change the solution algorithm (i.e. switching the boundary condition from downstream to upstream with all the consequences for the matrix inversion) though the nature of the approximation can be significant in some cases (Abbott and Ionescu, 1967)

The implicit scheme has also as a main disadvantage that the time step of computation is the same over the whole domain of computation for which the matrix in the numerical solution is inverted. This means that the implicit techniques are in general sub-optimal, i.e. the smaller time step is only needed from mathematical point of view in order to satisfy convergence. In general this is not a problem for most practical problems, because computing speed are met by the currently available hardware. However, as the problems are becoming more and more complex, the scope of the computations increases, as it is for example the case of larger and larger river networks, and the requirement to simulate longer time series of rainfall events, hence there is the possibility that more efficient computing schemes could have value and needs to be investigated.

Though 1D models are important tools for modelling floods, they do have limitations when the phenomena is of 2D nature, especially when where there is a difference between the water level in the channel and the flood plain. One can still make use of the 1D model to simulate the river network and the flood plains separately from the channel. Alternatively a fully 2D model can be used.

There are many software models available for use for flood modelling; freeware, openware or commercial, such as SOBEK (Deltares) that is 1D, 2D or linked 1D2D; MikeFLOOD (DHI) option which is also 1D, 2D and 1D2D; and HEC-RAS of USACE that is 1D. TELEMAC of Electricité de France is a general-purpose 2D model that uses finite elements, as opposed to previous ones that are using finite differences. The finite element version has the advantage that can represent easily complex boundaries, whereas the finite difference models have more difficulty.

### 2.3. Benchmarking solutions

Historically coastal models evolved differently than river software because of different constraints, representing different hydraulic behaviour characteristics. Wind and tidal forces, have high importance in coastal environment (de Vriend, 1991), while they are negligible in river environments. On the other hand longitudinal slope and initial water level are very important in river modelling but they are not considered important in coastal modelling. However, the equations of the hydraulics are the same and so are the solution methods, hence coastal software could be applied for river problems. The application of a code outside its original domain needs to be verified and tested comprehensively before a wider application is attempted. One such software tool is the freeware XBeach.

The applicability of XBeach for river problems has been tested and reported in Hartanto et al (2011). XBeach has a finite volume solution of the shallow water equations that uses a rectilinear, non-equidistant, staggered grid to calculate bed level, water level, water depth and sediment concentration at cell centres, while velocities and sediment transport are calculated at the cell border (Roelvink, et al., 2009). A number of test cases were designed to mimic particular problems occurring during river flooding, so that proper benchmarking could be done. Comparisons were done with respect to the semi-analytical calculations, other modelling codes and laboratory experimental results, with the aim to investigate if an open source coastal modelling approach is applicable as well for river problems.

XBeach has been used as a stand-alone model for small scale coastal applications. It has many capabilities such as: depth-averaged shallow water equations for both subcritical and supercritical flow, time-varying wave action balance, wave amplitude and the depth-averaged advection-diffusion equations (Hartanto et al. 2011). The tests and investigation of its application for river floods solely focused on the depth-averaged shallow water equations solver.

In Hartanto et al (2011) XBeach is tested against a number of cases; firstly it is compared with results from semi-analytical solutions; secondly it is tested against the results from different fluvial codes; and the last comparison is against the experimental case defined by Soarez-Frazao and Zech (2008). Table 1 provides an overview of the performed tests.

*Table 1: Summary of tests performed for XBeach benchmarking*

| Test no. | Name | Description |
|---|---|---|
| **1a,1b**<br>**1c, 1d** | Semi-analytical | Comparison of the model runs with semianalytical solutions.<br>M1, M2 curves (mild slope);<br>S2, S3 curves (steep slope) |
| **2a** | Idealised | Flow in a straight idealised channel |
| **2b** | | Flow in an embanked straight idealised channel |
| **2c** | | Flow in a meandering idealised channel |
| **3** | EA case 1 | Wetting and drying of a disconnected body |
| **4** | EA case 2 | Low momentum flow |
| **5** | EA case 3 | Momentum conservation |
| **6** | EA case 4 | Flood propagation over a plain |
| **7** | EA case 5 | Dam break over a valley |
| **8a** | EA case 6 | IMPACT: Hydraulic jump and wake zone (laboratory scale) |
| **8b** | | IMPACT: Hydraulic jump and wake zone (realistic scale) |
| **9** | Experimental | Dam break through an urban area |

***Tests cases which can be solved using semi-analytical methods (direct-step methods) are simple ones such as gradually varied flow and backwater effects, marked as Test 1a-d in***

Table 1. XBeach code was tested to model mild slope types (M1 and M2) and steep slope types (S2 and S3) (Chow 1959; Cunge et al. 1980).The mild slope case (1a and 1b) is a fragment of a very wide river, 100 m, and frictionless walls. A gentle slope of 0.001 is created in the model bathymetry over a 10 km distance. Roughness is modeled using a Chézy coefficient of C=50. For the M1 case (Test 1a), a constant discharge of 2 m3/s/m is imposed as a upstream boundary and a constant 5 m water depth as downstream boundary condition. These conditions generate a M1 flow curve which varies from a water level of 1.17 m to 5 m. The M2 flow curve (Test 1b) was set up using a 5 m3/s/m discharge as upstream boundary condition and 1.37 m critical water depth as the downstream boundary condition, which generated a normal water depth of 2.15 m at the upstream boundary. Steep slopes were modelled by cases 1c and 1d (S2 and S3 curve types) using a 5 km long channel with various bed slopes (i.e. 0.03, 0.01 and 0.001). The upstream boundary condition is set as a constant discharge of 5 m3/s/m, and the downstream boundary condition as 2.15 m water level. Comparison between semi-analytical method using the direct step and XBeach performance for the 4 test cases are shown in figure Figure 2.

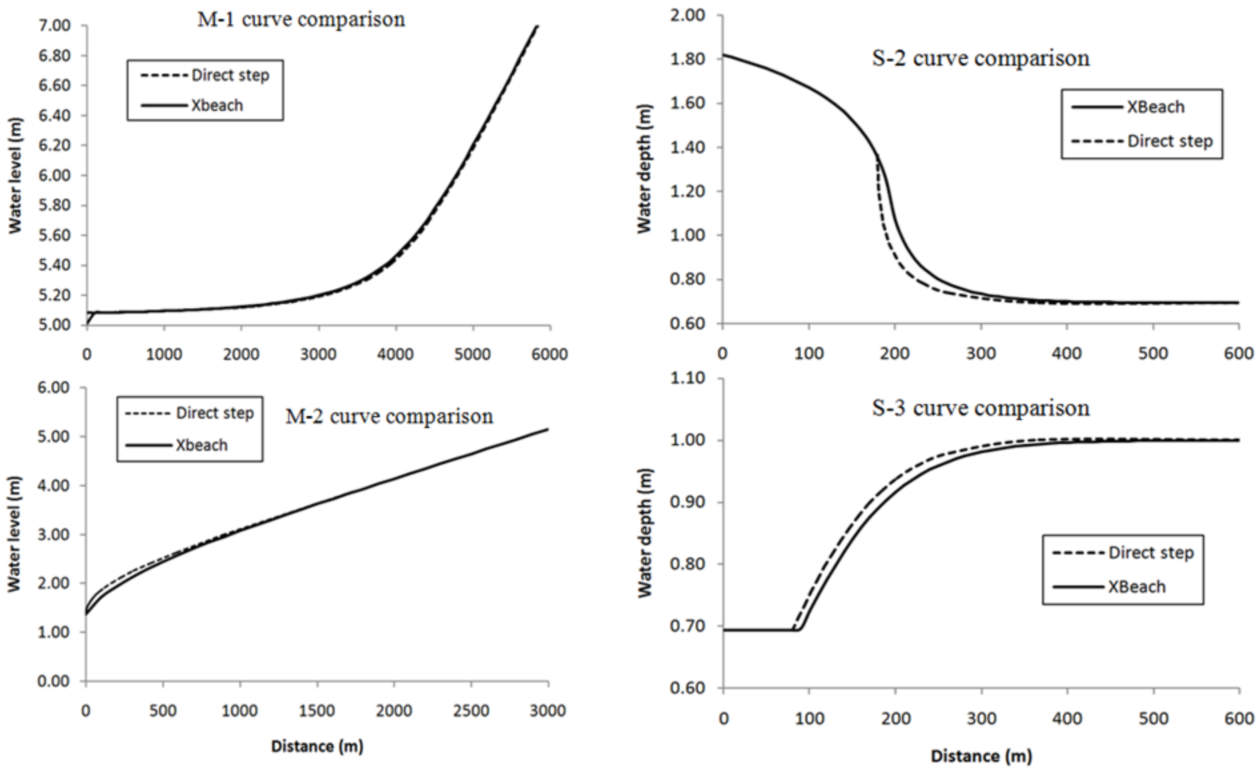


***Figure 2. Modelled and analytical solution of M1, M2, S2, and S3 types of flow (Test 1a, 1b, 1c, 1d)***

For the case of M1 and M2 curves a difference is observed at the boundary while for the S2 and S3 cases, the difference is along the profiles until the solution reaches normal depth. These differences are notices to appear at the transition from mild to a steep slope (M2, S2), while smaller values of differences are noticed at the transition from steep to mild slope (M1, S3). This is due to the transition from subcritical to supercritical flow and shows the ability of the code to capture shocks.

The other theoretical case used for testing were the cases of an idealised channel that is straight, embanked or meandering. For the case of a straight trapezoidal channel floodplains were defined on both sides, which has a uniform value of Chézy roughness coefficient for both. The test investigates the two dimensional flow calculations of XBeach. The cases represented a 5 km long straight channel, with a slope of 0.001 and a cross-section of 30 m width, 2 m deep and 30 m floodplain on each side of the river. The upstream boundary condition was a varying discharge (50 to 700 m3/s) with the peak discharge occurring after 43.3 minutes, such that overflow takes place at the peak of the hydrograph. In Case 2b dikes are constructed on both banks of the channel. Meandering channels are having complex hydraulic behaviours, hence a perfect sinusoidal meander river that has no slope was modelled in Test 2c, in order to identify how does water flow from the main channel to floodplain and vice versa.

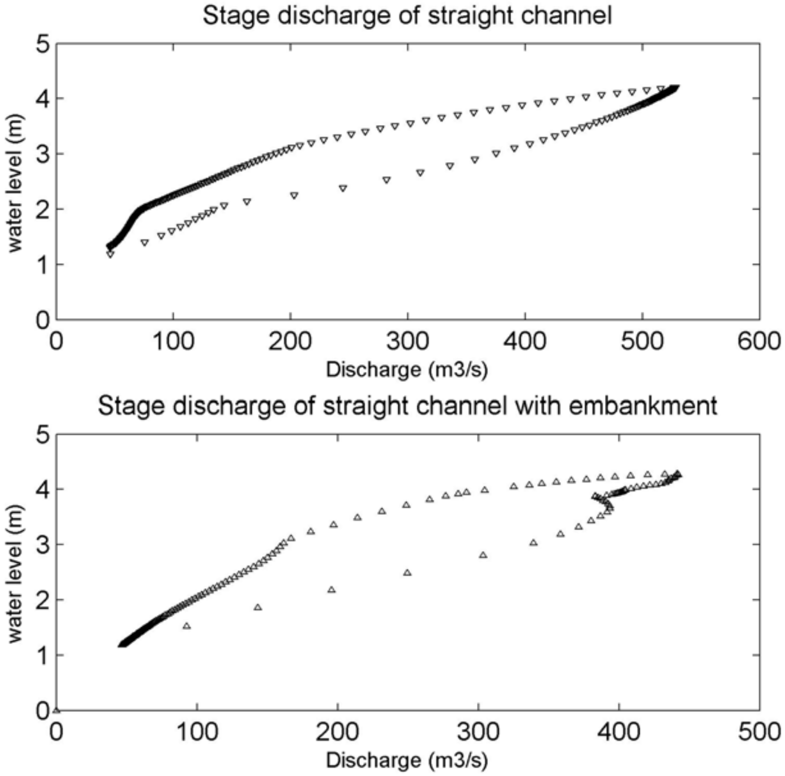


***Figure 3. Stage-discharge relationships for tests 2a and 2b in straight channel***

Figure 3 shows that XBeach models reasonably well the hydraulic behaviour of flow on the floodplain. The hysteresis effects, of the rating curves shows flows out of bank. In Case 2b when the river is embanked, the transition can be clearly observed in the hysteresis as the water overtops the levees and accommodates the available volume below.

Figure 4 shows the velocity of flow in a meandering channel, distinguishing clearly a pattern of flow with two characteristics; one flow in the channel and one over floodplain (Muto et al. 1999). The flood wave propagation can be observed. Tests 2a, 2b and 2c demonstrate that celerity of propagation of a flood wave is well represented in the numerical solution scheme.

In 2009, the Environment Agency of England and Wales carried out a benchmarking study for different 2D software. The benchmarking was undertaken to ensure that codes were appropriate for assessing flood risk (Heriot-Watt 2009). The final report of this study is available to the public (Neelz and Pender, 2010). Six out of eight EA2D tests were chosen to test the ability of XBeach in fluvial modelling situations, as described in Table 1. All details of the test cases are presented in Hartanto et al (2011). Herein results obtained in Test case 3(EAcase1); Test case 4(EAcase2) and 5(EAcase3) are presented.

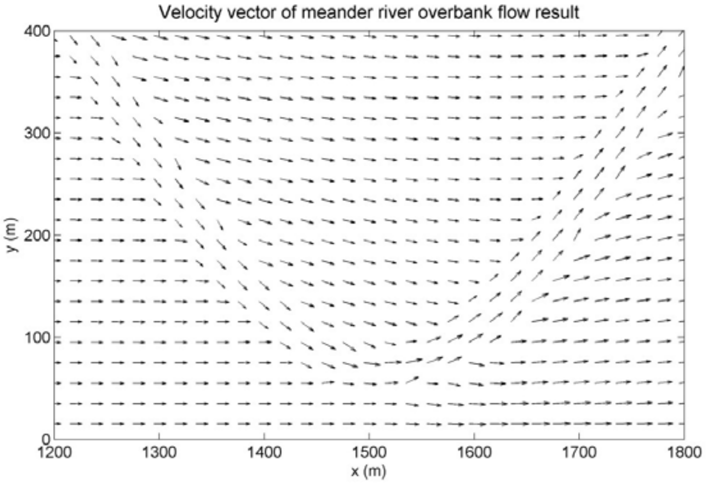


*Figure 4. Flow pattern in meandering channel*

Test case 3 investigates if XBeach can handle wetting and drying of a disconnected waterbody. The modelled domain is 100m x 700 m with a large bump in the middle of the bathymetry. The bump has the role of disconnecting the water bodies. Bump has an elevation of 10.25 m. The imposed boundary conditions are varying water levels on the left side of the model, between 9.70 m and 10.35 m at time t= 1 h to 11 h followed by decrease in water levels back to the value of 9.7m). The water level and velocity at two locations are compared (see Figure 5) for XBeach and two other codes that are recognized to perform well in such cases.

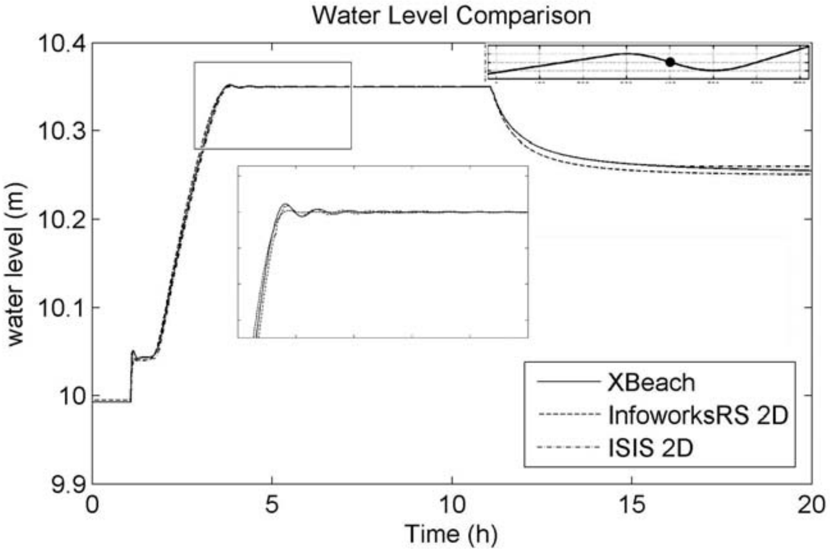


*Figure 5. wetting and drying of a disconnected body (results recorded at specified point)*

Instability is observed immediately after reaching maximum depth, where each compared code gives slightly different results. Differences are also occurring at initial and final water depths, however, the results of Test 3 show good comparison to other river software.

Test case 4 determines inundation extent over a sloped 2D domain, which has 16 depressions in order to retain a portion of the low momentum flows that enters in the upper corner of the domain. Moreover the wetting and drying capability over a floodplain is looked at from a different point of view than Test case 3, inundation extent is analysed at the end of simulation rather than at the moment when water depth is maximum. The model is defined as a square of 2000 m x 2000 m with 16 depression each of 0.5 depth. The overall slope in the north direction is 1:1500 and 1:3000 towards the east. As such there is a ~2 m drop of elevation from top left corner to bottom right corner. The boundary conditions are defined as flow at the top left side of the domain with a discharge of 20 m$^3$/s, for a period of 75 minutes starting at time t=10 minute; and closed boundaries everywhere else over the domain. The flow on the open boundary is defined over a length of 100 m. Results from three codes are presented in Figure 6

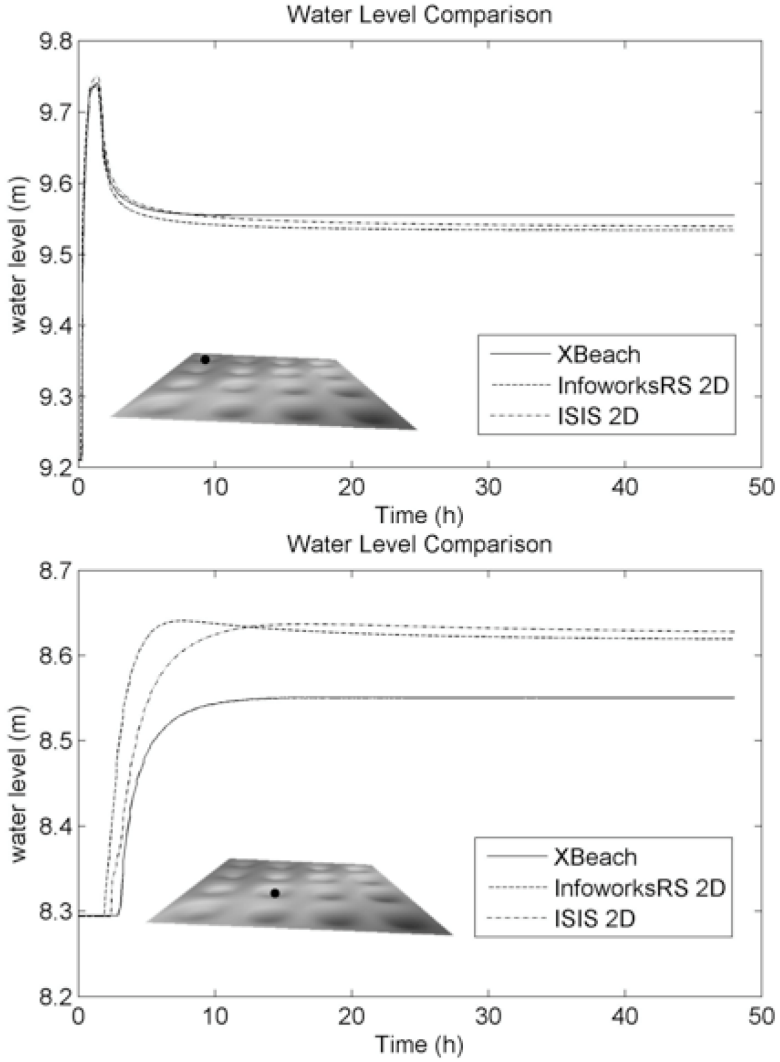


***Figure 6. Test case 4: Low momentum flow results***

Significant differences can be observed between XBeach and the other two compared codes. XBeach sets a threshold value for the wet/dry phenomenon. There is a great number of dry depressions in the model, hence many threshold values need to be fulfilled. The closer to the upstream boundary, where the inflow is, the better is the result in XBeach, as compared with other codes, however XBeach still shows poor performance in this test, because of the high threshold value of the wetting and drying which means a 2 cm of water retained in the domain, in places where there should be dry conditions. This condition is imposed by the mathematical formulation of the problem, because Manning coefficient is located in the denominator in Manning's equation of depth (d). If Chézy equation is used instead the problem can be avoided. A remark should be done here: XBeach has been changed by us during the experiments, in order to accommodate Manning equation because all EA tests requirements, which imposed the Manning model for representation of roughness as it is usually used for river codes by Environment Agency. This issue can be avoided if real rivers are modelled because the 2 cm threshold does not have significant influence at larger scales than the ones used for testing.

Test case 5 looks at momentum flow over a barrier. This capability is important in sewer or pluvial flood modelling in urban areas. The domain has an initial steep slope and a bump to disconnect the flow from a depression. The role of the initial slope is to accelerate the inflow. The boundary condition is a discharge of 65.5 m3/s for 10 seconds starting at time t=5 s with a peak at time t=15. The model is 300 m long with a bump of 25 cm height. The volume of the inflow is defined as such that it is enough to fill the depression. Physically it is expected that water will fill the depression then overtop the bump due to momentum and settle in the second depression. Such a test is designed to determine if codes incorporate all the terms in momentum equations or not.

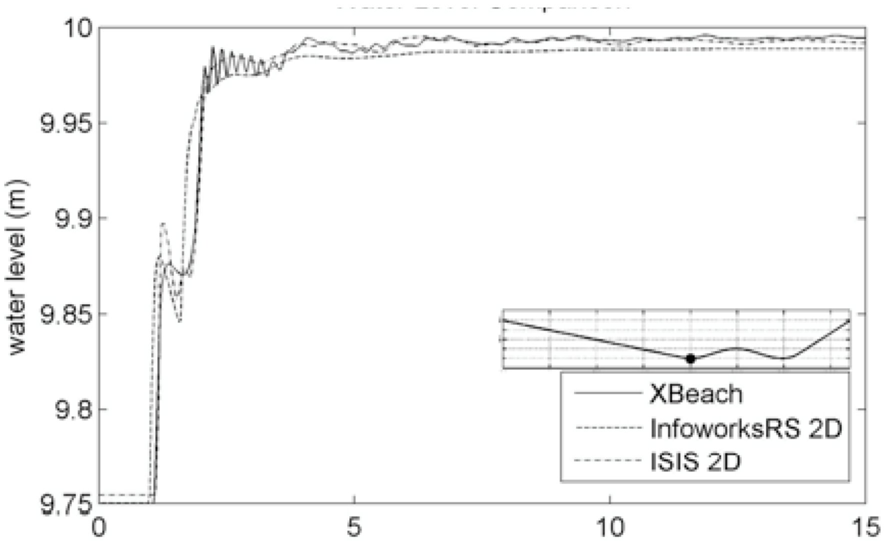


***Figure 7. Water level for momentum conservation test (measurements before the bump)***

Figure 7 and Figure 8 show that in case of testing momentum conservation there are minor differences between codes. Instability is observed however, in the XBeach solution, close to maximum depth. Each code gives different values for the water level at the end of simulation time, although all water levels are close to the 10 m, which is the expected value. These differences are very small and tests shows that momentum conservation is well represented by the solution algorithm.

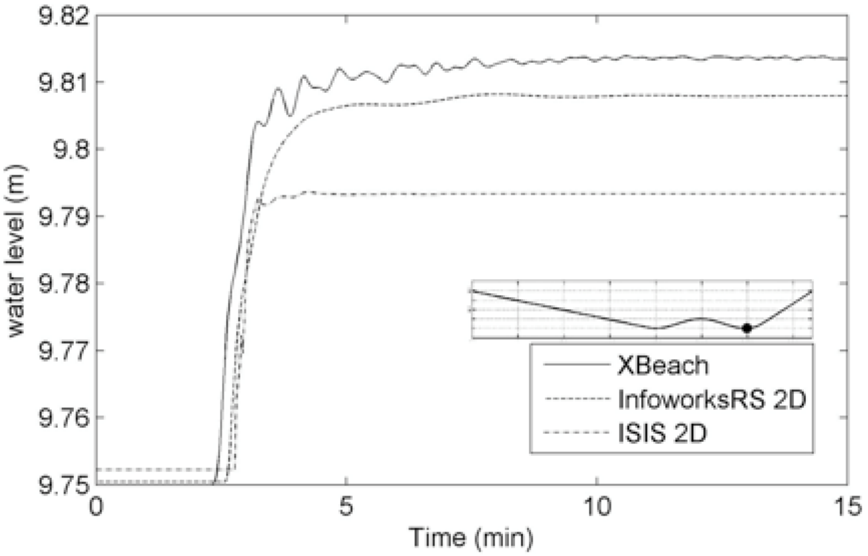


***Figure 8. Water level for momentum conservation test (measurements before the bump)***

The last results presented here are the ones of Test case 9, which compares the capability of XBeach to predict what is obtained by the experimental test of Sandra Soares-Frazao and Zech (2008). The experimental physical model is the one of an urban area with 25 buildings blocks flooded by a dam break simulation of a reservoir (Soarez-Frazao and Zech, 2008).

In case of Test 9, analysis of the results from Figure 9 show that there are large differences between XBeach and measured laboratory results, especially at the street level. If the computational mesh is refined better results are obtained, however the structured rectangular grid of XBeach would require a large number of cells to represent the system in detail.

In conclusion XBeach proves to work well for river modelling scenarios, when compared to other similar codes. It has the advantage to be an open source code, to which users may modify routines to adapt it to specific river situations. This adds flexibility in usage. However, some deficiencies are still present, such as the way boundary conditions are represented, which are adequate for coastal environments, but not always applicable for river modelling purposes. There are however still several cases, which were not tested in this study for which XBeach needs to be further checked, such as spillways, or chute blocks, etc,.

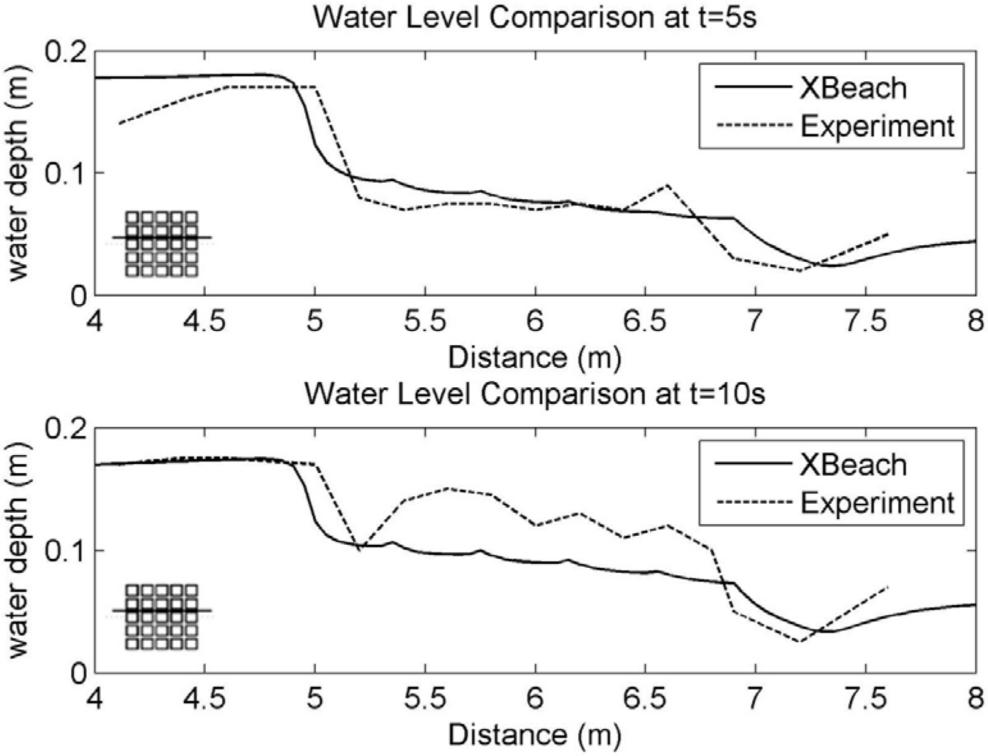


***Figure 9. Test 9: Comparisons XBeach-laboratory experiments***

In conclusion it is important to reemphasize that the main objective of the benchmarking study was to see the capability of the XBeach code to solve floods in rivers. The code solves the Shallow Water equations under assumptions that restrict the application of it for flow problems with a steep bed slope (in particular problems of supercritical flow). Consequently testing spillways with XBeach implies changes to be implemented in the code. Pipe flow was also not tested in this study.

XBeach uses a structured staggered grid, which is not too easy to be used for complex river geometries. An unstructured grid option is recommended to be further developed and tested, which would could also solve the necessity of using very fine grids.

Finally, the conclusion of this research opens up the possibility to use XBeach for both hydraulic and potentially morphological problems in river and coastal areas and hence in the transition part, such as it is the case of estuaries and deltas.

### 2.4. Surrogate modelling

This section is detailing the theoretical contribution of the candidate to the methodology of flood modelling. This research has been developed in the last 5 years. The theory is presented in detail in Castro Gama et al (2014b), and the application of the proposed methodology to the case of Yellow river in China is presented in Castro Gama et al (2014a) (selected paper [1]).

### 2.4.1. *Description of the proposed methodology*

Management of a river imposes different tasks at all institutional levels in every part of the world. One of the most challenging situation is the management of floods in a large river system, where flow is mainly regulated through man-made reservoirs. Majority of the big rivers in the world have reservoirs build on it, hence the management strategy needs to be adapted based on the operation rules. As presented in Castro Gama et al (2014b), the main approaches so far for replicating river behaviour during flood events is to use complex simulation models. An alternative to an approach based on an optimization model is the use of an inference simulation model between two sets of variables; a set of explanatory variables, which refers to the relation between the operation of reservoirs and the input hydrographs into the reservoirs; and a set of descriptive variables that refers to the resulting flooding hydrograph at a hydrological station located downstream of the reservoir network. The methodology can be applied in practice for any reservoir driven system.

The method shows that in flood control situations, practitioners can make use of a particular model to get quick responses to the operation alternatives that they are proposing. The method proposes the use of a simplified simulation model of the actual reservoir operation to determine a multiple linear regression model between the set of explanatory and descriptive variables. In practice the set of explanatory variables is very large and not all may be relevant for the study. Hence each selection of an explanatory variable should be based on a correlation analysis with respect to the available original set. Application of the method to a specific case study Castro Gama et al (2014a) shows that the reduction of the number of variables does not decrease the model fitness and robustness.

Variables defining the above defined modelling process are:

- parametric definitions of the reservoirs (e.g. maximum reservoir capacity, minimum reservoir capacity, shape of hydrograph);
- variables related to hydrographs flooding (e.g. peak discharge of hydrograph);
- variables related to flooding (maximum flooded area, maximum flooding volume, etc).

The concept of the inference model (see Figure 10) is to perform a combined correlation analysis and multivariate regression between variables of a hydrograph obtained downstream of a system of reservoirs and the flooding area further downstream. Inference is obtained by performing multivariate regressions between parameters and variables. An input hydrograph to a reservoir is classified by a "type", depending on its shape and return period. Selection refers to the parameters that shows higher correlation based on a hypothesis test.

Inference studies on modeling flood (Hunter et al., 2005; Merwade et al., 2008) focused on model calibration for observed extreme flood events. Approaches used differ from study to study however the main approach was to vary sets of information and sources of data from the topographic, hydraulic and hydrological point of view, while at the same time try to reduce the sources of uncertainty. Design or recorded hydrographs are used to ensure that there is no uncertainty in the input. So far the principal calibrated parameters were Manning coefficients. The results obtained are usually presented as a flood map, in two ways deterministic or probabilistic maps. The latter is seen as a measure of uncertainty as well. A critical discussion of this approaches is given by Schumann, G. et al. (2009), however such review is not addressing reservoir driven systems.

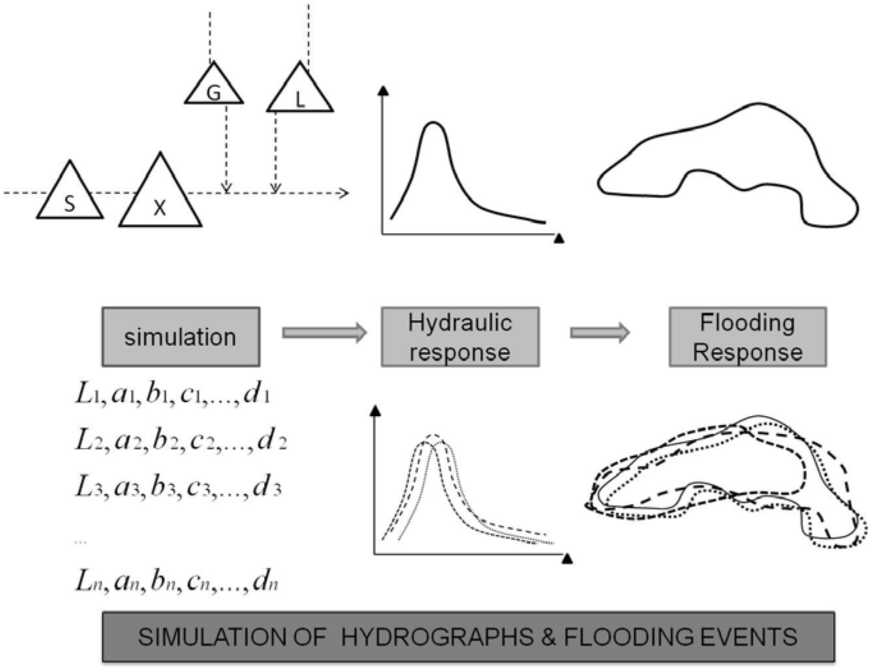


***Figure 10. Schematic representation of the inference process***

The proposed modeling approach comprises of five steps:

- the development of the inference model, which is a Monte Carlo sampling of independent variables such as input hydrographs and reservoir operational thresholds;
- releases coming from the operation of the reservoirs should be routed to the downstream hydrological station using a physically based model approach;
- resulting hydrograph at the downstream point of the reservoirs is used to estimate several descriptive dependent variables;
- a correlation between the explanatory variables and hydrograph variables is seeked, in order to obtain the set of the most relevant explanatory variables;
- a set of multivariate regression models is built and the selection of the best models, for each hydrograph variable, is based on the ANOVA method.

In case that there is no data available on the studied reservoirs of a river system, in order to start the first step of the inference model, a pre-step is necessary. This step generates input in a reservoir. A simple reservoir operation model can be built. Such a model generates hydrographs resulting from the operation of the considered system of reservoirs. This is done in order to address the curse of dimensionality (Yeh, 1985; Wurbs, 1993, Labadie, 2004) for reservoir operations; as well as to overcome possible lack of data in a large regression model, when a subset of parameters can effectively reduce the requirements without reducing the accuracy of the inference model. The variables taken into account in the reservoir model correspond to the maximum and initial water level in the reservoirs. These variables are defined as percentages from a full reservoir. The assumption is made that minimum required environmental discharges are taken into account in the operation rule. There is also an imposed constraint in the operation, the limit of the reservoir capacity, during seasonal operation.

### 2.4.2. *Mathematical formulation*

In order to carry out the above, described methodology the exact mathematical formulation is detailed here.

Given a number of *n* reservoirs on a river system that has a flooding area downstream of the reservoirs, an inference model between the operation of the reservoirs and the flooding in the downstream can be defined. In between the reservoirs and the flooding area, a hydrological station is considered (be it real or virtual). The reservoir operation will give a set of hydrographs at the downstream hydrological station. A number of parameters should be selected as the main subset that is related to the understanding of flooding events in a river. The hydrographs at the downstream hydrological station provide input for a flooding model which covers the downstream part of the river. Rules of operation of reservoirs are based on a basic reservoir level pool method (Chow et al., 1988).

Two constraints are used in modelling the reservoir operation; the minimum reservoir level (INI%) that ensures a minimum flow and/or environmental flow downstream of the reservoir; and the maximum reservoir levels (MAX%) that incorporates the flood management operation rules. The main outcome is that given the objective of flood management, the minimum reservoir level is not a determinant factor in the operation. It is advisable that during the simulations reservoirs are initialized from levels at least 1% lower than the maximum water level in the reservoir, so that at least a small amount of filling should be performed initially in the reservoir model. Climatic variability should be a considered factor and different types of hydrographs should be considered as possible input for the reservoir system.

The explanatory variables selected to represent a hydrograph are four: base flow ($Q_b$), peak flow ($Q_p$), time to peak flow ($T_p$), and the skewness of the hydrograph ($S_k$). These four selected variables will result in a total of maximum *4xn* explanatory variables, where *n* is the maximum number of reservoirs in the system under consideration. In case that reservoirs are located in series, and not in parallel, this number will be smaller than *4xn*, because the operation of the upstream reservoir will determine the inflow hydrograph in the reservoir located just downstream of it.

The complete set of explanatory variables, is mathematically represented by the vector X (see eq.3)

$$X(R_i) = \{MAX\%(R_i), INI\%(R_i), Q_b(R_i), Q_p(R_i), T_p(R_i), Sk(R_i)\}, \quad R_i = \{1,..,n\} \qquad \text{eq. 3}$$

where $R_i$ is a particular reservoir of the *n* number of reservoirs.

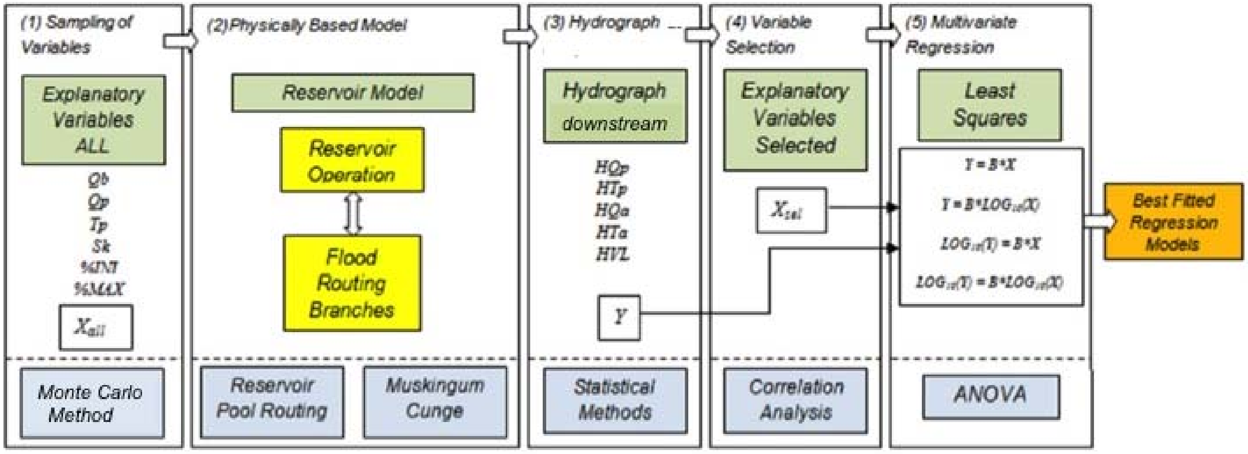


***Figure 11. Schematic representation of the mathematical formulation of the inference model***

Every sample set of explanatory variables creates a time series hydrograph at the downstream station (see Figure 11, step (3)). Each hydrograph is then characterized by five dependent variables (called "hydrograph variables"); peak discharge (*HQp*); time to peak discharge (*HTp*); average discharge (*HQa*); average time equivalent to the centroid of the hydrograph (*HTa*); and the total volume of the hydrograph (*HVL*).

A set of dependent variables is defined as a vector Y*i* for each obtained hydrograph (see eq. 4):

$$Yi = \{HQp, HTp, HQa, HTa, HVL\}i \qquad i = 1,2,\ldots, \qquad \text{eq. 4}$$

A set of training group of simulations is performed in order to determine the correlation between selected parameters of reservoirs and the resulting hydrograph variables. The hypothesis of no correlation against the alternative that there is a non-zero correlation should be used, while developing this correlation. A correlation based on p-values larger than 0.05 is used, which creates the possibility to select a number of relevant parameters for every variable that describe hydrographs downstream of the reservoir systems. The new subset of parameters, are called ($X_{sel}$), while the original number of parameters are called ($X_{ALL}$). A multivariate linear regression model is developed between the vector $X_{sel}$ as predictor, and the hydrograph and flooding variables ($Y_i$) as dependent variables.

For each variable in $X_{sel}$ a regression coefficient $\hat{\beta}$ is estimated, using an expression of the form:

$$\hat{\beta} = (X_{sel}^{T} \cdot X_{sel})^{-1} X_{sel}^{T} \cdot Y \qquad \text{eq. 5}$$

Four types of regression models are suggested to be developed before deciding which inference to be used; one linear (5.1) and three non-linear (5.2-5.4).

$$Y = \hat{\beta} \cdot X_{sel} \qquad \text{(eq 5.1)}$$
$$Y = \hat{\beta} * \log(X_{sel}) \qquad \text{(eq 5.2)}$$
$$\log(Y) = \hat{\beta} * X_{sel} \qquad \text{(eq 5.3)}$$
$$\log(Y) = \hat{\beta} * \log(X_{sel}) \qquad \text{(eq 5.4)}$$

The simple non-linear models (power and exponential functions) are good to be compared with non-linear models, which may be of interest. An analysis of variance (ANOVA) of every regression model can be performed considering the values of the coefficient of determination ($R^2$), the adjusted coefficient of determination ($R^2$ adj), and the model correlation (r). The single best type of regression model should be selected, for each flooding variable based on Mean Square Error (MSE) and r.

The application of this method is demonstrated for the case of Yellow River, for the 4 reservoirs already existing in the middle reach, from which two are located in parallel.

## 2.5. Reservoir-driven system: Example of Yellow river, China

### 2.5.1. *Introduction*

The present sub-chapter presents the contribution of the author to the modelling research of floods, in particular the one referring to very large river systems. The concept developed by the candidate together with a PhD student and two colleagues is demonstrated on the special case of the Yellow River, in China, which is one of the largest hydro-systems in the world. However, as presented in the previous section, the methodology can be easily applied to other river systems.

Flooding is a major problem for the Yellow River in China, hence a large number of interventions have been made in its reaches and tributaries in the last 50 years with the aim of controlling and reducing the flooding events in the lowland area located downstream of the Huayuankou hydrological station.

The latest developments in Hydroinformatics, as well a the new adopted approaches of the Yellow River Commission (YRCC) regarding support to decision making have raised possibilities for managing the river in the case of flooding and reducing loss of life of the people living within the embankment area of the river.

The Yellow River is an important area for the development of economic activity in China, hence it is important to improve the understanding of the river behavior, in times of flooding events. In Yellow River flooding processes are especially triggered by the reservoir operation, therefore it is important to model possible reservoir operation scenarios and test if they produce flooding of a specific area. The main goal of the research presented herein was to investigate and develop the statistical inference between the operation of reservoirs on the

Yellow River and a set of variables able to describe the downstream flooding, such as the total flooding volume and the peak discharge. The research proved that it is possible to use such inference models as decision support tools. The innovative approach of the research is the fact that a surrogate model has been used and it has been proved that a reduced number of explanatory variables could be determined to be included in the simulations carried out to determine the appropriate reservoir operation.

### 2.5.2. *The Yellow River system*

The Yellow River basin covers a large catchment area that is typically classified into three sections (see Figure 12), as follows:

1) The upper Yellow River, which is the largest part of the basin. This section is well known for its complexity regarding the balance between water and sediment volumes. It is located upstream of the Sanmenxia Reservoir, up to the Yellow river spring in Qinghai province. Out of the total sediment volume of the river, 90% is coming from this area. Water volumes carried out by the river are 56% originating as well from this area;

2) The mid section of the Yellow River, which has a system of reservoirs built with the aim of management of the river in case of extreme flooding events. In times that no flooding events are occurring the reservoirs are used for irrigation, water supply and hydropower generation;

3) The lower yellow River, located from Dongpinghu hydrological station to Bohai sea.

Because of its special characteristics the Yellow River is unique in the world. These characteristics are:

- high ratio of the sediment/water volume, i.e. a small average annual natural runoff (approx.$58*10^9$ $m^3$) as compared with the average annual sediment transport ($1.6*10^9$ t). There are 13 large rivers in the world exceeding the annual sediment transport of $100*10^6$ t, of which Yellow River is the first;
- river cross-section is mainly conveyed inside dykes;
- the "hanging river" property, which is due to the fact that the riverbed is, on average, higher than the land surface by 4 to 6 m. In order to protect the lowland area around the river from flooding, high embankments are built along the river banks. This characteristic is one which makes flooding on the Yellow river rather unique in behavior.

Flooding on the Yellow River has been an important issue throughout time. Records show that the river went over its banks 1590 times, which is equivalent with an average flooding event t every two-three years (Guoying, 2010). The flooding events are happening mainly on the reach located between Tianjin city and Jianghuai. The duration of flooding event is varying from a week to more than one month. Given these facts adaptation strategies and reduction of flood risk have always been important. As a result the overall water resources management and the operation of the river structures are handled by a high authority, the Yellow River Conservancy Commission - YRCC (Guoying, 2010).

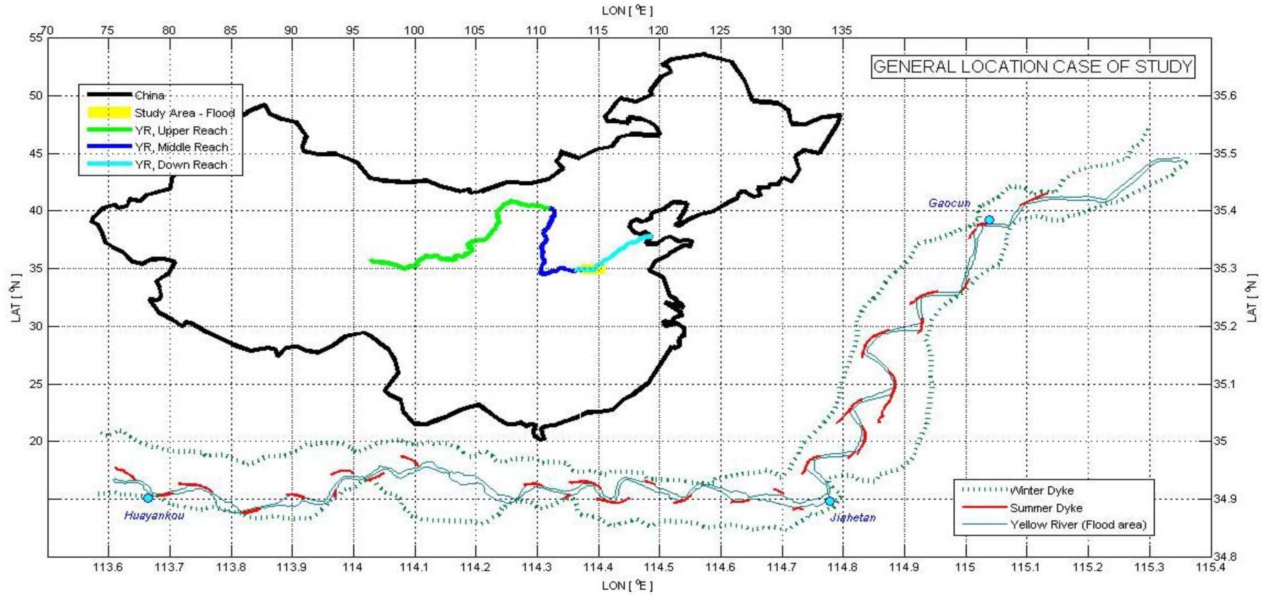


***Figure 12. Yellow River location and areas subject to frequent flooding***

A system of four reservoirs is build in the middle section of the Yellow River, two of them in parallel (Guxian and Luhun) along the Yihe and Yilohue tributaries; and two of them in series (Sanmenxia and Xiaolangdi) located on the main reach (Figure 13). Huayuankou hydrological station is the first downstream point, after the reservoirs. Measurements done at this hydrological station are used for the river management in terms of downstream flooding. The water levels measured at this point can be used in determining the way reservoirs should be operated in such a way that flooding is minimized in the downstream of the river. The reservoir system is complex (Lund and Guzman, 1999), the largest storage capacity being at Xiaolangdi dam (101.20*10$^{9}$ m$^{3}$) while the smallest is at Guxian (11.09*10$^{9}$ m$^{3}$). The combined resulting capacity of the four reservoirs is 179*10$^{9}$ m$^{3}$ and the maximum simultaneous released discharge is of 50,156 m$^{3}$/s (see Table 2). The main channel is able to convey a hydrograph without generating a flood event in the lateral lowland areas if the maximum peak does not exceed 4,000 m$^{3}$/s.

Yellow River is defined to be under extreme flood events if hydrographs with return period higher or equal with 1/100 years for discharge peaks of 16,000 m$^{3}$/s occurs. In order to cope with extreme flood events dykes on both banks of the river have been raised during the last four decades.

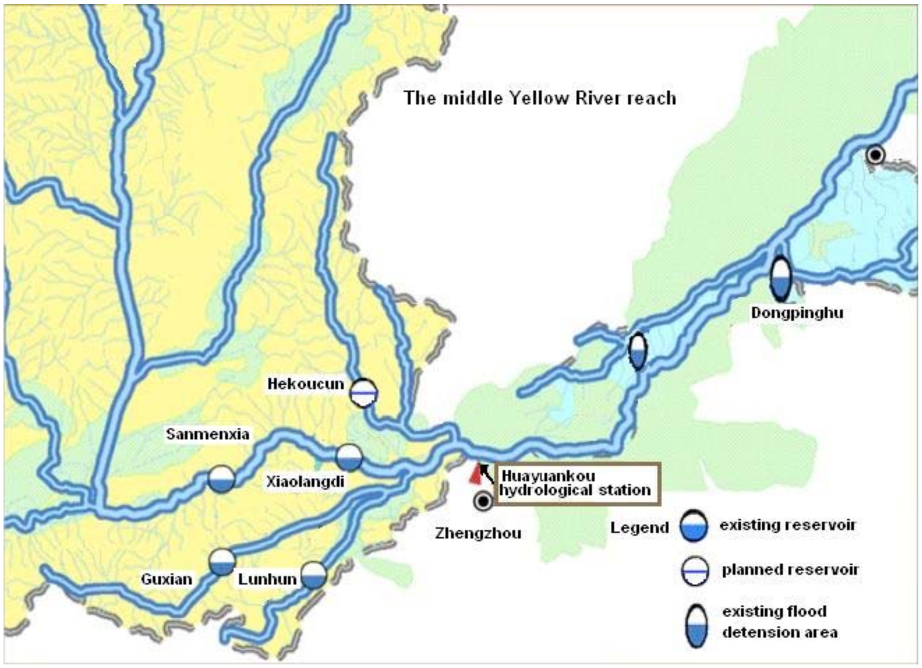


*Figure 13. The Yellow River eservoir system*

*Table 2. Main characteristics of the Yellow River reservoirs*

| VARIABLE | UNIT | XIAOLANGDI | SANMENXIA | LUHUN | GUXIAN |
|---|---|---|---|---|---|
| Latitude | DEG N | 34°55'23.58" | 34°49'42.99" | 34°12'1.13" | 34°14'22.39" |
| Longitude | DEG E | 112°21'51.13" | 111°20'43.74" | 112°10'57.25" | 111°16'41.93" |
| Minimum Level | masl | 200 | 290 | 290 | 478 |
| Maximum Level | masl | 275 | 335 | 333 | 551 |
| Minimum Storage | $10^9m^3$ | 0.2 | 0.0 | 0.3 | 0.1 |
| Maximum Storage | $10^9m^3$ | 101.2 | 54.6 | 12.5 | 11.1 |
| Minimum Release | $m^3/s$ | 2,8308 | 0.0 | 112.0 | 150.0 |
| Maximum Release | $m^3/s$ | 16,030.1 | 15,060.0 | 5,638.6 | 13,427.0 |

### 2.5.3. Managing flooding events on the Yellow river

When dealing with flooding events, river management authorities from the YRCC have to address the questions of when to evacuate, which areas are more susceptible to flooding and how long it would take for a flooding event to be routed out of the basin? Throughout the world, considerable effort is invested in the improvement and development of tools for flood management (Balica et al, 2013, Gichamo et al, 2012; Popescu et al, 2010; Van et al, 2012). Similarly, in China , at YRCC a concept known as the "Three Yellow Rivers" has been developed in terms of tools developed for the management and understanding of the Yellow River's behavior. This has three elements to it; the first part is the *real Yellow River* concept, which is mainly related to the actual river and the mechanisms to acquire and manage data; the second, conceptual part is known as the *scale model* or *prototype river*, which is related to the different physical scale models located in several laboratories of the YRCC; and the third part known as the *digital river* that includes different mathematical models that are used to simulate the behavior of the river. The research presented herein relates exclusively to the third part, the digital river, and only deals with the relations between the operation of reservoirs and flooding events based on the methodology detailed in section 2.4 above.

The Yellow River digital model is used for the day-to-day modeling of the flow processes and it is used as the main decision support tool for decision and management of the reservoir system. The main outcome of such a model is a descriptive single flooding response for each performed run. Such a response can be used to determine the extent of the area that will be flooded in the downstream river valley, or to determine what would be the maximum time length of the flooding. Because of the complex river system and associated model an extensive time is required for the simulation to be performed, hence multi-scenario approach is not an option during the time of flooding events. During a flooding event based on real-time forecasts operational meetings are held every 4 to 8 hours in order to decide how to operate the reservoirs. In order to operate properly in the case of extreme events, it is necessary to have the largest amount of information possible at all times, about the possible river behavior. The current existing models will give an answer to decision makers too late, hence a new approach needs to be taken, that is able to give reliable responses to decision makers in real-time. Moreover, in addition to the computation requirements for each detailed physically based model a set of elements need to be considered such as the operation of the reservoirs, the objectives of each stakeholder in the area, and the number of possible scenarios for response provided by the digital model. Such a huge task is difficult to address in an emergency situation.

In order to overcome such deadlocks preparation for flooding events is done well in advance by taken into consideration all possible flooding situations and simulating these probable events. A simpler approach that helps decision makers to take advantage from the runs done when no flood event is taking place is to use surrogate models (Castro Gama et al., 2014b). The proposed surrogate model helps the decision makers in finding an answer in a short time. Moreover by using surrogate models the memory and experience of past events is kept in a database of results, and it is retrieved easily whenever a new practitioner starts using the model. In this way decision makers do not depend on a small group of experts any longer, but they can rely on the model itself. Such an approach has been applied to Yellow river with good outcomes.

### 2.5.4. *Surrogate modelling of floods on the Yellow river*

The development of the surrogate model for the Yellow river follows the steps defined in Figure 11. First stage is to select explicit variables. The main variables taken into account for simulating reservoir operation and flooding in the mid Yellow River are all related to the input hydrographs in Sanmenxia Reservoir. Initially the input of explanatory variable subset was selected based on discussions with YRCC specialists (Li, 2013). Because of lack of data about

1/100 return period inflow hydrographs three kinds of synthetic upstream hydrographs were defined: a) Gamma functions (NERC, 1975; Todini, 2007), b) triangular functions; and c) uniform values. For each of the tested input type of hydrographs explanatory variables are selected as follows:

- for Gamma type four explanatory variables describe the hydrograph; the base flow (Qb), peak flow (Qp), time to peak flow (Tp) and skewness of the hydrograph (SK), hence a total of 12 explanatory variables are selected, (Sanmenxia and Xiaolangdi are reservoirs in series therefore only three hydrographs are input for each simulation);
- for triangular hydrographs, nine explanatory variables are enough to describe the hydrograph, because the skewness coefficient is not important;
- for uniform type of hydrographs, three explanatory variables are used, corresponding to peak of the input hydrograph in each reservoir.

The ranges for base and peak discharges of the defined hydrographs are based on hydrological values coming from YRCC. These are presented as box-plots in Figure 14.

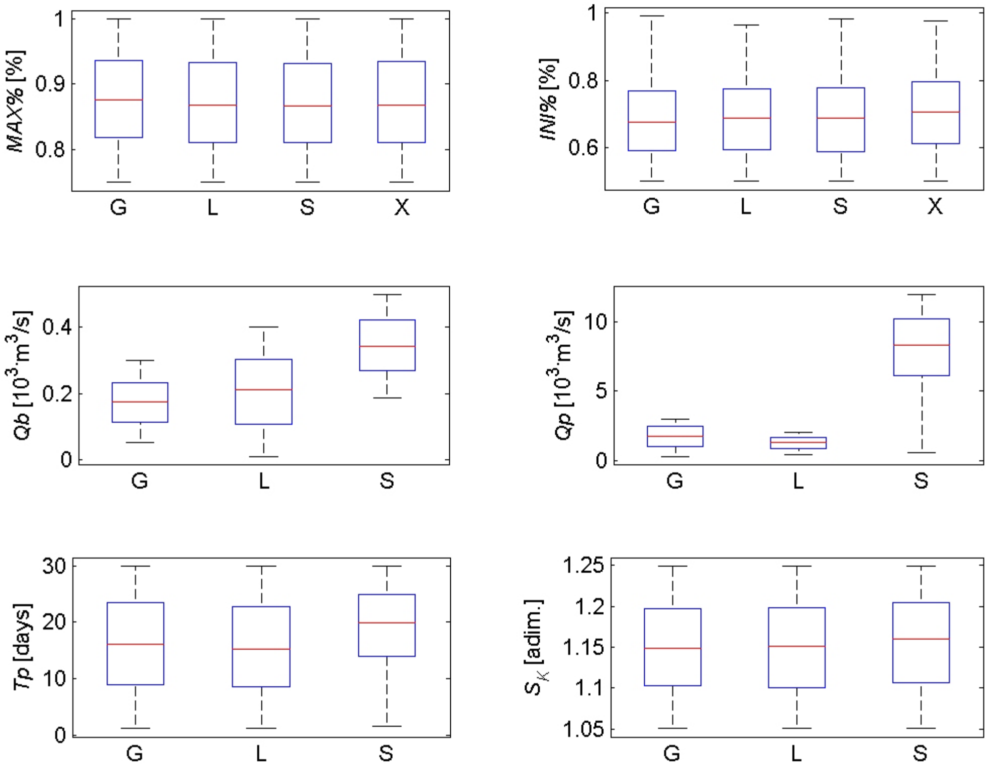


***Figure 14. Explanatory variables of the Yellow River surrogate model***

In Figure 14, G, L, S, X stands for Guxian, Luhun, Sanmenxia and Xiaolangdi reservoirs respectively. Based on the selected explanatory variables and provided variable ranges from YRCC, a total of 1,000 input hydrographs are randomly generated. The total time, of each generated hydrograph, is 60 days. After 60 days, the base flow is defined as uniform value until reaching 100 days.

In case of reservoirs the selected explanatory variables are the initial (INI%), and the maximum (MAX%) reservoir levels, resulting in 8 explanatory variables. The range of variables INI% are defined to be larger than 50 % and less than 99 % (taking into account reservoir operations). The maximum capacity of the reservoirs (MAX%) is restricted to the range of 75% to 100%. As for the input hydrographs variables a set of 1000 initial and maximum water levels are randomly generated.

Second step in developing the surrogate model is to build a model of the reservoir operations. Based on information from YRCC the reservoir system is operated as an explicit reservoir level pool method (Chow et al., 1988). Three basic operation rules apply; if the reservoir is full the amount of flow entering the reservoir is released; after deciding the amount of water to be released a volume balance is computed and if water level in the reservoir results to be lower than the minimum, then the release is the minimum ecological flow; and between the maximum and the minimum reservoir water levels store as much water as possible.

As part of the second step, the hydrographs obtained at the toe of each reservoir, due to operation rules are routed downstream towards the Huayuankou station using a Muskingum-Cunge approach (Cunge, 1969; Todini, 2007). Determination of the coefficients of the method is based on data surveys performed every year by the YRCC. The time discretization used for the routing scheme is 2 hours, for a total simulation period of 100 days. Routed hydrographs are overlapped in order to obtain one final hydrograph at Huayuankou. Analysis of the hydrograph provides i forms the set of hydrograph variables; peak discharge (HQp), the time to peak discharge (HTp), the average discharge (HQa), the average time of the hydrograph (HTa) and the total water volume routed (HVL).

In third step the hydrograph at Huayuankou is used as a upstream boundary condition for a 2D flooding model. A total number of 339 flooding models were used for analysis. Flooding results generated very big files that were stored in separated netCDF files. Flooding variables that were extracted from these results are: 1) maximum flooded area (FMA); 2) time required for the maximum area to be flooded (FTA); 3) maximum flooding volume (FMV); and 4) time required for maximum flooding volume to occur (FTV).

The 2D flooding model used during research was an unstructured grid model developed at Deltares, the D-FLOW FMβeta. The model is a Finite Volume Method solution solver of the vertically integrated 1D2D shallow water equations (Kramer and Stelling, 2008; Kernkamp et al., 2011). At the moment of research the model was in development and the test executed on the model were used to test and improve its performance. The advantage in the use of unstructured grids is that it allows an increase in the refinement for narrow areas, while using coarse refinement in areas where solutions are not fundamentally required (Kernkamp et al., 2011). The flooding model is build for the area inside the dykes, without any storage area, between Huayuankou and Gaocun for a length of 240 km.

Figure 15 shows an example of the several tested grids for a small reach of The Yellow River.

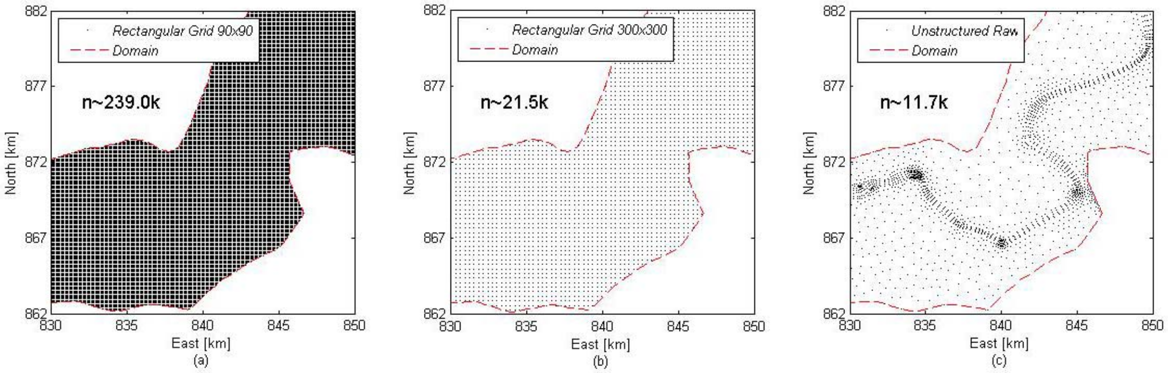


***Figure 15. Discretization grids at Jihaetan point on Yellow River***

The data for the river network is based on freely downloadable SRTM (Shuttle Radar Topography Mission) data of the area (CIAT, 2004) under study. The use of such type of information for similar rivers has been tested previously for the Amazon River (LeFavour and Alsdorf, 2005) and Missisipi River (Quinn et al, 2010; Muste et al 2011).

One of the main challenges in using the 2D flooding models for Yellow River was calibration. Unfortunatelly no data is recorded and available for calibrating a flooding model for such extreme events. Several studies on floods focused on calibration of known extreme events by using sets of information and sources of data from the topographic, hydraulic and hydrological point of view, trying to reduce the sources of uncertainty (Dinh et al, 2012; Gichamo et al., 2012; Hunter et al., 2005; Merwade et al., 2008; Moya Quiroga et al, 2013). Design hydrographs and/or observed data are used to reduce the uncertainty of the input and the calibration is focused on roughness coefficients. A critical discussion of the approaches is presented by Schumann et al.(2009), however there is no example of a reservoir-driven system calibrated for spatial flooding taking into account different reservoir operation scenarios. This is however of extreme importance for YRCC. If a calibrated hydraulic model is available to decision makers, then knowing which explanatory variables of the reservoir are relevant to avoid flooding in lowland areas is much more useful than knowing the probability of flooding.

Fourth step of model development involves working with the set of explanatory variables (*Xall*). The set is split in two: 800 sets for training the model; and 200 for its validation. Moreover an analysis of correlation was performed between explanatory variables and the resulting hydrograph variables, in order to check the no correlation hypothesis. Based on this analysis a subset of explanatory variables is *Xsel* selected.

In the last step the multivariate linear regression model is developed between the selected explanatory variables (*Xsel*) as predictors; and the dependent variables (Y); the hydrograph (*YH*); and flooding variables (*YF*).

In Figure 16 the inference between input variables into the surrogate model and the flooding variables downstream is shown in form of hystograms.

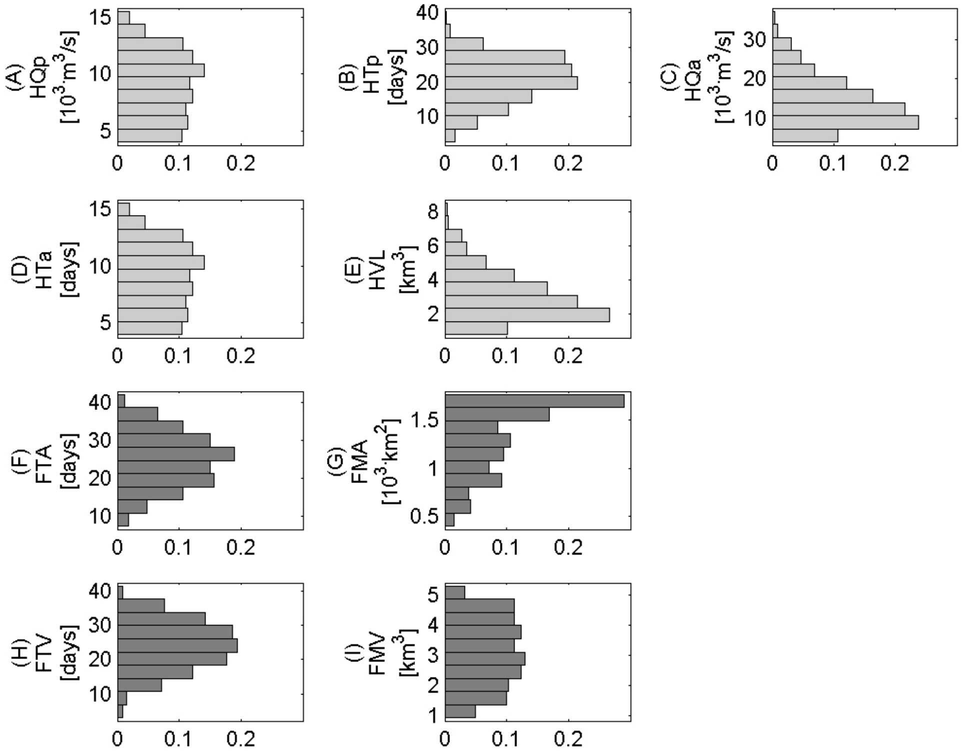


***Figure 16. Hydrographs at Huayuankou and flooding variables at Gaocun (Gamma input hydrographs)***

In Figure 17 results coming from the inference model are shown. Cases that are analyzed at length in paper Castro Gama et al., 2014a are highlighted as 1-6, in the figure.

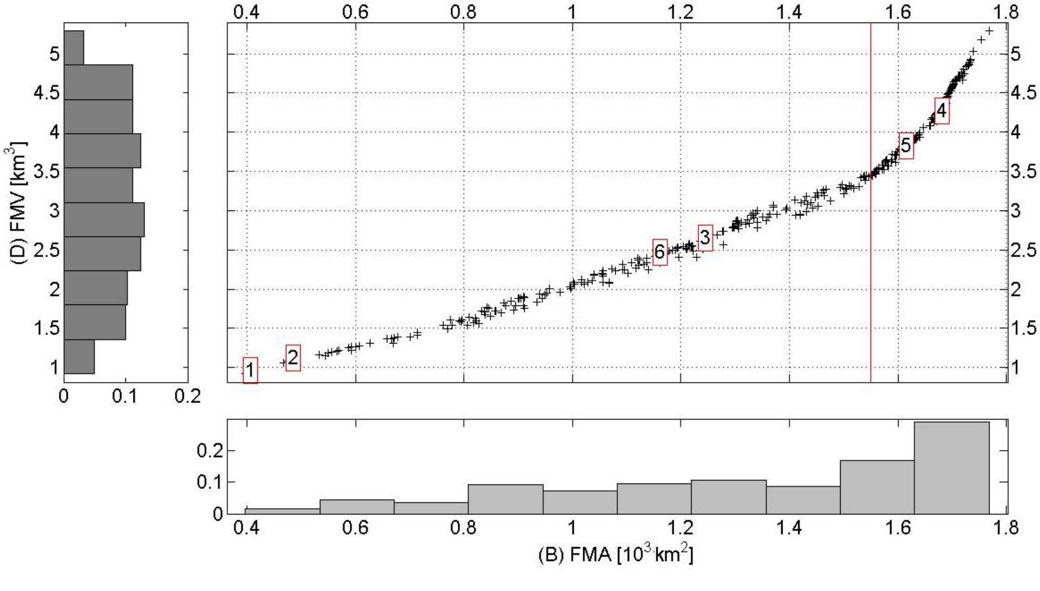


***Figure 17. Dispersion of the maximum flooded volume (FMV) versus maximum flooded area (FMA)***

The main research shows that it is difficult to find good regression models between the variables of the reservoirs and the flooding variables, because of the complexities of the river and the uncertainty in data. Moreover sediment transport of the river is significant in the historical development of the river, hence it should be included in the simulation.

### 2.6. Ice triggered floods

This section of the report is based on research presented in paper Fu et al,(2014) (selected publication [2]). During winter season the Yellow River is subject to ice triggered floods, in particular in the Ning-Meng reach. One of the main ice triggered floods effects is the possibility of dike to break due to ice. This creates threat to the region located along the river. The Ning-Meng reach of Yellow River includes Ningxia Hui and the Inner Mongolia Autonomous Region (Figure 18). This reach is experiencing very often ice dams and jams that causes dike-breaking and overtopping on the embankment. Big number of casualties and property losses are mentioned to have occurred throughout history. Hence there is a growing need to develop capability in forecasting and analysing of river ice floods. YRCC is developing a numerical to help understand the physical processes of river ice on the Yellow River, so called Yellow River Ice Dynamic Model (YRIDM). This model has been tested by a group of researcher, including the candidate of this thesis, for capabilities to conduct ice flood forecasting. Several scenarios were designed to explore the uncertainty of the YRIDM model for two bounds (5% and 95%) and probability distribution. The model is representing unsteady-state flow and it is capable to capture the basic regular pattern of ice floods. It is an important tool to support decision-making.

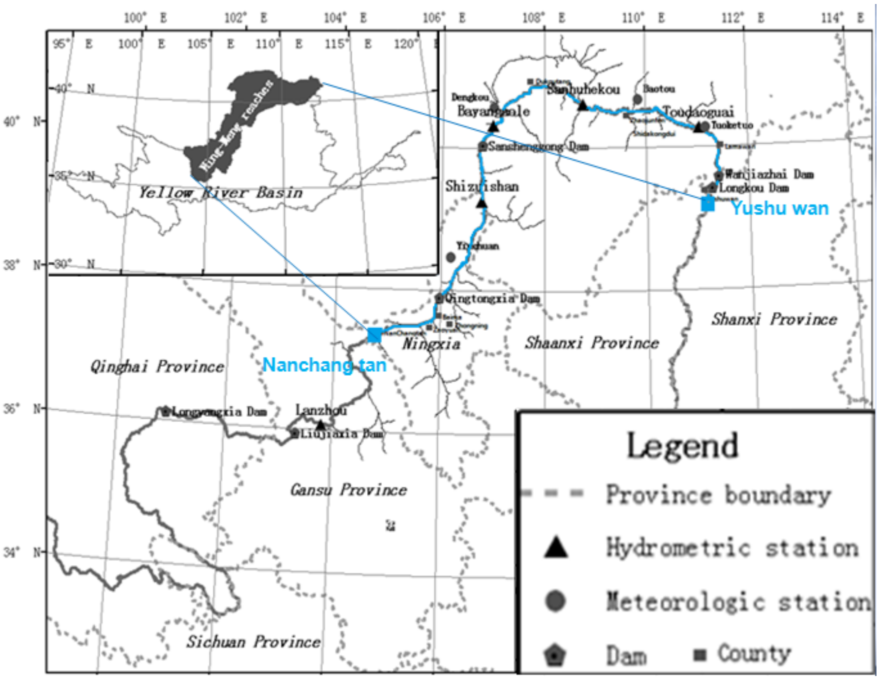


*Figure 18. The Ning-Meng reach of the Yellow River*

### 2.6.1. *State of the art of ice flood research and modelling*

Ice triggered floods in rivers are part of the river ice processes and are caused by ice jams, ice dams, and ice-snow melt (Liu et al., 2000). These processes are mainly important in the ice-covered and breaking-up time. An overview of these types of flooding is given in Table 3

***Table 3. Attributes comparison among the three types of ice floods***

| ***Atribute*** | ***Ice Jam Flood*** | ***Ice Dam Flood*** | ***Ice-snow Melt Flood*** |
|---|---|---|---|
| Occurrence Time | At the initial stage of freeze-up period and after freezing up | During the break-up period | During the break-up period |
| Location | Mostly at river bends and places with the slope changing from steep to gentle | The same as the ice jam flood, and at the front edge of ice cover and blocking area. | In the frozen reach |
| Air Temperature | Sudden air temperature drop and continuous low temperature | Sudden raise of air temperature to 0□, follow by sudden temperature drop. | Gradual raise of air temperature to 0□ (small fluctuations) |
| Backwater Height | Dependent on upstream inflow volume, incoming frazil ice quantity, and blocking degree of the river Xsection. | Same as Ice Jam floods plus hardness of ice quality. Mostly backwaters are high. | Dependent on upstream inflow volume, and degree of blocking of ice run. |
| Length of Backwater | Depending on upstream inflow volume, ice run quantity, and duration period with low temperatures . Backwater is 10km ～20km in length. | Usually 10km～30km in length. | Moving towards the lower reach with the ice flood peak. Length can reach several hundred kilometres. |
| Channel Storage | Large channel storage. | Channel storage of the reach is in upper reach of the ice dam. | Decrease of channel storage along the river |
| Ice Flood Peak | No distinct flood peak | Large ice flood peak may occur before the formation of ice dam; as well as after the outburst of ice dam. | Distinct ice flood peak occurs and grows along the river. |
| Evolution Features | Three stages: formation, steadiness and melting. | Three stages: formation, steadiness and outburst. | Stages: melting, ice flood peak, high water level rise and recess. |
| Outburst Situation | Slow outburst | Abrupt outburst by hydrodynamic action or human activities | After moving toward lower reach, the river course gets back to normal condition. |
| Ice Flood Disaster | Partially severe flood damage. | Partially big flood damage and ice run damages to water conservancy facilities. | Light flood damage |

Shen (2006) mentiones that in the past fifty years engineering and environmental issues regarding river ice research have significantly advanced, however, as presented by Beltaos (2008) thought understanding and quantifying the complex river ice processes are well defined, many problems are only partially solved and still remain to be studied.

The research of river ice phenomena are concentrated on two main areas; calculation of the energy budget and water temperature distribution (before and during the freezing-up period); and determination of the frazil ice, frazil floc, anchor ice and ice dams evolution in time. Water temperature distribution is well defined and understood (e.g. Shen and Chiang, 1984), as well as the mechanisms of super cooling and frazil ice formation (Osterkemp, 1978; Daly, 1984), while the evolution of frazil ice, frazil floc, anchor ice and ice dams needs to be further studied (Ye et al., 2004; Hammar et al., 2002). Knowledge on the mechanism of ice pans and ice floe formation, and transitional conditions among different ice run regimes are not yet fully understood. Moreover complete analytical formulation of the mechanical breakup is not yet formulated.

Mathematical modeling is an essential part of the river ice research progress, hence ice flooding models are available for 1D steady and unsteady state and 2D models. Data-driven models are also applied for forecasting ice triggered floods.

Because 1D steady state models are limited in representation of ice phenomena, 1D unsteady state models, such as RICE (Lal and Shen, 1991), RICEN (Shen et al., 1995), and the Comprehensive River Ice Simulation System (CRISSP1D) model (Chen et al., 2006), were developed. The limitation of these models is lack of detailed description of the complex flow taking place (Shen, 2010), by not taking into consideration the effect on the water body mass balance due to the change in ice phase; the two-layer ice transportation theory; and the thickness of the ice layer on the water surface is equal to the thickness of the ice block floating on the water surface. However such models have been successfully used simulating the ice regime for rivers; the RICE model was used for the Upper St. Lawrence River near New York; Peace River in northern British Columbia (Li et al., 2002); and the RICEN model was used for the simulation of the 1995 ice jam on Niagara River, in Canada.

Further on, in order to overcome the limitations of 1D unsteady state flow models, 2D models such as DynaRICE (Shen et al., 2008) and CRISSP2D (Liu and Shen, 2006) were developed to simulate ice regimes. These models solve the 2D depth-integrated hydrodynamic equations for shallow water flow, with two main additions to the Saint Venant assumptions; the movement of the surface ice layer is continuous; and ice is a continuous medium. DynaRICE has been applied to model and understand ice jam evolution and consequently design ice boom in the Niagara Power Project, on the Missouri-Mississippi River, and on the Shokotsu River in Hokkaido, Japan.CRISSP2D has been applied to simulate ice regime on Nelson River (Malenchak et al., 2008); on Red River near Netley Cut (Haresign and Clark, 2011) and for investigation of the potential ice growth and anchor downstream of Conawapa Power Plant (Morris et al., 2008).

Data driven methods have been used to forecast ice jam formation (Mahabir et al., 2002; Mahabir et al., 2006; Wang et al., 2008). Data-driven modeling was applied on the Yellow River (Chen et al., 2012) as well. However, such methods are not yet giving good results because ice processes are too complex to be captured by data-driven models.

### 2.6.2. *Ice floods on Ning-Meng reach*

The Ning-Meng is 1,237 km long and is comprised of two consecutive reaches; the Ningxia and Inner Mongolia reaches (see Figure 18). The total length of the Ningxia reach is 397 km. On this reach from Nanchangtan to Zaoyuan there is seldom freezing because of the steep river slope, which generates large flow velocities. As soon as slope becomes gentle, downstream of Zaoyuan, river often freezes. The Inner Mongolia reach is in the north of the Yellow River basin, has a length of 830 km; and it is wide with a gentle slope and meandering twists and turns.

According to historical data ice triggered flood disasters appeared every year between 1855 and 1949, and dams were destroyed 27 times. In addition, there were 28 ice flood seasons between 1951 and 2005 (Rao et al., 2012).

The Yellow River basin is under the influence of cold air from the vicinity of Siberia and Mongolia. The mean air temperature during the whole winter is below 0 ℃, lasting for 4 to 5 months. Due to the special geographical location of Ning-Meng reach the downstream part of the river freezes and breaks up earlier than the upstream part. Therefore ice jams leading to backwater formation are easily formed, which result in ice flood events. On the Yellow River the main causes of ice floods are ice dam and ice jam that triggers dike breaks and overtopping on the embankment.

Research presented herein uses the 1D unsteady state YRIDM model, that is based on the RICE and RICEN models. Schematisation of the model is given in Figure 19. The YRIDM model is simulating the ice dynamics, using RICE model for the description of the skim ice formation and frazil ice. Skim ice formation is defined by Matousek (1984) through an empirical equation;while frazil ice is described by the mathematical model of Shen and Chiang (1984). The ice dynamics is defined by Svensson et al. (1989) as a critical value. Though YRIDM is based on the RICE model, the major difference in the implementation is on how the break-up of the ice is checked in the model. In the YRIDM model critical discharge is based on an empirical equation, while in RICE the break-up appears at a clear defined value for discharge. Usually a clear constant value is determined apriori of using the model, by conducting experiments on site.

Based on the available data for the Ning-Meng reach of the Yellow River, the YRIDM was tested for capability in modeling ice flood for middle-term prediction (10-15 days ahead). The model was set-up to simulate the ice floods that occurred between 2001 and 2011, namely the one from 2007/ 2008 and 2008 /2009 winter. The winter from 2008 to 2009 was used to calibrate the model, and the winter from 2007 to 2008 was used to verify the model. Results of model verification for water levels and temperatures at different stations along the river are shown in figures 20, 21, 22.

The main conclusion of the research is that model is not applicable when the water level exceeds the embankment. In the winter of 2007/2008, the water level exceeded the height of embankment at Duguitalakuisu county, and resulted in a dike breach. Hence, the YRIDM should be improved so that it has the ability to deal with such problems.

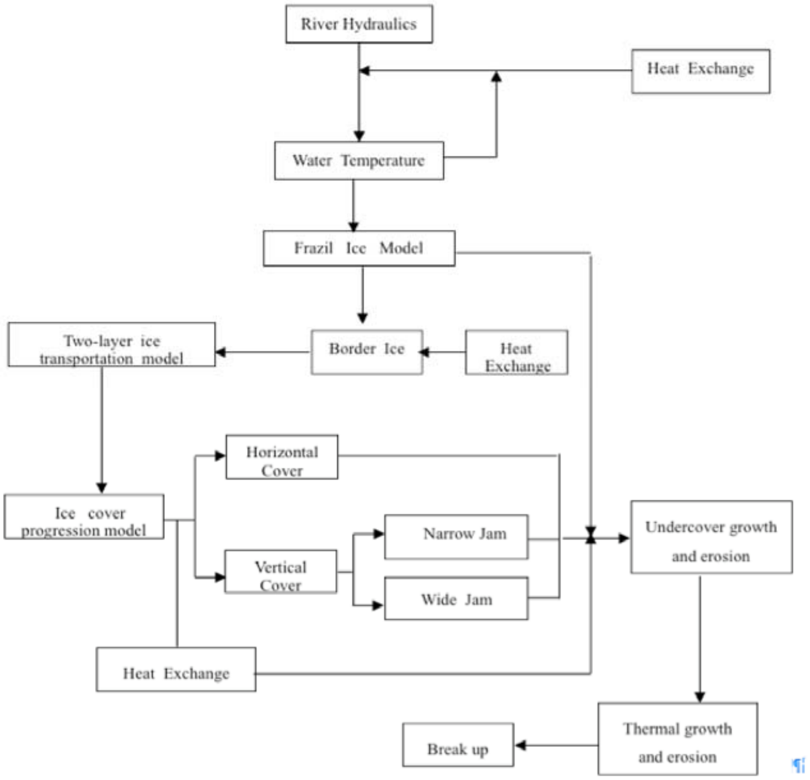


*Figure 19. The YRCC River Ice Dynamic Model flow chart*

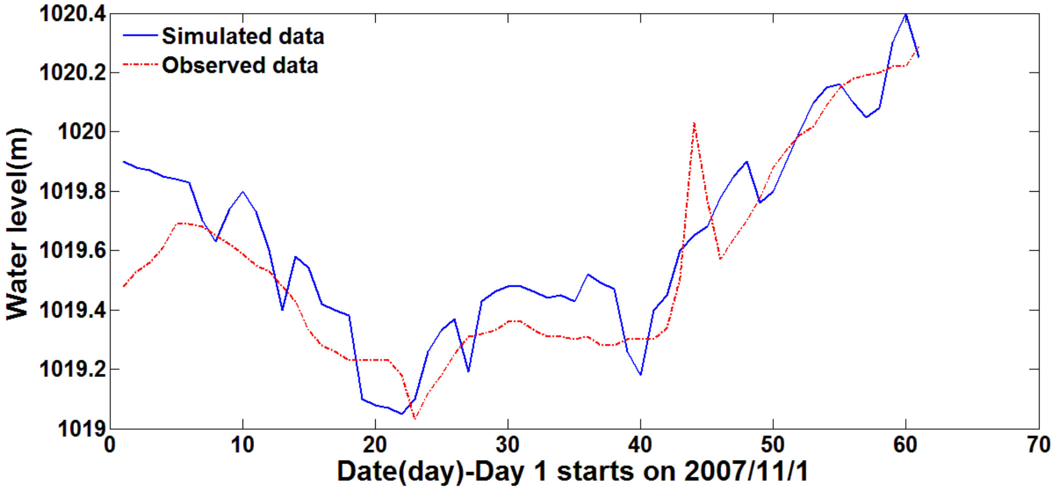


*Figure 20. Water levels verification results at downstream end of the reach*

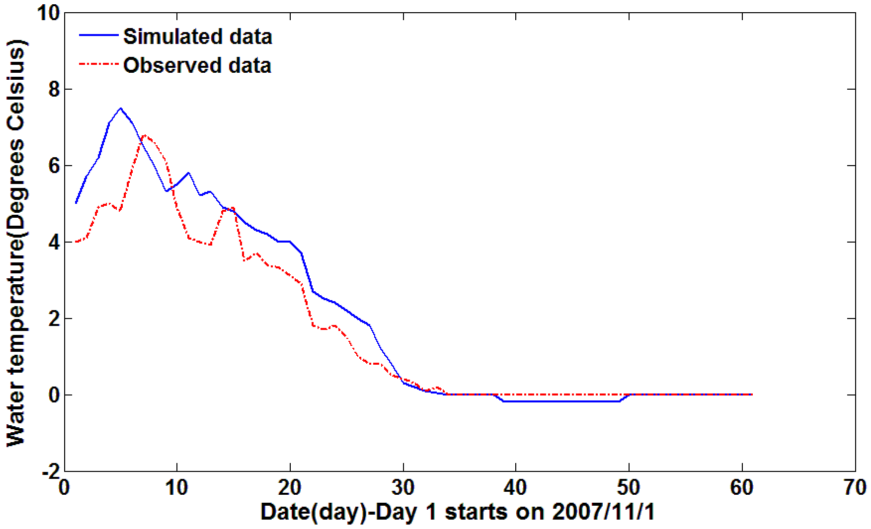


***Figure 21. Water temperature verification results at downstream end of the reach***

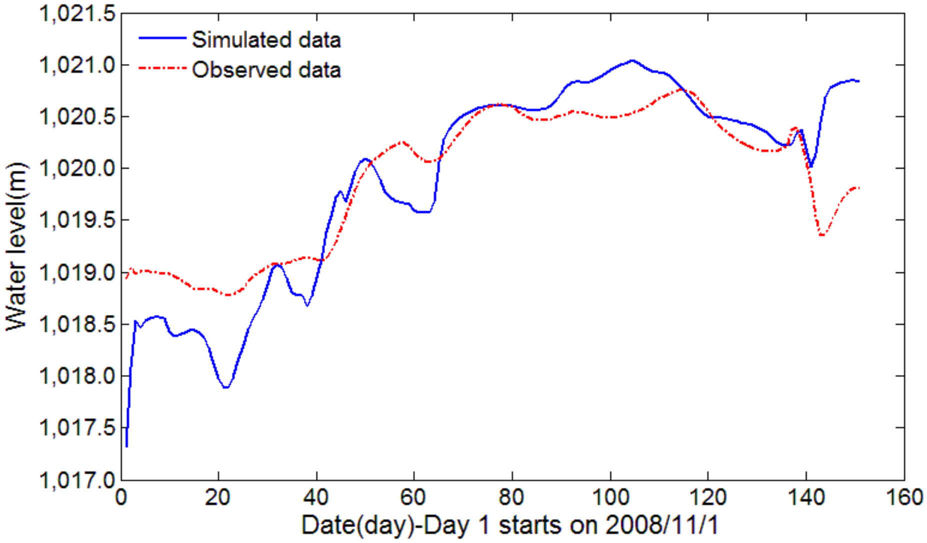


***Figure 22. Water levels verification at Sanhuhekou station***

A second performed tests was to determine the uncertainty bounds of the model. Results are summarized in Figure 23, which shows the observed data, and the 5% and 95% percentile bounds for the 500 cases simulations. Probability distribution of the uncertainty analysis results, show that uncertainty analysis results are good Fu et al.(2014).

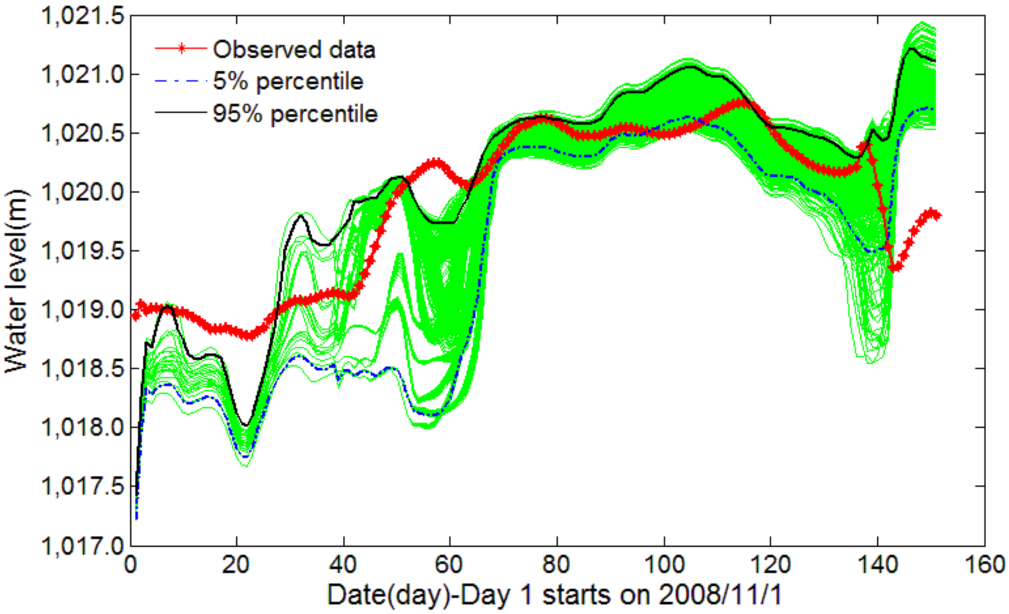


*Figure 23. Water levels at Sanhuhekou station*

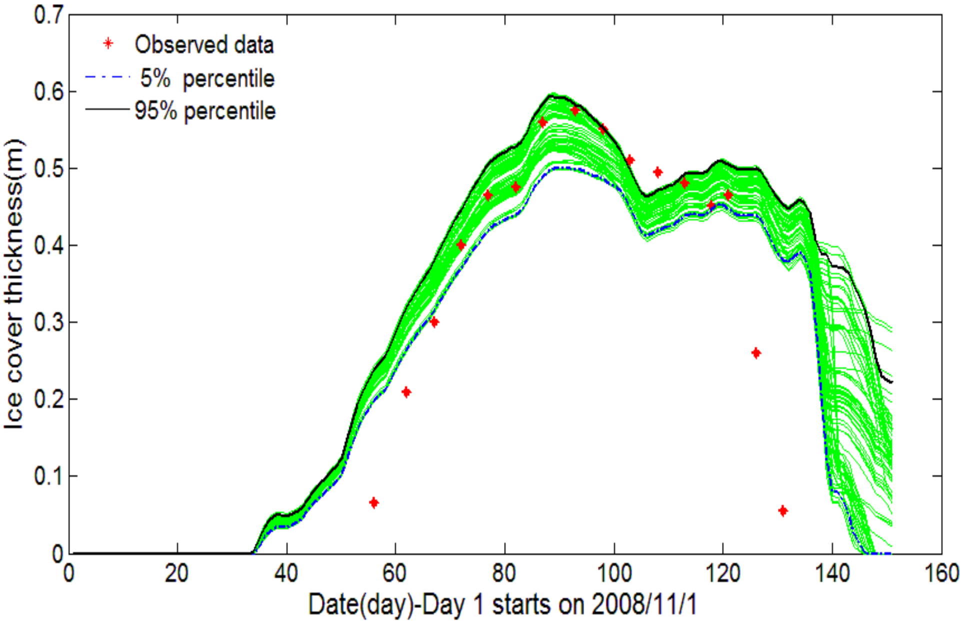


*Figure 24. Ice cover thickness*

Obtained results show that YRIDM model is applicable to the Ning-Meng reach for simulating ice regimes. It can be used to support decision making by forecasting the ice regime, after proper calibration has been carried out. Decision makers however should be aware of its limitations, i.e. it cannot simulate mechanical breakup during the breakup period (the effect of ice phase change on the water mass balance is ignored).

### 2.7. Flood vulnerability

This section of the thesis is based on the research outcomes presented in paper [3] of the habilitation thesis (see page 3 of this thesis).

While the notion of vulnerability is frequently used within catastrophe research, researchers' notion of vulnerability has changed throughout time. There have been several attempts to define and capture the meaning of the term vulnerability and the most common, accepted definition is that "vulnerability is the root cause of disasters" (Lewis, 1999) and "vulnerability is the risk context" (Gabor and Griffith, 1980). Many authors discuss, define and add detail further the general definition (Balica et al., 2009).

Vulnerability definitions differ from author to author depending on the hazards societies are exposed to. IPCC (2001) gives a definition of vulnerability to certain specific hazards such as climate change or other sources gives the definition with respect to environmental hazards (Blaikie et al., 1994; Klein and Nicholls, 1999; ISDR, 2004). The main focus of the papers selected for the habilitation thesis is flood vulnerability, hence that definition will be defined.

In the past United Nations (1982) have defined flood vulnerability as "the degree of loss to a given element, or a set of such elements, at risk resulting from a flood of given magnitude and expressed on a scale from 0 (no damage) to 1 (total damage)". Since the quantification of flood vulnerability can help in the decision-making processes, parameters and indicators (indices) are designed to produce information for specific target areas and they should provide information to counter attack this specific hazards which societies face such as, floods (Mirza, 2003). In recent years the impacts of floods have gained importance because of the increasing amount of people, economic activities and ecosystems that are impacted by its adverse effects.

The definition of vulnerability coming from natural hazards, such as floods used in the research presented in this section of the thesis is:

> "*the extent to which a system is susceptible to floods due to exposure, or perturbation, in conjunction with its ability (or inability) to cope, recover, or basically adapt* " (Balica et al., 2009).

In an effort to inform government, stakeholders and the public alike, flood risk and vulnerability has traditionally been communicated using the results of hydraulic models which produce potential inundation patterns (Pender and Neelz, 2007). Generally these models use increasingly sophisticated models which consider river topography, and couple this with accurate DEMs of floodplains created using remote sensing techniques such as LiDAR. Different hydrological scenarios are then simulated to create maps of flood extent to highlight areas of vulnerability. Improvements to flood extent predictions have been made through the increasing accuracy of remote sensing techniques; however this requires a high level investment in topographical data gathering (Gichamo et al, 2012). The lower the accuracy in the data, the lesser the accuracy in the predictions, therefore in areas that are data scarce this can result in bad or poor vulnerability predictions. Other methods, rather than these traditional established engineering methods have been developed to predict vulnerability, such as the flood vulnerability index (FVI) which is calculated linking to factors of vulnerability using different indicators at different spatial scales (Balica & Wright, 2010). In areas where detailed topographical data is scarce these may prove to be a more appropriate method to predict vulnerability. To validate new methods such as the FVI, it is necessary to benchmark compare these against traditional methods.

### 2.7.1. *FVI-The Flood Vulnerability Index*

The flood vulnerability index (FVI), is an indicator-based methodology, which determines locations that are potentially exposed to flood events in data rich and/or data scarce areas around the world. The main concept consists of determining different characteristics of a system, making it applicable to floods on different spatial scales, allowing a more extensive interpretation of local indicators and identifying actions to diminish locations of flood vulnerability. Moreover the methodology helps in identifying and developing necessary action plans to deal with floods. The four components of flood vulnerability are: social, economic, environmental and physical and their interactions affect the possible short and long term damages.

The four components of vulnerability can be assessed by different indicators in order to understand the vulnerability of the system to floods. A flood vulnerability index (FVI) is defined by linking the four components with three factors; exposure, susceptibility and resilience. FVI index aims to describe flood damage at various levels: river basin, sub-catchment and urban area. Consequently, through this identification decision makers can make informed choices on how to best allocate resources to ameliorate flood damage in the future.

Exposure can be understood as the spiritual and material goods that are present at the location where floods can occur (Penning-Rowsell et al., 2005). Susceptibility relates to system characteristics, including the social context of flood damage formation (Begum et al., 2007). Susceptibility is defined as the extent to which elements within the system are exposed, which influences the chance of being harmed at times of hazardous floods. Resilience to flood damages can be considered only in places where past flood events have occured, since the main focus is on the experiences encountered during and after floods (Cutter, 1996, Cutter et al., 2003, Pelling, 2003, Walker, 2004, Turner et al., 2003). Resilience describes the ability of a system to preserve its basic roles and structures in a time of distress and disturbances. This definition of resilience also implies that the system is capable to accommodate, acquire and mobilise sufficient to maintain necessary structures and processes within a coping or adaptation process (Adger et al., 2005).

The general FVI equation (Eq. 6) is summing up the exposure and susceptibility factors and subtracting the resilience factor.

$$\mathrm{FVI} = \frac{\mathrm{E \cdot S}}{\mathrm{R}} \qquad \text{eq. 6}$$

where E - exposure, S-susceptibility and R resilience.

The indicators belonging to exposure and susceptibility are increasing the flood vulnerability index; however the indicators belonging to resilience are decreasing the FVI. The

FVI are then normalized between 0 and 1, one being the most vulnerable to flood. Values of the FVI are given in Table 4

***Table 4 . Vulnerability ranges***

| Designation | Index Value | Description |
|---|---|---|
| Very small vulnerability to floods | <0.01 | Very small Vulnerability to floods, the area recover fast, flood insurances exist, Amount of investment in the area is high |
| Small vulnerability to floods | 0.01 to 0.25 | Social, economic, environmental and physical the area can once in a while experience floods, the area is vulnerable to floods and the recovery process is fast due to the high resilience measures, high budget, on the other hand if the area is less developed economic, even if a flood occurs the damages are not high, so small vulnerability to floods |
| Vulnerable to floods | 0.25 to 0.50 | Social, economic, environmental and physical the area is vulnerable to floods, the area can recover in months average resilience process, amount of investments is enough |
| High Vulnerability to floods | 0.50 to 0.75 | Social, economic, environmental and physical the area is vulnerable to floods, recovery process is very slow, low resilience, no institutional organizations |
| Very high vulnerability to floods | 0.75 to 1 | Social, economic, environmental and physical the area is very vulnerable to floods, the recovery process very slow. The area would recover in years. Budget is scarce. |

Birkmann (2007) reviewed attempts to measure risk and vulnerability applying indicators and suggested that risk and vulnerability index and indicator approaches are considered tools which can identify areas and targets where stakeholder intervention is most needed and these indicators can be used to “examine and discuss the root cause of risk and vulnerability”.

There are several methods available to determine the flood hazards, risk and vulnerability. All available methods can be classified in two main types:

- Deterministic modelling approaches which use physically based modelling methods to estimate flood hazard and/or probability of a particular event, coupled with damage assessment models which estimate economic consequences in order to provide an assessment of flood risks in an area; and
- Parametric approaches which aim to use readily available data to determine vulnerability of an area.

Physically based modelling and parametric approaches offer two different techniques for assessing flood risk and vulnerability and each of these two approaches were developed by different researchers and schools; the first one is the traditional one, routinely used in practice; while the second approach evolved from the concerns of global climate change which require evaluations of mitigation measures. Moreover structural and non-structural mitigation measures require a lot of preparation time, hence a quick guiding method to help guide decision making for assessing flood vulnerability was needed.

### 2.7.2. *Comparisons of FVI approaches*

Calculation of flood inundation depth and inundation extent using physically based models are based on solutions of the full or approximate forms of the shallow water equations. These types of models are one (1D) or two-dimensional (2D). The most common approach for simulating flow in a river channel are the 1D modelling methods, in which flow in a river is assumed to be in one dominant direction. In 1D models problems arise when the channel is embanked and water levels are different in the floodplain than in the channel. A solution to overcome these problems is the use of 2D models. The hydraulic results from a computer model are inundation depth, velocity and extent. Such kind of information can be used for loss estimation due to a particular design flood event, by combining the results of a hydrodynamic model with estimates of economic damage and loss in the affected area.

The parametric approach (Little and Robin, 1983), starts from the perspective of limited data availability. The parametric approach estimates the complete vulnerability of a system by a single value (index) using few available data of the system under consideration.

Four types of parametric approaches are available: i) estimating the complete vulnerability value of a system by using only few parameters relating to that system, ii) estimation of "the imputation of non-observable values" (Glynn et al., 1993), in which the observed parameters are used to model the non-observed ones; iii) the "parametric modelisation via maximum likelihood" (Little and Rubin, 1987), which is based on large number of assumptions; and iv) the "semi-parametric approach" (Newey, 1990) which allows modelling only of what is strictly necessary.

In light of these two distinct approaches, an important question for decision makers is what are the advantages and disadvantages in using an approach or another. In order to answer it is important to determine what type of information are decision makers looking for in order to reach their decisions. The following key components are identified to be of importance:

- Information on the mechanism and cause of flooding (flood hazard) in the studied area;
- Information on health and safety implications for the affected population by the flood;
- Information on the potential economic damages and losses given a particular flood event.

In addition to these key components it is important to understand how easily information is communicated, from the expert doing the analysis to the decison makers and from decision-maker to the public. In order to perform the comparison a study of application of the two techniques on an area on the Nzioa River in Western Kenya (Budalangi arae) was performed and results were compared. The whole study is published in Balica et al. (2013) and was carried out in order to seek the benefits and drawbacks of each approach.

The sequence of performing then analysis is highlighted in Figure 25.

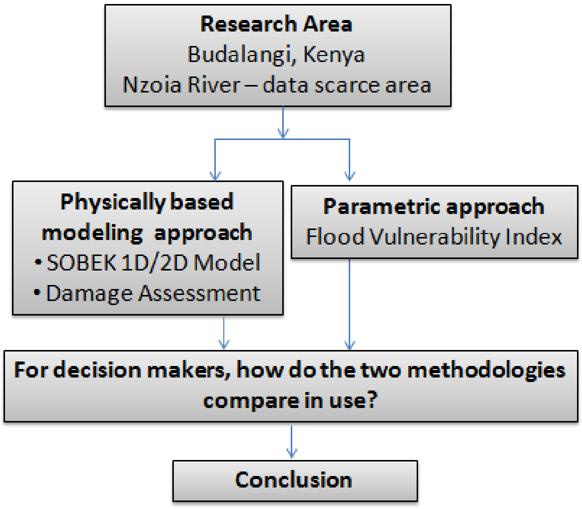


***Figure 25. Step by step procedure for comparison of the methods***

The Nzoia river originates in the South Eastern part of Mt. Elgon and the Western slopes of Cherangani Hills at an elevation of about 2300 m.a.s.l and it is one of the major rivers flowing into Lake Victoria. Nzoia river basin covers an area of 12709 km2 in Western Kenya and discharges into Lake Victoria in Budalangi, Busia district. The river is of international importance, as it is one of the major rivers in the Nile basin. Floods are frequent in the Budalangi area (WMO/MWRMD/APFM, 2004) impacting life, property and destroying crops. Moreover case study is data scarce. Unfortunately the lower the availability of data, the lesser the accuracy of computations, which can result in bad or poor vulnerability predictions.

For the purpose of the research the expected flood damage was assumed to be related only to the flood depth of the inundation. A SOBEK (Deltares) 1D2D model simulation of the 1:200 flood event was used to determine inundation extents and depths. Model results were validated by comparing the maximum inundation extent with a satellite image from 13 November 2008. The maximum inundation extent obtained with the model is of 12.6 km$^2$, which is approximately 97% of the inundation extent shown in the satellite image. Given the lack of data in the area, it is considered that this is good for the calibration result.

The evaluation of the impact of flood are evaluated based on flood water depths; which were less than 2m for 95% of the area; and bigger than 2m for the rest of 5% of the area. On average water depth is characterised by four main values; less than 0.5 m (30% of the inundated area); 0.5m (20% of the inundated area); 1m - 1.5m ( 35% of the inundated area); and 1.5 -2m (10%). Based on these water depths and using Forster method (Foster et al., 2008) and damage functions as defined by Duggal and Soni (2005), the potential damages of 1.54M Euros (+/-80000 Euros) was determined for the 1:200 return period event.

Socially, the area has very high vulnerability to floods, because population density is high there are no warning systems, and no good evacuation roads (no asphalted road).

Economically the region is high vulnerable because of the low exposure as the main economic activity is agriculture.

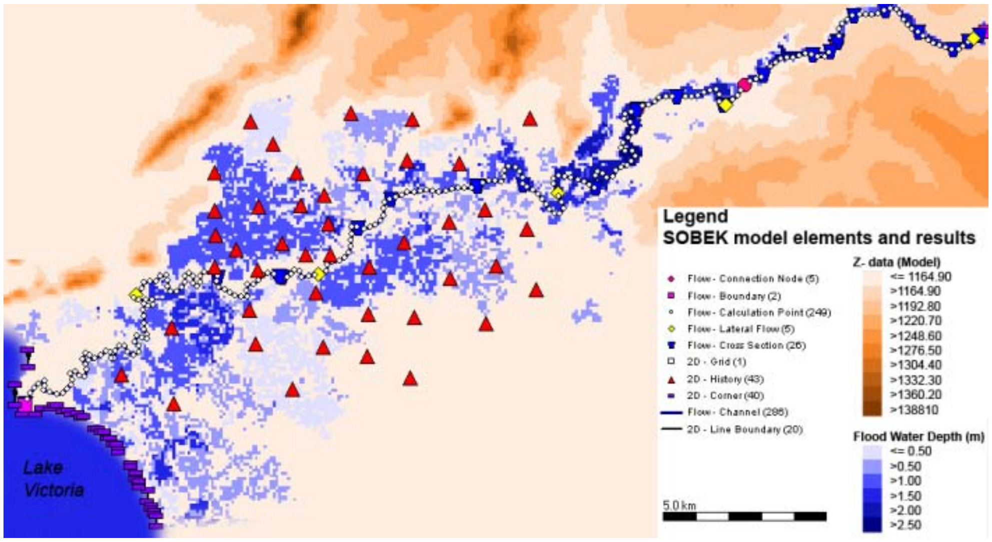


***Figure 26. Inindation depths on Nzoia river***

FVI results for the same area gives a classification as shown in Table 5

***Table 5. Budalangi FVI values***

| **Budalangi Flood Vulnerability Index** | | |
|---|---|---|
| **FVI Components** | **FVI Values** | **FVI designation** |
| FVI Social | 0.768 | Very high vulnerability to floods |
| FVI Economic | 0.521 | High vulnerability to floods |
| FVI Environmental | 0.314 | Vulnerable to floods |
| FVI Physical | 0.341 | Vulnerable to floods |
| FVI Total | 0.490 | Vulnerable to High vulnerability to floods |

If the results of the case study for the two approaches is studied it can be concluded that the advantage of using physically based models is their high capability for prognosis and forecasting, while the main disadvantage is the high requirement for input data demand. In the present study however, though the data was scarce, the 2D model was still able to predict well the flood extent. This shows that if the model is well defined from mathematical point of view, it does not require calibration (Cunge et al, 1980) and even in an un-gauged catchment can give a good understanding of the physics of the phenomena.

The FVI method on the other hand is not designed to assess directly the flood risk, but has a valuable contribution in assessing the risk itself. Risk as a notion concerns only the economic consequences, but vulnerability goes a step further covering important aspects, such as social, environmental and physical ones. The FVI parametric approach through its indicators is capable to quantify vulnerability to floods and has the advantages of giving a wider evaluation, though it is less rigorous. Hence FVI is useful for larger-scale vulnerability assessments, and a deterministic approach is better for focused studies. the FVI could be used to decide where a deterministic model is necessary to be used.

# 3. OPTIMIZATION OF RESERVOIR OPERATIONS

## 3.1. Scientific and technical contributions to aspects of reservoir operation

The main aim of this chapter is to present the added value of the approach taken by the candidate in modelling and optimization of rezervoir operations. Presented theory and applications are based on article [1] and [9] of the habilitation thesis (see page 3 of this thesis).

The final goal of modelling and optimization of reservoir operation is to support decision makers in managing reservoirs when they are build to serve several purposes. Objectives of functioning of a reservoir need to be assessed for different time scales; for different magnitudes of extreme events; seasons (e.g. winter, summer, for crops); yearly functioning of the reservoir; or for the project life span.

Reservoir operation presented herein addresses the following aspects:

- Developing a framework for conducting model- based optimization of reservoir (Hassaballah et al,2012); (selected publication [9]);
- Testing and checking different operation rules in case of complex reservoirs (Castro Gamma et al., 2014a; (selected publication [1]).

Apart from the published papers in peer reviewed journals, research results were disseminated to conferences, such as:

- 5th International Yellow River forum, 24-28 September, 2012, Zhengzhou, China
- 10th International Conference on Hydroinformatics, 14-18-July, 2012, HIC 2012, Hamburg, Germany
- 9th Interrnational Conference on Hydroinformatics 2010 Tianjin, China

## 3.2. Reservoir operations

In case of managing and operating single- or multi- purpose reservoirs for hydropower generation, flood management, irrigation, recreation and water supply, measured variables such as reservoir storage, released discharge, reservoir water levels, water quality or total sediment are relevant when assessing the objective of a reservoir (Loucks D., and E., van Beek, 2005; WMO, 2008). The management objectives of the reservoirs are usually assessed for different time scales; for different magnitudes of extreme events; seasons (e.g. winter, summer, for crops); yearly functioning of the reservoir; or for the project life span.

Reservoir operations are based on policies regarding the total storage capacity of it. Total storage capacity of a reservoir is split into zones or "vertical pools" (see Figure 27). A typical reservoir consists of one or more of these zones.

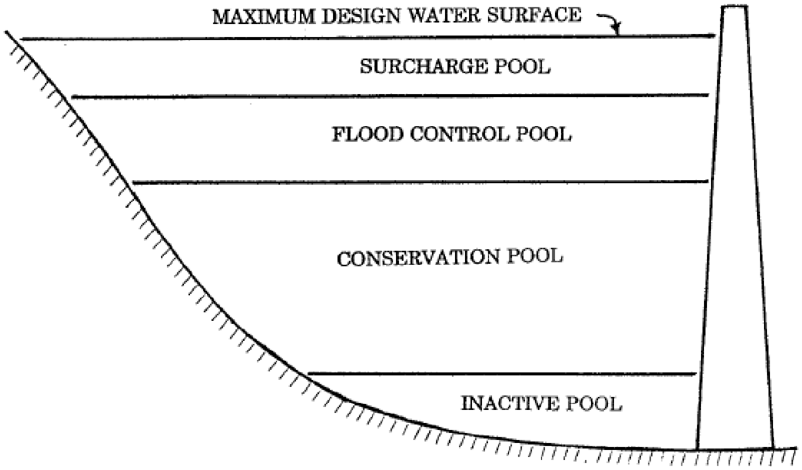


***Figure 27. Definition of typical reservoir's zones***

Withdrawals or water releases are not made from the inactive pool (dead storage), with the exception of the natural processes of evaporation and seepage. The top of the inactive pool elevation may possibly be fixed by the invert of the lowest outlet or, in the case of hydropower, by setting the elevation to ensure efficient operation for the turbines. The inactive zone might provide a portion of the sediment, reserve head for hydroelectric power and water for fish habitat. Conservation storage provides water for domestic water supply, industrial, irrigation, navigation, hydropower, and in stream flow maintenance, involve storing water during periods of high stream flow or low demand for later beneficial use as needed. The flood control pool remains empty except during a flood event. The top level of the flood control zone is, usually determined by the crest of the emergency spillway.

The evaluation of reservoir management strategies implies to look for an optimization problem, while trying to achieve the maximum or the minimum of an objective function. Reservoir operation systems analysis techniques have been reported in literature in a large number of publications during the past several decades. It has been viewed as an area of water resource planning and management having particularly high potential for beneficial application of optimization models. Reservoir system operation rules can be derived from computer models which rely on optimization techniques.

U.S.A.C.E. (1991) categorized the system analysis models commonly used in studies for optimization of reservoir operation systems as being:

- descriptive simulation models;
- prescriptive optimization models, or
- hybrid simulation and optimization models.

Descriptive models demonstrate what will happen if specific decisions are made. Prescriptive models determine what decision should be made to achieve specific objectives. All simulation models are descriptive. Inside the deterministic and stochastic operations research approaches (OR) there are: linear programming (LP), dynamic programming (DP), stochastic dynamic programming (SDP), differential dynamic programming (DDP) and nonlinear programming (NLP). Yeh (1985) describes operation research techniques used for the development of reservoir rule operation for simplified schemes and have concluded that these models are difficult to be adapted to real applications, if required to respond to changes on a daily basis. Wurbs (1993) reviewed the available simulation models for reservoir optimization (descriptive or prescriptive ones) and concluded that they failed to represent the operational approach. Nowadays it is known that climatic variability is integral part of the modelling process (Milly et al., 2002; Stocker and Raible, 2005) and during simulation of flooding events the classical approaches of using design flows seem to lack significance when based just on historical records (Merwade et al., 2008; Jung and Merwade. 2012).

Labadie J. 2004 added heuristic techniques as artificial neural networks (ANN) and fuzzy rule-based systems (FRBS) to the discussion, but went further to show that because of the involvement of public work agencies the vagueness in the objectives make efficiency and reduction of costs not mandatory even in the United States. Recently Adeyamo (2011), conjugated the promising results of multi-objective reservoir operation, for agriculture, using also heuristic algorithms such as evolutionary algorithms (EA), genetic algorithms (GA), differential evolution (DE), but the objectives were two and the sense of multiple objectives was lost during the review. Dittman (2009) explored multi-objective reservoir operations in a dam altered river, with a new two step rule for flood management, while incorporating the concept of low variation of flow regimes for ecology.

Different evolutionary algorithms have been tested to solve the multi-objective optimization problems. Deb et al., 2002 developed NSGA-II as an improvement of NSGA, and compared its performance with two other elitism multi-objective evolutionary algorisms: Pareto-Archived Evolution Strategy (PAES), and Strength- Pareto Evolution Algorithm (SPEA). The result shows that, NSGA-II (Non-dominated Sorting Genetic Algorithm) was able to maintain a better spread of solutions and converge better in the obtained non-dominated front compared to the others two elitisms.

Recent literature review demonstrates that, while traditional optimization methods such as LP, NLP or DP are still being used, very promising results can be obtained by search-based algorithms (e.g. GA), in which the optimal solution is sought through intelligent search through the solution decision space, leading to continuous improvement of the objective function. Frequently the evaluation of the objective function is provided by a simulation model. Given that the simulation model is not too demanding in terms of computing time, this coupled simulation-optimization approach can lead to successful solutions for a variety of problems.

In case of complex river system, that have several reservoirs build across the river such as it is the case of Yellow or Yangze, in China; or Colorado (Gilmore 1999) or Tennesse, in USA; determining a representative number of parameters to be used in modelling the reservoir operation for each reservoir becomes extremely useful. Implementation of complex modeling codes that are used as solution for reservoir management (Li. 2013) can help decision makers obtaining the optimal reservoirs operation scenario such that flood management downstream of a reservoir is achieved (Guoying, L. 2010). The main difficulty still remains for the case of extreme flooding events, when the outcome of a possible reservoir operation strategy needs to be determined quickly.

The first challenge in case of complex multi-purpose reservoirs is that the simulation model addresses the singularities of the characteristic curves, as it is for example the case shown in Figure 28. The example is the one of Xiaolangdi reservoir, which needs to operate as follows: when a flood event occurs the releases to the downstream are restricted to a maximum discharge of 16,000 m3/s. Operationally this is done by closing two of its release structures. In case the water level in the reservoir reaches 250 m.a.s.l. (see Figure 28) the effect of the closure is an increase in the water level in the reservoir, which in turn requires a higher release. Higher release is an increased flood risk. The fast increase in water level show the need of operators to take fast decisions in order to maintain the safety of the dam, while reducing the flood risk downstream.

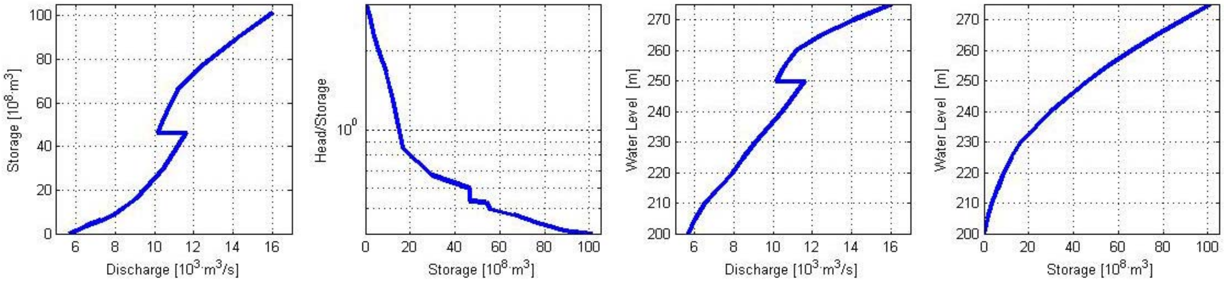


***Figure 28. Sample characteristic curves for Xiaolangdi reservoir of the Yellow River, in China***

## 3.3. Case study: Strategy of filling Mandaya reservoir in Sudan

### 3.3.1. <u>Introduction</u>

In recent years a number of hydropower dams are planned on the main Blue Nile River within the Ethiopian plateau. In 1964, the United States Bureau of Reclamation (USBR), upon invitation by the Ethiopian government, performed a comprehensive investigation and study of the hydrology of the upper Blue Nile basin. The USBR's study was an optimistic list of potential projects within Ethiopia, including preliminary designs of dams for irrigation and hydroelectric power along the Blue Nile River. Four large hydroelectric dams and reservoirs along the Blue Nile within Ethiopia were proposed. Those dams are: Karadobi, Mabil, Mandaya, and Border. In the pre-feasibility study of the Mandaya dam conducted by EDF-Generation and Engineering Division, and Scott Wilson Consultancy, five simulations have been performed to assess the impact on the hydroelectric power generation downstream within Sudan and Egypt during the first two years of filling the Mandaya Reservoir. The results demonstrate that the hydroelectric power generation within the Sudanese dams is significantly reduced by about 25 % (EDF-Generation and Engineering Division and Scott Wilson, 2007). For this reason developing an optimal filling program for Mandaya reservoir is required to reduce the downstream hydropower generation losses in Sudan during the period of filling and to ensure a win-win situation for both countries.

A study has been developed to determine what is the optimal filling strategy of Mandaya Reservoir for minimum impact on power generation in Sudan (primarily Roseires), and ensuring power generation at Mandaya Reservoir during the filling period? In addition the study demonstrated how such filling program will improve the Blue Nile water resource system performance in terms of hydroelectric power generation in Sudanese dams; timing and period of filling downstream reservoirs; and downstream water demands.

A methodology based on coupled simulation-optimization approach for determining filling strategy for the proposed Mandaya Reservoir with minimum impact on hydropower generation downstream in Roseires Reservoir, and ensuring power generation at Mandaya Reservoir. using a Multi-Objective Model-Based Optimization approach has been developped and applied in order to assist decision making in water resource planning and management.

### *3.2.2. Description of the study area*

The Blue Nile headwaters originates at the outlet of Lake Tana in the Ethiopian highlands, as presented in Figure 29. It is joined by many tributaries, draining the central and south-western Ethiopian highlands before it reaches the lowlands and crosses into Sudan. It covers nearly 850 kilometres between Lake Tana and the Sudanese-Ethiopian border, with a difference in elevation of 1,300 meters; the slopes are steeper in the plateau region, and flatter along the lowlands. After approximately 30 kilometres downstream of Lake Tana the river flows through deep rock-cut channels. Very few stream gauges exist along the Blue Nile River within Ethiopia, and those that do tend to have incomplete or limited records, and are often not publicly available. After Lake Tana, the hydrometrical station that has substantial records is at Roseires dam in Sudan. Stations with shorter records exist at Kessie, downstream of Lake Tana, and at El Diem at the Sudanese-Ethiopian border. The very last station provides about 40 years records of daily flows.

The climate in the Blue Nile River basin varies a lot between its springs in the highlands of Ethiopia and its confluence with the White Nile River. Lake Tana is at an altitude of 1,830 meters above sea level with an annual average precipitation of approximately 1,000 mm, and evaporation rates of 1,150 mm per year. Most of the highlands of Ethiopia are at elevations between 1,500 and 3,000 meters, that are wet, lush and green, and have daily mean temperatures that fluctuate between 15°-18° Celsius. As the Blue Nile reaches the lowlands and enters Sudan, rainfall decreases and evaporation increases, resulting into a significant loss of water. Temperatures also increase in variability, and reach substantially higher levels than at Lake Tana. The Sennar region, located in the south-eastern part of Sudan, experiences evaporation rates of 2,500 mm per year, yet only receives 500 mm of rain annually; mean daily temperatures approaching 30° Celsius (Block, 2007).

The flow of the Blue Nile reflects the seasonality of rainfall over the Ethiopian highlands where the two flow periods are distinct. The flood period or wet season extends from July to October, with the maximum flow in August-September, and low flow or dry season from November to June. Therefore the annual Blue Nile hydrograph is in a form of a constant bell-shape, regardless of the variation in the annual flow volumes. The average annual flow of the Blue Nile and its tributaries, upstream of the confluence with the White Nile at Khartoum, is about 50 billion m$^3$; the daily flow fluctuating between 10 million m$^3$ in April to 500 million m$^3$ in August (Frenken, 2005).

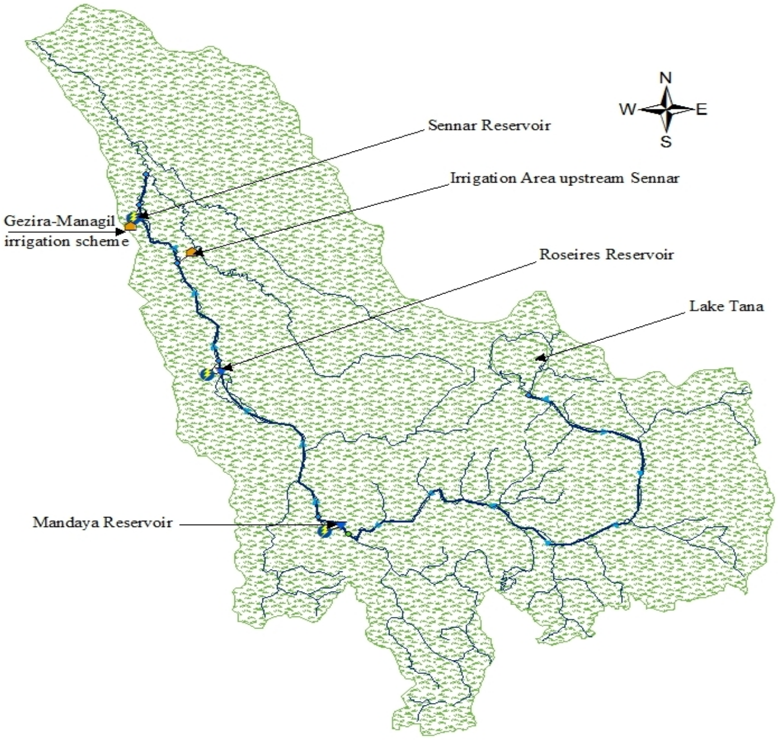


*Figure 29. The Blue Nile catchment*

Monthly precipitation records shows summer to be the heavy rain season (Block and Rajagopalan, 2007). The rainfall during the summer season near Sennar dam, in Sudan, account for 90% of total annual precipitation, while in the Ethiopian highlands, approximately 75 % of the annual precipitation falls during the heavy rainy season. Although the deserts of Sudan and Egypt receive no significant precipitation during the rainy season, the intense upstream rainfall gives rise to annual Nile floods, whose impacts are felt through the entire Nile basin. The evaporation in Nile reservoirs, river channels and irrigation practices is estimated to 10 billion m$^3$.

Allocation of the Nile waters is a controversial issue since a very long time. More recently, in 1959 an agreement was signed between Egypt and Sudan, regarding Nile water volumes for each year for each of the countries. These volumes are 55.5 and 18.5 billion m$^3$, for Egypt and Sudan, respectively. The treate does not specify any allotment to Ethiopia (Johansson and Turkenburg, 2004; Said, 1993), hence Ethiopia does not acknowledge this agreement. In 1999, the Nile Basin Initiative was created to stimulate cooperation between all Nile countries in to work and find amicable solutions for water resources management in the basin such that everyone would benefit from this.

### 3.3.2. *Dams on the Blue Nile*

Due to water needs in Sudan and Etiopia several dams were build and are planned on the Blue Nile. The Sennar dam was built in 1925 in Sudan to irrigate the Gezira Scheme. It is fundamental to the Sudanese economy and up to 60 % of the country's agricultural production is dependent on water availability from this reservoir. The total area of the reservoir of Sennar dam is 140-160 km$^2$ with maximum averaging depth of 26 m. The total volume of the reservoir is 480 million m$^3$, though initial volume was almost double, 930 million m$^3$, but sedimentation reduced the volume.

The Roseires Dam, also located in Sudan, started to operate in 1966, as a hydroelectric power plant, of 280 MW supplying nearly half of Sudan's power output. Hydroelectric power varies a lot throughout the year because flow changes a lot. The dam is also used for irrigation purposes for Gezira Plain. The reservoir resulted from the dam construction is 75 km in length has an area of 280 km$^2$; and a maximum average depth of 50 m that will be higher after the dam heightening is completed. The total storage volume of Roseires reservoir in 1966 was approximately 3,024 million m3. Due to the high sediment load of the Blue Nile during the flood season the reservoir is operated for four months at Normal Minimum Operating Level (MOL) of 467 masl, to route the majority of the sediment through the reservoir with minimum deposition. At the end of the flood season, the reservoir is filled to the Maximum Operating Level of 481 masl, to store sufficient water for the dry season. In spite of this particular operation a storage volume of approximately 1,000 million m$^3$ is lost due to sedimentation.

Characteristics of Sennar and Roseires dams are given in table Table 6. The operation rules of these two resesrvoir are defined as follows:

- During the flood period (July-August), Roseires reservoir is kept at the minimum operation level (MOL) of 467.60 masl and Sennar at 417.20 masl.
- Filling of Roseires reservoir starts during the last week of August as the earliest date if in the last week of August the flow from El Deim branch is below or equal to 350 Mm$^3$/day;
- Filling of Roseires reservoir starts after the end of August if the flow at El Deim is 350 Mm$^3$/day for at least three days.
- Filling of Roseires reservoir starts on 26 September as the latest date even if the river flows continued above 350 Mm$^3$/day.

***Table 6. Characteristics of Rosieres and Sennar Reservoirs***

| Reservoir | Dam completed | Live storage billion m$^3$ | Full supply level (masl) | Minimum operating level (masl) | Installed capacity (MW) |
|---|---|---|---|---|---|
| Roseires | 1966 | 2.12 | 481 | 467.60 | 280 |
| Sennar | 1925 | 0.48 | 421.70 | 417.20 | 15 |

A new dam is proposed to be build in Ethiopia, 700 km downstream from Lake Tana, the Mandaya dam. The main research question is how will this dam affect the functioning of the two Sudanese dam, and if there is any possible optimum strategy for filling this reservoir in such a way that the impact of filling it is minimum. The reservoir just downstream of Mandaya is Roseires dam.

### 3.3.3. *Model-based optimization of the filling of Manadaya reservoir*

In order to analyze the present and predict the future water resources in the Blue Nile basin, in the case of the connected system of Roseires and Mandaya reservoirs, a simulation model, developed in MIKE BASIN was used. The simulation model was coupled with the NSGA-II optimization model in order to determine possible optimal filling rules of Mandaya reservoir.

This study focused on Multi-Objective Optimization (MOO) model framework development and its application to reservoir optimization. To link the MIKE BASIN simulation model engine and the optimization model (NSGA-II), a code was written in MATLAB to run the MIKE BASIN in a loop, and to guide the optimization process to calculate and pass the objective functions to NSGA-II for evaluation.

The sources and demands are spatially distributed in the studied basin, hence a Geographical Information System (GIS) was chosen to prepare the input data, and present the results of a simulation model. MIKE BASIN modelling environment was chosen to built the simulation model of Roseires and Mandaya reservoirs.

MIKE BASIN is a simulation model designed to solve water allocation problems by representing the hydrology of the basin in space and time, as defined in the DHI 2005 user manual. Build with the aim of addressing integrated water resource management and planning MIKE BASIN is a computer model that integrates GIS (specifically ArcGIS) with water resource modelling. This gives the main users of the system ( managers and stakeholders) a framework through which they can address water allocation and environmental flow in a river basin.

In order to represent the current and future operation of the reservoirs system as accurate as possible, data from relevant institutions in Ethiopia and Sudan were used (e.g. hydrological data and the physical characteristics of the existing and proposed reservoirs). The available hydrological data for the Roseires dam covers 39 years (1965–2003) of daily data, and 50 years (1954–2003) of monthly data for the proposed Mandaya. The available data on the operating rules of the Roseires reservoir was available for a 10- day interval, therefore all collected data was transformed into 10-days average intervals (three periods per month).

The Mike BASIN model consists of two reservoirs (Figure 30) connected via a reach (the Blue Nile). The Blue Nile reach is divided in several computational points, in which the continuity of mass is applied for each computational time step.

***Figure 30. MIKE BASIN model of the connected system of reservoirs Mandaya-Roseires***

The input data for the model are hydrological data, physical characteristics of the reservoirs along with their operation rules. The hydrological data are inflow, irrigation demands, evaporation and water levels at Mandaya and Roseires. Downstream river water level and flow discharge from Roseires reservoir are used to derive rating curves relations. Rating curves are used to find the downstream water levels for a given discharge passing through the dam, then the downstream water level is subtracted from the upstream water level to get the head difference which is required for hydropower computation. Since Mandaya Reservoir does not exist yet (it is just proposed), no tailwater table has been specified to be used for hydropower computations. Therefore, the simulation model computed the head difference automatically as a difference between the water level and the bed level of the reservoir.

One special characteristic for the operation of Roseires dam is that it is designed to pass the large annual flood volume through the dam during the flood period (Jun 15 - September 15), which is 80% of the annual flow of the river. The rule curve of Roseires reservoir operation is given in Figure 31.

As stated in section 3.2.3. and represented in Figure 31 the filling of the reservoir starts in September after the peak flood has passed and lasts for 45 days until top retentions level is reached. The same policy of operation has being used for the Sennar reservoir with its corresponding water levels .

For consistency of the operation of the reservoir system the assumption was made that same operation policy of Roseires and Sennar reservoirs are valid for Mandaya reservoir.

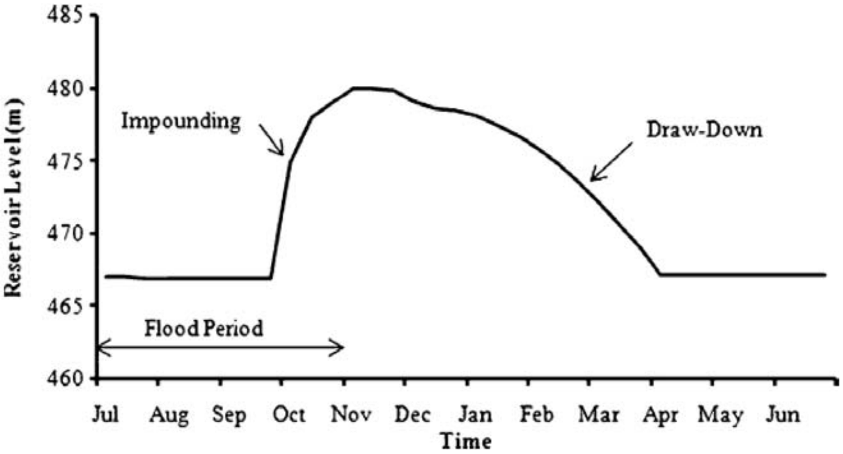


*Figure 31. Roseires rule curves for reservoir water level*

Two conflicting objective functions were considered in the optimization process:

- Maximization of generated power at Mandaya power plant; and
- Maximization of generated power at Roseires .

The objective functions are computed as Max[PMandaya,PRosaires], where, P is the cumulative generated power.

In order to perform the optimization decision variables were set. These were 36 monthly flows from Mandaya reservoir. The values of decision variables are randomly generated between 100m$^3$/s and 1000 m$^3$/s. The 100 m$^3$/s is the minimum environmental release computed as 10% from the annual average flow at Mandaya site, while the 1000 m$^3$/s is the capacity of the bottom outlet of the proposed Mandaya dam. The 36 values are monthly flow control values corresponding to the first 3 years of the filling time of Mandaya reservoir. The flow control corresponds to the minimum environmental release downstream Mandaya. All simulation scenarios results show that after the first 2 years of operation the minimum environmental release is directly satisfied through turbine outflow, hence decision to specify minimum environmental flow only in the first 3 years. Figure 32 gives the interval of the decision variables for the three years.

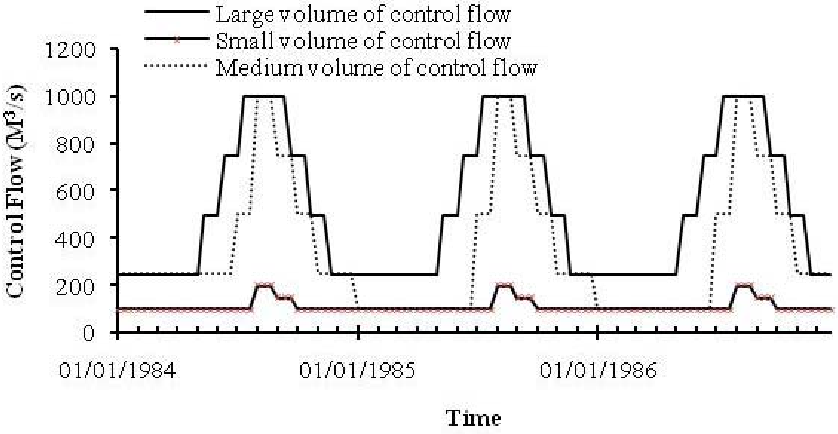


*Figure 32. Intervals for decision variables (control flows)*

In order to run MIKE BASIN in 10-day time step is chosen, which is equivalent with 108 values of 10-day control flows over a period of 3 years, i.e. each of the 36 values are assigned three times. These 108 decision variables generated from NSGA-II are used as input for MIKE BASIN. Hydropower calculations are performed by MIKE BASIN runs using head difference and release at each time step.The cumulative hydropower production values are determined at each MIKE BASIN run. After model computation the objective functions (cumulative generated power) are evaluated by the NSGA-II and a new set of decision variables is generated.

A step by step algorithm of the optimization is:

I. Initialize NSGA II for first generation

II. Modify MIKE BASIN input according to the decision variables.

III. Run MIKE BASIN model and calculate the objective functions (generated power) for each population

IV. Pass value of objective functions to NSGA II.

V. Perform non-dominated sorting and crowding distance sorting in NSGA II

VI. Generate new offspring population based on genetic operators (selection, crossover and mutation)

VII. Repeat loop steps from II to VI until all generations are run and provide outputs.

### 3.3.4. *Results*

Optimization results are evaluated via three comparisons using Pareto front solutions. The three types of control flows are A (small flows), B (medium flows) and C(large flows). The comparison is made for optimization time horizon of 2 years for Roseires, and 5 years for Mandaya. Results are presented in Figure 33, Figure 34, and Figure 35 respectively.

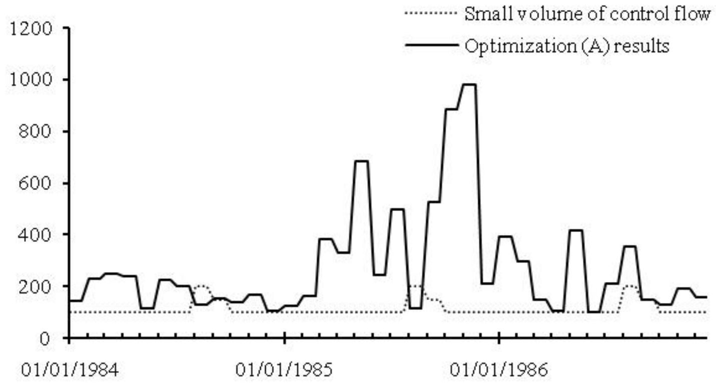


***Figure 33. Comparison of small volume of control flow with optimization (A) results***

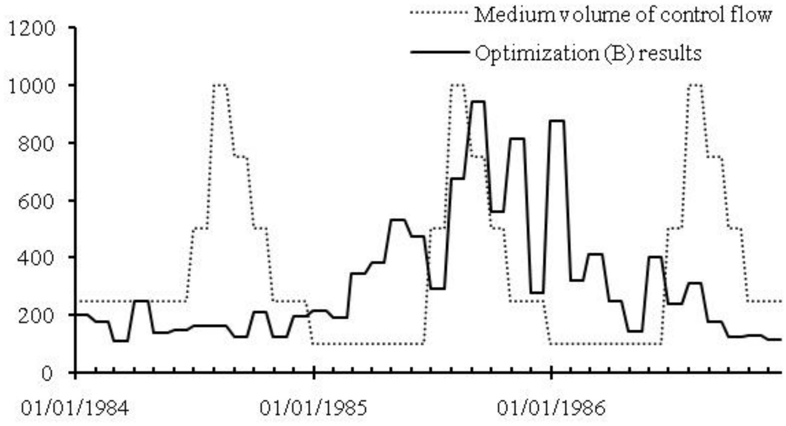


***Figure 34. Comparison of medium volume of control flow with optimization (B) results***

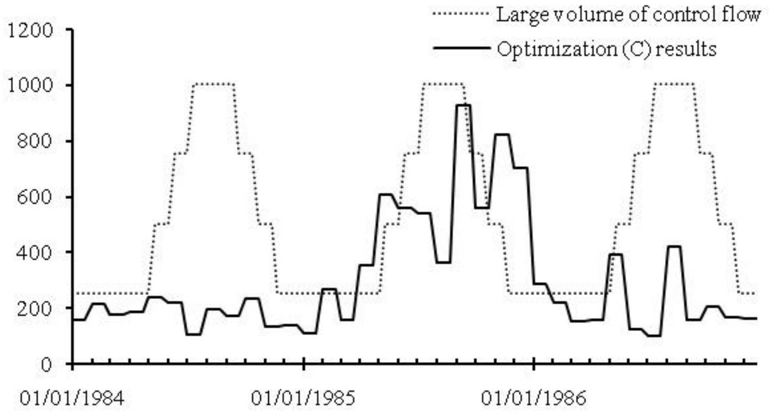


***Figure 35. Comparison of large volume of control flow with optimization (C) results***

Results are summarized in Table 7,Table 8, Table 9, and Table 10.

***Table 7. Cumulative generated power during the period of filling with medium volume of control flow***

| **Reservoir** | **Roseires (Year)** | | | **Mandaya (Year)** | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 1 + 2 | 1 | 2 | 3 | 4 | First 4 | First 5 |
| Target Power (GWh) | 873 | 883 | 1759 | | | | | | |
| Generated Power (GWh) | 702 | 1048 | 1752 | | 2904 | 8250 | 8535 | 19537 | 28617 |
| Power deficit (%) | -20 | +19 | -0.3 | | | | | | |

* Positive deficit = gain

*Table 8. Solution (A) better for Mandaya reservoir (upper left point of the Pareto)*

| **Reservoir** | **Roseires** | | | **Mandaya** | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 1 + 2 | 1 | 2 | 3 | 4 | First 4 | First 5 |
| Target Power (GWh) | 873 | 883 | 1759 | | | | | | |
| Generated Power (GWh) | 695 | 1172 | 1872 | 0 | 5343 | 7643 | 7611 | 20451 | 28561 |
| Power deficit (%) | -20 | +32 | +6 | | | | | | |

* Positive deficit = gain

*Table 9. Solution (C) better for Roseires reservoir (lower right point of the Pareto)*

| **Reservoir** | **Roseires (Year)** | | | **Mandaya (Year)** | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 1 + 2 | 1 | 2 | 3 | 4 | First 4 | First 5 |
| Target Power (GWh) | 873 | 883 | 1759 | | | | | | |
| Generated Power (GWh) | 687 | 1258 | 1950 | 0 | 4530 | 6749 | 6321 | 17466 | 25110 |
| Power deficit (%) | -21 | +42.5 | +11 | | | | | | |

* Positive deficit = gain

*Table 10. Solution (B) good for both Roseires and Mandaya reservoirs (Pareto midpoint)*

| **Reservoir** | **Roseires (Year)** | | | **Mandaya (Year)** | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 1 + 2 | 1 | 2 | 3 | 4 | First 4 | First 5 |
| Target Power (GWh) | 873 | 883 | 1759 | | | | | | |
| Generated Power (GWh) | 693 | 1121 | 1919 | 0 | 4677 | 7634 | 7720 | 19886 | 28051 |
| Power deficit (%) | -20 | +38 | +9 | | | | | | |

* Positive deficit = gain

By comparing the simulation scenario of filling with small volume of control flow it is noticed that it is the best one for Mandaya power generation. Simulation result shows 22% deficit in power generation at Roseires during the first year of filling. In the second year the simulation result shows a gain of 7%, while it can also be seen from the optimization results that there is a 32% additional gain in power generation.

When comparing the simulation scenario of filling with large volume of control flow, which is best for Roseires power generation, it is shown a 12% deficit in power generation in Roseires during the first year of filling, while the optimization result shows 21% deficit.

In the second year the simulation result shows that power generation in Roseires grew rapidly to1187 (GWh) having a gain of 34%,

In conclusion the developed approach shows it can assist decision making in water resource planning and management. The output of the optimization is a set of Pareto front optimal solutions which offer decision makers different solutions from which they can agree to choose one. It should be noted that these optimization results are supporting decisions, the final decision will depend on the negotiation between decision makers.

# 4. DECISION SUPPORT SYSTEMS AND STAKEHOLDER INVOLVEMENT

## 4.1. Scientific and technical contributions to aspects decision support systems

The main aim of this chapter is to present the added value of the approach taken by the candidate in developing frameworks for decision support systems for flood related problems. Presented theory and applications are based on article [8] (see page 3 of this thesis).

The final goal for development and usage of a DSSs is to help decision makers in their day to day work, as well as to inform and involve stakeholders. An added aspect of the problem is the necessity to deal with complex environmental situations, which requires a multidisciplinary approach that can be achieved through virtual organizations over a web-based environment.

Decision support systems presented herein addresses the following aspects:

- Developing a framework for decision support systems (Popescu et al,2012b); (selected publication [8]);
- Demonstrating the use of framework.

Apart from the published papers in peer reviewed journals, research results were disseminated to conferences, such as:

- 5th International Yellow River forum, 24-28 September, 2012, Zhengzhou, China
- 9th Interrnational Conference on Hydroinformatics 2010 Tianjin, China
- BALWOIS 2010 Conference on Water Observation and Information System for Decision Support, Ohrid, Republic of Macedonia
- 8th Hydroinformatics International Conference, January, 2009, Conception, Chile
- European Conference on Flood Risk Management, September, 2008, Oxford, UK
- International Symposium "Preventing and fighting hydrological disasters", 29 June-1 July, 2006, Timisoara, Romania

On invitation workshops and keynote presentations related to the topic of decision support systems were done as follows:

- Conducted a workshop on Decision Support Systems for Black Sea Catchment at BALWOIS, International Conference on water, climate and environment, 28 May – 2 June 2012, Ohrid, Republic of Macedonia
- Invited speaker at Agua 2007, 2007, Cali, Colombia on “How to make use of knowledge from data rich areas to solve water supply problems in data scares areas”
- Invited speaker on “Hydroinformatics and the use of Technology for Facilitating Sharing of Environmental Services”, at Department of Computer Science, Bicocca University, (Milan, Italy, 2011)

Candidate has organised the following symposia related to the topic of decision support systems:

- Co-organiser of Open Water Symposium, April, 2012Delft, The Netherlands;
- Organiser of LENVIS - Localised ENVironmental Information Systems symposium November, 2012, Delft, The Netherlands;
- International workshop on Planning and design of Observatories Obermann centre, August, 2007 Amana, US;

## 4.2. Introduction to decision support systems

The requirements for development and implementation of DSSs are particularly pronounced in developing countries, where pressures arising from economic development, population growth and environmental concerns are presenting challenging and complex water resources problems (Jonoski and Popescu, 2004). Many of these countries are at the same time struggling with not sufficient human capacity for addressing these challenges, especially regarding the competences for design, development and usage of a DSSs. The multidisciplinary demand of such systems can be achieved by using a web-based environment. The advantage of such an approach is the reduced costs and increasing efficiency of environmental management. More importantly such approaches facilitate sharing of common interests and objectives among different agencies, but also among concerned citizens. Not only efficiency criteria, but also citizenship as a fundamental democratic concept in Europe, require facilities for citizens' active involvement in environmental management. Such goals have been addressed by the research work presented in Popescu et al.,(2012b) and Almoradie et al, (2013a,b) and are work results of DSS-Romania project and enviroGRIDS project respectively (research grants). The outcome of the research are web-based systems that serve as demonstrators on how sharing of information and stakeholder involvement can potentially be achieved with the support of the latest technologies for web-based provision and sharing of information.

The architecture of such a system is presented in Figure 36, and the description of the demonstrators is given in section 4.3. and 4.4 of this thesis.

## 4.1. Timis-Bega Flood decision support system

The west part Romania is one of the regions most vulnerable to floods, because many rivers in this region are of trans-boundary nature. The rivers in this area share their basins either between Romania and Serbia, or, Romania and Hungary. Any flooding event on these rivers is advected and affecting both Romania and the two downstream countries. A typical example is Timis River, which caused a lot of flooding in both Romania and Serbia. In the last years unexpectedly flood propagation was faster than usually causing severe floods and damages due to the flood protection dikes located along the river.

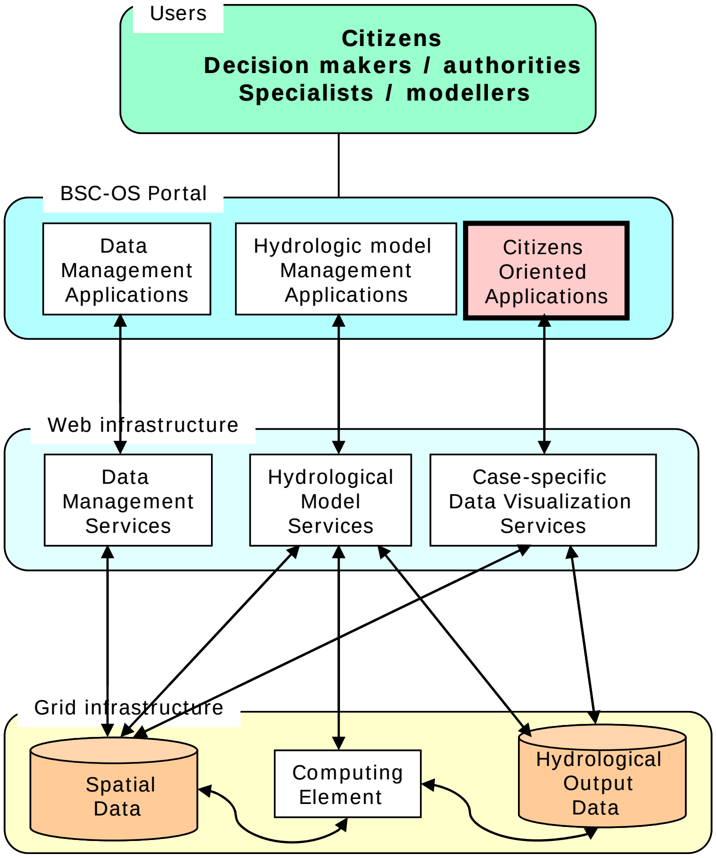


*Figure 36. Portal tools and services relevant for the citizens-oriented applications*

A demonstrator of a flood forecasting system for the Timis and Bega river catchment, was developed within a collaborative project between Romania and the Netherlands. This was done in order to prove the capability of such a system to support operational water management, especially during extreme flood events when quick decsions need to be taken.

Because of the particularities of Timis and Bega rivers, these were considered to be as one single catchment (and river). The system has a set of hydraulic structures that allows the transfer water between the rivers, making them one river system. The Timis - Bega catchment is of transboundary nature, discharging water beyond Romanian border, in Serbia. Bilateral agreements betweenRomania and Serbia specify the amount of discharge and water quality to be conveyed from one country to another (Stanescu and Drobot, 2005).

The system of transferring water from one river to another is 250 years old, and has been developed as an engineering solution to the recurring floods in the area. The hydrotechnical work comprised correction of the river path; construction of dykes and of several permanent and non-permanent reservoirs (trasnversal and/or lateral); drainage of swamps; construction of a network of drainage canals, together with pumping stations. The main hydrotechnical work is the double canal connection between Timis and Bega Rivers. These cannals are working gravitationally, transferring flow from one river into the other, depending on the flow conditions. In normal flow conditions water flows form Timis to Bega in order to supply a minimum amount of water for the city of Timişoara. In highwater conditions, water is flowing from Bega to Timis, in order to ensure flood protection of Timişoara.

Inspite of all these efforts, several extraordinary flooding events were recorded in 1912 and 1966 (at Lugoj); or in 2000 and 2005 (at Grăniceri), in the Timis-Bega catchment. The events triggered dike overtoppingand. In 2005 three dyke failures; one along Timis, and two breaches along Bega, upstream of Timişoara (the largest city in the area) resulted in flooding of 25,000 ha of land, with a volume of 300 - 350 million m$^3$ which led to severe damages (Moya Quiroga et al, 2013).

Given the above events it is clear that a decision support system that will help authorities to forecast and envisage flooding events and mitigation measures would be helpful. Moreover such a system could have a component that would allow warning of the concerned citizens. Such a system would need to integrate hydrological and hydraulic data and models, of past year events, and map them using GIS tools. Such a system requires ICT technologies and knowledge. While coding such a system attention needs to be given to the quality of data and models with respect to users' demands. Users requirements are mainly concerning presentation and communication of model results. This is a very important aspect to be addressed while developing a DSS, because it ensures the use of the system by users (Jonoski and Popescu, 2004, Popescu et al, 2012b).

For the Timis Bega catchemnt such a system has been developed within the DSS-Romania project. The architecture of the system is presented in Figure 37. The main components of it are:

- Presentation layer, that visualizes in maps and graphs data already available in a database. The elements of catchment are spatially located; hence a geo-graphically user interface is normally used for the presentation layer. The main elements of the system are rivers and canals, roads and/or cities and are represented on a map.
- The database with results. This databases contains model results and on site measurements.
- Two modelling components; an on-line simple rainfall-runoff model, and an off-line detailed hydraulic model.

The on-line component used the USACE HEC-HMS modelling system (a hydrological model), focusing on real-time flood forecasting, based on real time meteorological and hydrological data measurements. Such models are used for short term operational DSSs.

The off-line model combines the HEC-HMS component with a 1D HEC-RAS hydrodynamic model and a SOBEK 1D-2D model f to determine flood inundation extent.

The on-line model is used to determine water levels and discharges in identified critical points of the catchment. The HEC-HMS hydrological model of the Timis- Bega catchment contains 20 sub-basins, clustered based on their common physical characteristics. Any result coming from this model is stored in the DSS layer containing the database, along with measured discharges and precipitation.

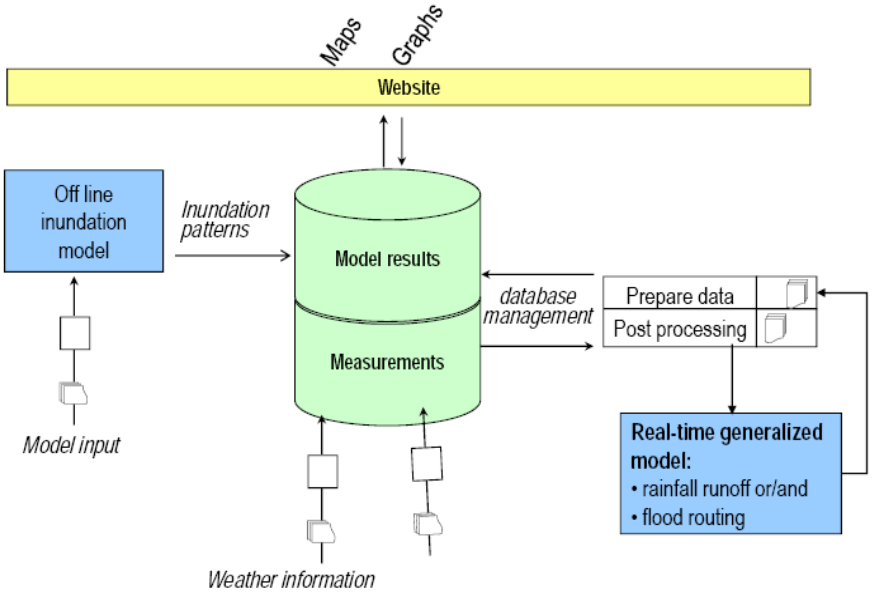


***Figure 37. Architecture of the Timis-Bega flood DSS***

The database is also used to dynamically input data into the on-line HEC-HMS model. The results of the on-line model are deployed on a web interface that has graphs with model results, or reports and tables. Forecasted discharges for Timis and Bega rivers obtained based on the HEC-HMS model are part of the presentation in the web-based part of the DSS-demonstrator. All results can be viewed from any computer. Due to the sensitivity of presented information, at the moment the webpage is secured with a password. Snapshots of the interface of the DSS are presented in Figure 38, and Figure 39, where points of interest where forecasts are given can be seen, as well as graphs with forecasts, as soon as a point of interest has been selected.

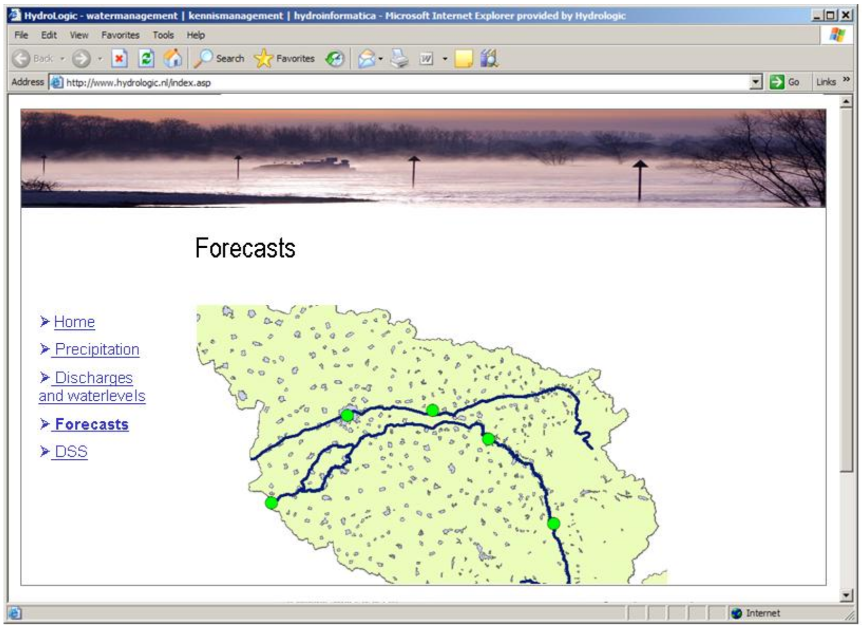


***Figure 38. Web-based user interface: Forecast menu***

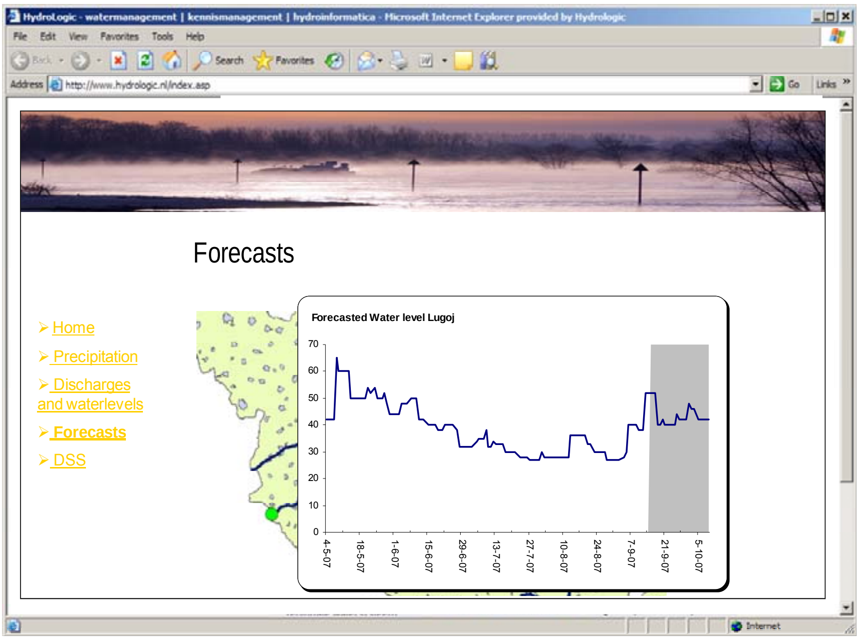


*Figure 39. Web-based user interface: Graph visualisation*

The main conclusion is that on-line results coming from a flood modelling that has data available in real-time is important in forecasting and warning, because it helps to understand how flood was generated and can help in identifing potential risk areas. This allows for proper on-time warning of the downstream communities. Flood modelling used in off-line facilitates long-term planning in order to reduce flood damage, by analysing different possible alternatives. these alternatives can be evaluated both from environmental and economical point of view

The requirements are different however for on-line and off-line models. The on-line models, for flood forecasting, require fast and accurate simulation of discharge peaks for a known water system, while off-line models need to provide a physically-based reliable simulation of the flood behaviour for a wide range of conditions. The DSS demonstrator developed in the above mentioned project shows the potential of using such systems in flood management. The system can be further improved to include historic flood data, property, infrastructure and community data and thus assist in the development of emergency evacuation plans.

### 4.2. Citizen observatories

Present section presents the outcome of research carried out within EnviroGRIDS 4-year project (2009-2013) funded by the EC Seventh Framework program (FP7). EnviroGRIDS aimed to gather, store and provide analyzed, processed and visualized information about the freshwater resources of the entire Black Sea Basin to decision makers and to the public so as to enable sustainable development of the area following the requirements of the Water Framework Directive. The project has been set up in recognition of the need for harnessing the potential of the latest ICT technologies for data collection, storage and sharing, together with latest developments in modeling technologies, in order to deal with the complexities of achieving sustainable development in the region.

With 30 partners distributed in 15 countries, the enviroGRIDS project aimed at building the capacity of scientists to assemble an observation system in the Black Sea Catchment, the capacity of decision-makers to use it, and the capacity of the general public to understand the important environmental, social and economic issues at stake. Detailed reports are available at www.envirogrids.net . In this section the work done in the area of providing citizens with access to a BSC-OS portal (i.e. Black Sea catchment-Observation System portal) is presented. Such a portal gives users access to resources, tools, applications, and platforms. Main challenges and issues regarding the development of such a portal are presented.

Web-based systems are potential tools for flood information sharing, dissemination and participation. Moreover, the use of standards for publishing data in web-based system allows for efficient data transmission, data analysis and decision making. These three tasks (transmission, analysis and decision) are performed by different professionals, hence users, and consequently require different types of applications corresponding to their specific needs. Sharing same data in different perspectives requires specific data representation standards to be used. Within EnviroGRIDS project publishing water-related data over the web based was done using OGC WaterML 2.0-GeoServer framework developed by Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO). The usage of these standards is only one component of a web-based flood information system (FIS) developed for Somesul Mare basin in Romania. The FIS was developed as a demonstrator of how flood management authorities can share information to potentially-affected citizens, as well as how decision makers can collect relevant information from them. The latest technologies for collection, archiving and sharing of environmental data, using web-based Spatial Data Infrastructure (SDI) were implemented.

Somesul Mare is a sub-catchment of the Somes. The catchment is 5078 km$^2$, vulnerable to flooding during the spring season especially because of snow melting in the mountainous area of the catchment. Flood is even worse when rainfall and snowmelt occurs in the same time. In 1970 the corresponding 1:100 years return flood has occurred. Lately, on Somesul Mare there are often flash floods occurring, as it is for example the event from 2009. Such occurences demonstrate that there is a clear need for studiesthat would allow implementation of a better flood risk management strategy on Somesul Mare catchment.

Flood risk awareness of the citizens and information sharing is one of the last paradigms and approaches in flood management. An innovative solution to succeed in the implementation of a system that would reach the citizens in order to share information is through a web-based flood information system. The present section shows the implementation of a web-based FIS for Somesul Mare catchement that was designed to be simple, informative, interactive, customizable and flexible. The work was developed within the framework of EnviroGRIDS project. The system uses map based applications for publishing the available geospatial data, a web infrastructure , and data standards.

The FIS has three main components: (1) FRM awareness, (2) Flood information access and (3) Citizens participation. Figure 40presents the conceptual design of the FIS portal.

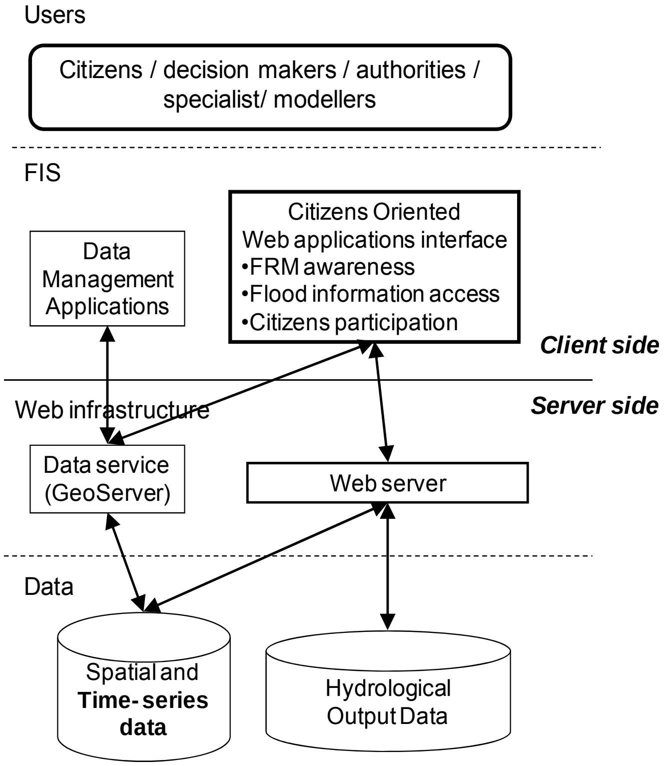
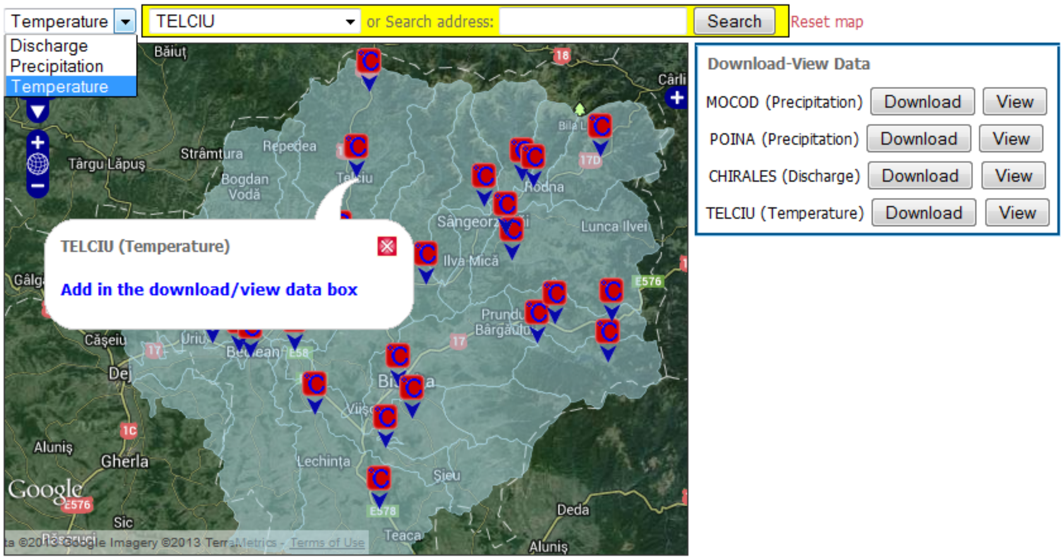


*Figure 40. ICT architecture of the FIS Somesul Mare observatory*

The web-based interface for the implemented architecture can be seen in Figure 41



TELCIU (Temperature)

Add in the download/view data box

Download-View Data

MOCOD (Precipitation) Download View
POINA (Precipitation) Download View
CHIRALES (Discharge) Download View
TELCIU (Temperature) Download View

*Figure 41. Snapshot of web-based screen for downloading data*

# 5. HIGHER EDUCATION IN HYDROINFORMATICS

Motto: " *Nu zidurile fac o scola, ci spiritul care domneste in ea"*
*(It's not the walls that make a school, but the soul that reigns in it)*
-Ferdinand I, of Romania-1920 –

## 5.1. Challenges of water-related education

Universities and higher education institutions offering water-related engineering education are facing new challenges in delivering support for lifelong learning and online educational courses. The curricula changes all the time along with the form of delivery because nowadays water problems require interdisciplinary approaches, which requires diverse expertise (Jonoski and Popescu, 2012; Popescu et al. 2012). Diverse expertise leads to shortage of graduates in key areas while in the same time there is a clear need of the graduates to find employment. Moreover water related problems are not country specific, they cross boundaries, both geographically and professionally. This requires linking different professionals from different locations, hence creating alliances As such new working styles are created, that become important in managing water-related assets and the aquatic environment. Therefore appropriate education becomes highly important leading to definition of curricula that has diversification of disciplines. Even though curricula, is comprised of many disciplines, diverse expertise can only be maintained through continuous professional development. As such Hydroinformatics education is challenged to find appropriate combinations of course delivery while developing relevant curricula.

In addition to all of the above stated education challenges an important element in defining curricula is introduced by the European Credit Transfer System (ECTS), which defines education in Europe at two levels, i.e. Bachelor's and Master's, with 180 to 240 ECTS for Bachelor and 60 to 120 ECTS for Master. These degrees (Bachelor and Master) are formulated with defined learning outcomes and competencies, so that comparison of higher education among different universities and countries is easily done (Gonzalez and Wagenaar, 2003).

In the above European context of education and employability needs of the graduates, the fact that universities in Romania as well as the institute where I am currently employed, UNESCO-IHE, are undergoing an accreditation procedure every 5 years, shows that it is very important to understand what is the education message that we sent to our students, and what we can do so that we fulfill students needs to join the work market after graduation (Birnbaum, 2000).

From academic point of view, the analysis that " institutions should" not " neglect systematic and regular formative evaluation of their teaching and learning policies, practices, support services, and built environment in order to improve learning outcomes and to demonstrate accountability", as pointed out by Sylvia Huntley-Moore and John Panter (2006), remains a must.

## 5.2. Defining courses in Hydroinformatics

This section of the thesis is based on the findings of paper [6] of the selected papers (see page 3 of this thesis).

UNESCO-IHE offers post-graduate Master of Science education for 18-months, composed of two parts: a taught part for the first 12 months and a research part for the last 6 months, with a total of 106 ECTS points. The taught part is structured in 14 blocks of 3 weeks, called Modules, which cover a particular field or domain within the offered MSc Programme. Each module has, on average, a load of 5 ECTS and 140 study load units. Within a particular module, several topics are covered. These are called courses, and each course is delivered in the form of lectures, exercises, debates, movies, hands-on exercises, etc.

A graduate in Hydroinformatics needs to know a diversity of technologies for the development of Hydroinformatics applications. The knowledge of a diversity of tools depends on appropriate educational approaches. The most adequate Hydroinformatics expertise is obtained trough educational programmes at master of science level. This is suitable for hydrotechnics, civil engineering, environmental engineering or computer science graduates. Shorter training courses in Hydroinformatics related area are also available at different universities, however most often these are linked to the content of existing MSc programmes. Such short courses are targeting experts who seek continuous professional development (Kaspersma et al., 2012), while dealing with rapidly evolving Hydroinformatics technologies.

The MSc specialisation in Hydroinformatics at UNESCO-IHE is an example on how to introduce the common structuring of a typical Hydroinformatics programme. The programme starts from the classical approach of developing mathematical models, as a means for solving engineering problems, followed by methods of new types of modelling paradigms such as data-driven or agent-based modelling. The different modelling approaches are demonstrated for different application along with their advantages and disadvantages. The structure of the programme together with the targeted application areas and associated tools and techniques are presented in Figure 42.

Attending courses in the classroom (traditional setting), however may be expensive for prospective Hydroinformatics professionals, especially those from developing countries, who may have difficulties in securing funds to follow such a course. New methods of transferring Hydroinformatics education are via web-based collaborative engineering (Molkenthin et al., 2001) or online courses (Popescu et al, 2012).

As a lecturer at UNESCO-IHE I have been involved in the development of two on-line courses for the same topics that I am presenting here as research topics; flood modelling and decision support systems .The main challenge in development and implementation of an online course is the development of suitable learning material. Learning material, such as lecture notes, tutorials and exercises, that are available for the face to face version of the courses are not sufficient for mastering the topic by the distant learners. Special learning material using audio-visual material in electronic format is needed. This requires a serious effort and time for development.

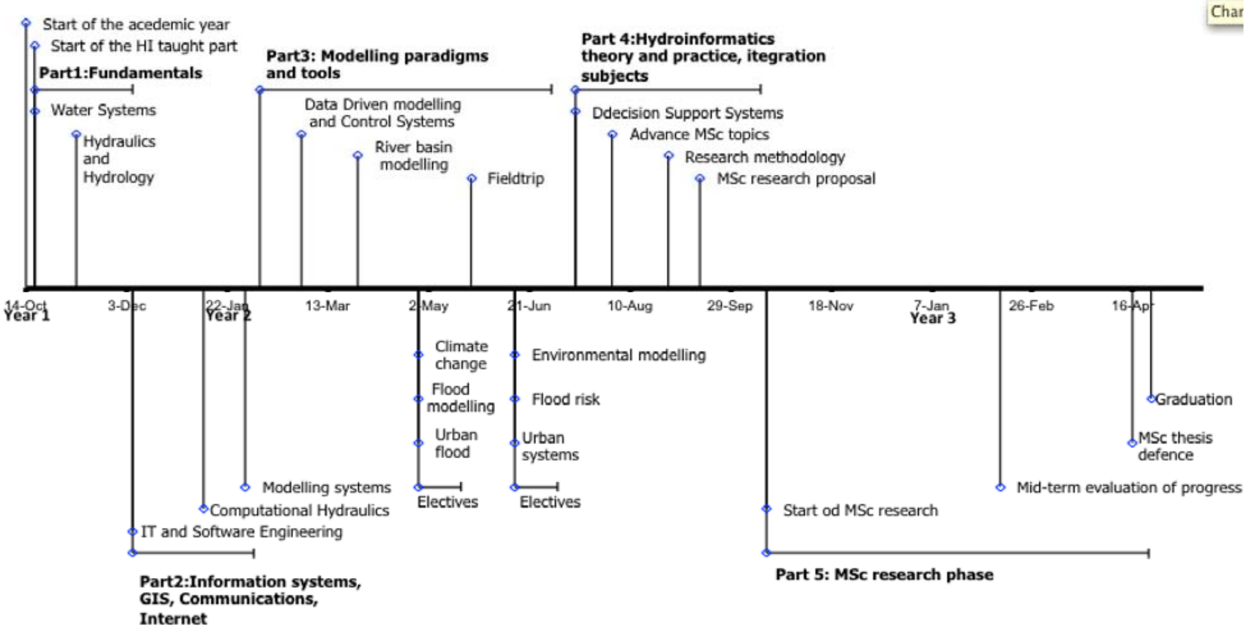


***Figure 42. Time sequence of the taught part and the research period of the MSc programme in Hydroinformatics.***

Popescu et al, (2012) gives extended description on how two online courses have been developed. An evaluation between face to face and on-line education of the two courses is presented in the same paper. The main conclusions are that in the face to face setup most of the lecturer's time is spent in a clear concentrated period of the day (during lecture and exercise sessions), while in an online course a longer time of the lecturer is required in order to verify the questions that arise, as well as to elaborate answers that need to be prepared in a written format. The time investment of a student in an online course is better because he/she has a higher control on the time spent for learning, while in a face to face course, learning time is stricter defined.

## 5.3. Evaluation of face to face flood modelling course

As an academic I have been involved in developing the active learning courses mentioned above, both face to face and on-line types. Before explaining the motivation for developing curricula in Hydroinformatics, I find it important to state what is my personal teaching philosophy. This is as follows; (i) as a teacher one should always learn, and because I do like to constantly learn, I do enjoy teaching; (ii) inspire students to be curios about the topics taught raise their wish to explore these topics; (iii) while teaching students, one way or another I have always learned something new, all my students have taught me something; (iv) always answer questions, always explain, even if you have to stop and use associations with trivial examples from everyday life, in order to make them understand; (v) Though IT tools (power points, smart boards) are very useful for delivering clear and good content, never depend solely on them, teach what you know, be prepared to close all IT and notes, take the chalk and give a class, you might make mistakes, do not be afraid of it because student questions will correct these and you will make things right.

After teaching for over 24 years, of which over 14 years in an international environment, looking at the teaching philosophy I have, one should always question ones self if the philosophy is met or even if the philosophy is good enough.

The advent of computers has enabled applied mathematicians, engineers and scientists to find solutions to previously unsolved problems, therefore the teaching of *Computational Hydraulics* became an important theoretical topic in any engineering curricula, not just for water engineers in particular. In order to improve this particular course that I am teaching, an extended evaluation of my own course is carried out every year based on an own developed evaluation questionnaire for the course, which it is distributed every year to the students. The overall result of the academic year 2013-2014 is presented in Figure 43.

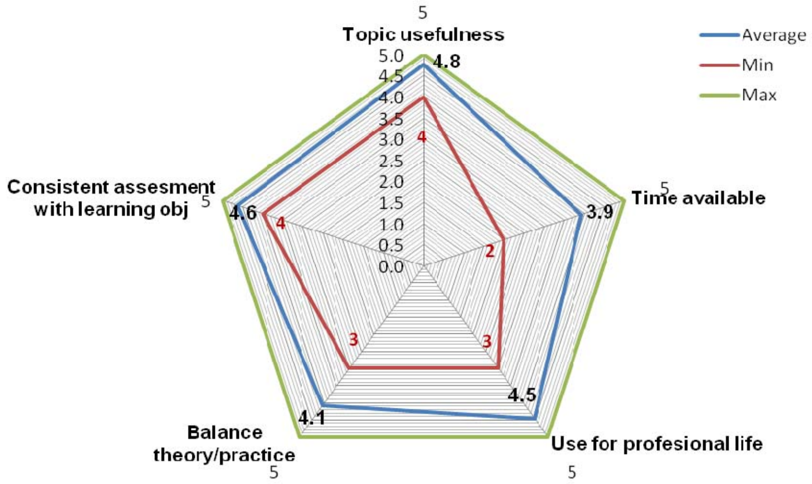


***Figure 43. Evaluation of the students for the course Numerical Methods***

In Figure 43 several components of the course such as time available and topic usefulness are evaluated. The scale considered is from 1 to 5 (1 - lowest and 5 - highest). The maximum obtained values, as well as the minimum, are shown on the spider evaluation diagram. The average obtained score for the evaluated elements is also shown in the graph.

The evaluation of the course in terms of the clarity of teaching and of the material provided to students, for the same academic year (2013-2014) is given in figure 6 and 7.

In figure 6 the scale is from 3 to 5 for better representation of the skills that need improvement.

## (B-ii) Scientific, professional and academic future development plans

### Research

As presented in (B-i) my current research agenda highlights the main area of research of Hydroinformatics, from which three main thrust areas of research are emphasized; mathematical modelling and methods with special focus on floods; use of optimization methods to enhance the use of models; and decision support systems for stakeholders empowerment.

The first of my interests involves exploring numerical methods in Computational Hydraulics and accuracy of models for river systems for 1/2/3 dimensions, with special focus on floods. Computation and all aspects of floods is the research area I am heavily involved in and will develop further. A new numerical method is explored currently for flood modelling, the Smooth Particle Hydrodynamic (SPH) method. As presented I am currently involved in flood modelling on the Yellow river, Mekong river delta, Niger delta, as well as in Panama through studies on flood wave propagation due to dam break. I have been previously involved in flood studies related to the Mississipi basin (US); Timis-Bega, Somes and Danube rivers (Romania); Elbe river (Germany); and Dhalai river (Bangladesh). I choose to emphasize in this thesis the research done on the Yellow river in China. Most importantly I will continue on the development and testing of an accurate model for such large river systems, where different discretisation and solution methods (structured versus unstructured meshes, finite differences versus finite volumes) are applied and the best technique and accuracy of result are tested. The special research line about the inference between flooding of large river systems and the operation of the complex system of reservoirs is investigated and developed further. Moreover, since 2009 I am exploring within a PhD research, that I supervise, ice-triggered floods on the Yellow river. This is quite a novel topic, not largely addressed in the (scientific) world, though of interest to the research arena.

Since 2005 I have also been addressing the vulnerability of floods in the Mekong delta and adaptation strategies in case of climate changes However, the aim is to further extend the concept in which flood vulnerability is regarded just as one number, by coupling vulnerability with physically based models and developing a methodology in doing flood damage assessment. This is an on-going work for which the advancements were presented in the habilitation thesis. The work has been extended to Niger delta and a new vulnerability index proposed together with one of the PhD students that I supervise. The new developed index has been presented at several international conferences and in peer review papers.

As one could never develop a field without sound check with his colleagues in the field, in all research I am collaborating and developing the field with my colleagues at UNESCO-IHE and outside the institute (IIHR Iowa (USA), Leeds University (UK), Yellow River Commission, Romanian Waters-Banat Branch, etc).This is done through research projects in which we are working together.

Another aspect regarding lakes and reservoirs, which I am involved in, is the optimisation of reservoir operation. I have been involved in the research study regarding the optimisation of the filling of the Mandaya reservoir in Ethiopia and its impact on Roseirs reservoir in Sudan. Furthermore the integration between this second research topic and the first one has been addressed by doing research on the operation of complex reservoir systems of the lower Yellow river and their operation strategy in case of floods. In this context an inference model between the operation of the reservoirs and the flood extent in the downstream reach of the Yellow river has been developed. Such a study is currently used by Yellow River Comission to see how such model can improve their strategy in decision support and how can decision makers learn from models and data.

In the case of reservoir operation optimization, conventional reservoir management strategies typically optimize energy and economic benefits and address ecosystem values as constraints on reservoir releases. Future research on reservoir optimization will focus on optimization that will explicitly include environmental objectives. It is my conviction that this helps in developing sustainable management strategies for reservoir operations.

So far I have been addressing many aspects of modelling floods, however the future lies into the possibility of involving stakeholders and migrating to intelligent Decision Support Systems that will provide a platform for collaboration and negotiation, not only of professionals but also of citizens affected by a particular decision. Steps have been taken towards this line of research, and the vision is to take advantage of the available technologies and to further integrate flood modelling with decision support systems. In the case of mathematical models, some processes (as for example eutrophication, evaporation, sediment transport etc) are still not fully described in the models, therefore the inclusion of modern techniques, such as remote sensing, will be on my research agenda for the future.

As part of the examples given, the use of technologies for proper involvement of stakeholders and citizens, for sharing information about environment is at the center of my research as well. Sharing of data regarding water is an important aspect.

On a general level I would like to mention that my research is geared towards development and application of integrated tools for decision support systems. I am collaborating with different research groups in the world, which assures that the Hydroinformatics group is well connected with its pears and up to date with the developments therefore ensuring that we are contributing to developments in the field.

### Education (Academia)

Education is considered to be crucial for the success of individuals and countries, and as a consequence the concept of lifelong learning form the basis for the so-called "knowledge-based" economy. Water resources management are an essential part of economies, thus, education, training, and transfer of technology for water resources are important aspects of societal policies for a sustainable future.

"What does the water profession expect from education?" is one of the questions that I am trying to address in my work for development of programs by considering the need to match demand and supply, as well as by doing a continuous quality assessment of the education and training delivered. In this context, so far, my career includes experiences with several academic programs and research projects that have taught me a lot and have inspired my teaching of others. Although my current research tends to be focused on floods and decision support systems, my educational background allows me to effectively teach a diverse array of graduate courses (Computational hydraulics, River system modeling, Decision support systems, Collaborative Engineering, etc).

Throughout the years I have also been active in guiding MSc research, as well as performing coordination tasks regarding the taught programmes at UNESCO-IHE and at former Faculty of Hydrotechnics in Timsioara, Romania. Since I have finalized my own PhD I have coordinated the specialization of Hydroinformatics (2005-2007), and the Water Science and Engineering programme (2010-2011).

It was the constant wish for exploring modern ways of teaching along with classical ones that made me further pursue my desire to "e-volve" from a chalk teacher to one capable of mixing different methods and approaches to education. Therefore the teaching methods applied by me range from regular face to face teaching and teaching in on-line environments to interactive involvement of students through student centered learning methods. In order to check and support these methods, I have followed, throughout the years, different specialization courses regarding teaching methods. The last such course is the University Teaching qualification course, which was finalised in 2011, and for which I had to involve my students in the evaluation. The experience enriched my understanding of what students expect from classes and also gave me the chance to do a sound check, with students and colleagues, of my own teaching.

I have been equally involved in research projects varying from testing and implementation of educational paradigms and platforms (www.TENCompetence.org), short course delivery, collaborative engineering works, tailor made programmes, organizing educational networks (www.etnet21.net) (please see CV for a list of projects), and conference sessions and workshops related to education. A direct consequence of my involvement in organizing educational sessions is that I was the IAHR Chair of the Educational and Professional Development Committee, In addition to my significant contribution in Education, I look forward to develop and strengthen the education at UNESCO-IHE MSc specializations and at different universities in Romania, by connecting them and by trying to facilitate exchange of master and PhD students, as well as academic staff exchange, so that both institutions would benefit from such exchanges.

The main focus in education would be to continue and develop advanced courses in Computational Hydraulics, Mathematical representation of physically based models and Flood modeling. These courses are developed both at a programme level and as short courses. Apart from developing on-line courses, and being involved into the Open Courseware initiative where I teach Computational Hydraulics as a free Open Courseware course, based on need and demand I will continue developing tailor made courses for the topics I am responsible for, and I will contribute to other courses when needed.

Development of online courses is still one of my continue work. It requires significant efforts in developing learning material and supporting the online learning process of diverse groups of learners. For many water-related fields, including water resources planning and management, many aspects can be covered by standard approaches of developing electronic versions of lecturing material. However for the field of DSSs, the development and implementation of online courses becomes challenging, because by nature, this topic requires exemplification of software tools and systems, such as simulation models, encapsulated optimisation techniques, or MCA tools (Calizaya et al. 2010). The learning environment therefore should take into account the working professional environment of the learner (Makropoulos et al. 2009; Cortés et al. 2011).

I consider that it is very important to mention that through my work in Education, I collaborate with colleagues from within the department, other departments and other universities by delivering different courses, as well as by involving colleagues in the modules that I am teaching, which I consider to be one of the important skills which an academic seeking to mentor and supervise PhD work should maintain.

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