Towards a Decision Support System for Flood Management in a River Basin
Towards a Decision Support System for Flood Management in a River Basin

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TOWARDS A DECISION SUPPORT SYSTEM FOR FLOOD MANAGEMENT IN A RIVER BASIN

ABSTRACT

The world is experiencing a countless number of impressive and devastating floods causing a range of health impacts and risks with hundreds of thousands of people losing their lives or becoming homeless in a matter of hours. These hydrological extremes are of growing concern for global, regional and national authorities due to the human tragedy and the associated socio-economic losses. EU Floods Directive requires the developing of flood hazard maps, which may include information on hydrological and hydrodynamics characteristics of vulnerable regions, i.e. inundated areas, river flow discharges and water levels. Prediction of flood events can accurately be achieved by applying mathematical modelling for describing rainfall-runoff phenomena as well as surface waters hydrodynamics.

In this work a platform for flood forecasting, FEWS-LIMA, implemented with Delft-FEWS software, was successfully applied in the case study of the Portuguese river Lima basin. This platform integrates SOBEK Sacramento hydrological model, SOBEK rivers hydrodynamic models that work together in predicting river hydrodynamics behaviour, and a comprehensive hydrological database. The calibration of these models was achieved using historical river flow discharges and water levels data in different rainfall events and considering the existence and inexistence effect of upstream river dams operation. Models predictions use rainfall time series as input data obtained from meteorological forecasting services, based on atmospheric models.

The performance of FEWS-LIMA platform created for the river Lima basin was verified in real rainfall events, using a backcasting approach to 4 flood events occurred in specific weeks in the years 2006, 2010, and 2011 in order to demonstrate the accuracy of the modelled processes. In addition, a forecasting event was also considered in order to show the applicability of this methodology in future situations.

It was verified, in this case study, that the obtained results have a high correlation to the actually measured typical flood hydraulic parameters (river flow discharges and water levels).

Keywords: decision support system, flood forecasting, hydrodynamics, hydrology, modelling
RUMO A UM SISTEMA DE SUPORTE À DECISÃO PARA A GESTÃO DE CHEIAS NUMA BACIA HIDROGRÁFICA

RESUMO

Nas últimas décadas tem-se registado um número crescente e impressionante de inundações devastadoras com centenas de milhares de vítimas mortais ou desalojados numa questão de poucas horas. Estes fenómenos hidrológicos extremos são motivo de crescente preocupação para as autoridades globais, regionais e nacionais, devido às tragédias humanas e aos prejuízos socioeconómicos que lhe estão associados. A Directiva da UE sobre cheias estabelece a obrigatoriedade de elaboração de cartas de zonas inundáveis, que devem conter informação sobre características hidrológicas e hidrodinâmicas de regiões vulneráveis (áreas inundadas, níveis de água e caudais). A previsão de cheias pode ser realizada com precisão com o auxílio da aplicação de modelos matemáticos que tentam descrever os fenómenos precipitação-escoamento, bem como a dinâmica dos meios hídricos naturais.

Neste trabalho foi criada uma plataforma de previsão de cheias (FEWS-LIMA, implementada no software Delft-FEWS) a qual foi aplicada, com sucesso, ao caso de estudo da bacia do rio Lima. Esta plataforma integra ferramentas de modelação de hidrologia e hidrodinâmica (SOBEK) que, em conjunto, prevêem o comportamento hidrodinâmico do sistema fluvial. A calibração destes modelos foi conseguida utilizando dados históricos de caudais e níveis de água em diferentes eventos de precipitação e considerando a existência ou não do efeito da operação das barragens a montante. Os modelos utilizaram, como dados de entrada, séries temporais de precipitação obtidas a partir de serviços de previsão meteorológica baseados em modelos atmosféricos.

O desempenho da plataforma FEWS-LIMA foi verificado em eventos reais de precipitação, aplicando-se uma abordagem de “backcasting” em quatro eventos de cheia ocorridos em 2006, 2010 e 2011 por forma a demonstrar a precisão dos processos modelados. Para demonstrar a aplicabilidade desta metodologia em futuras situações considerou-se, ainda, um cenário de previsão.

Foi verificado, neste estudo, que os resultados obtidos demonstram uma elevada correlação com os parâmetros hidráulicos medidos (caudais e níveis de água).

Palavras-chave: sistema de suporte à decisão, previsão de cheias, hidrodinâmica, hidrologia, modelação
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ACRONYMS

1DFLOW  One dimensional flow model
ADIMC   Tension water contents of the ADIMP area (mm)
ADIMP   Maximum fraction of an additional impervious area due to saturation
DSS     Decision Support System
EU      European Union
FEWS    Flood Early Warning System
GIS     Geographic Information System
GFS     Global Forecast System
GUI     Graphical User Interface
IPCC    Intergovernmental Panel on Climate Change
IT      Information Technology
LZFPC   Lower zone free primary contents (mm)
LZFSC   Lower zone free supplemental contents (mm)
LZFPM   The lower layer primary free water capacity (mm)
LZFSM   The lower layer supplemental free water capacity (mm)
LZPK    Depletion rate of the lower layer primary free water storage (day\(^{-1}\))
LZSK    Depletion rate of the lower layer supplemental free water storage, day\(^{-1}\)
LZTWC   Lower zone tension water contents (mm)
LZTWM   The lower layer tension water capacity (mm)
NOAA    National Oceanic and Atmospheric Administration
NWSRFS  National Weather Service River Forecast System
PCTIM   Permanent impervious area fraction
PFREE   Percolation fraction that goes directly to the lower layer free water storages
PI      Published Interface
REXP    Shape parameter of the percolation curve
RIVA    Riparian vegetarian area fraction
RR      Rainfall Runoff
RSERV   Fraction of lower layer free water not transferable to lower layer tension water
SAC-SMA Sacramento Soil Moisture Accounting model
SIDE    Ratio of deep percolation from lower layer free water storages
SNIRH   Portuguese National Information System for Water Resources
SREX    Special Report on Managing the Risks of Extreme Events and Disasters
SSURGO  Soil Survey Geographic database
UZFWC   Upper zone free water contents (mm)
UZFWM   The upper layer free water capacity (mm)
UZK     Interflow depletion rate from the upper layer free water storage (day\(^{-1}\))
UZTWC   Upper zone tension water contents (mm)
UZTWM   The upper layer tension water capacity (mm)
VBA     Visual Basic for Applications
XML     Extensible Markup Language
XSD     XML Schema Definition
ZPERC   Ratio of maximum and minimum percolation rates
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"When it is not in our power to determine what is true, we ought to act according to what is most probable."

Descartes (1596 – 1650)
CHAPTER 1  INTRODUCTION

1.1 Motivation and scope

Hydrological extreme (floods and droughts) and related geo-hazards (storms, forest fires, landslides and earthquakes) are of growing concern for global, regional and national authorities, since they cause heavy human tragedy and socio-economic losses. A significant proportion of these losses is caused by floods. Over the last decades, the world has experienced an increasing number of impressive and devastating floods, with hundreds of thousands of people losing their lives or becoming homeless in a matter of hours, abundantly reported by the media throughout all the continents: China (1931, 1939, 1980, 1998 and 2008), Philippines (2009), India (1978 and 2013), Pakistan (2007), Iran (1993), United States of America (1972, 1972 and 2005), Argentina (1958 and 2013), Brazil (1966, 1967, 1970, 1988, 2004 and 2010), African nations floods (Sudan, Nigeria, Burkina Faso, Ghana, Kenya, Ethiopia, Somalia, Mozambique) in 2006, 2007 and 2013. Severe fluvial floods, some of them with a trans-national dimension have taken place in Europe, such as the Rhine-Meuse floods in 1993 and 1995, the Oder floods in 1997, the Po floods in 1994 and 2000, the Elbe and Danube floods in 2002, the UK floods in 2007, and the Seine Floods in 2013 were considered as catastrophic natural disasters (De Roo et al., 2009).

According to EM-DAT (EM-DAT, 2013), floods comprised 43% of all disaster events for the period 1998–2002. During this period, Europe suffered about 100 major damaging floods. The European Environmental Agency estimated that floods in Europe between 1998 and 2002 caused about 700 deaths, the displacement of about half a million people and at least 25 billion euros in insured economic losses (EEA, 2003).

The environmental impact of floods occurring in large rivers includes: the clogging up of water treatment plants (potentially leading to the release of large quantities of contaminants); damage to vegetation, in some cases due to the duration of residence of water in the soil, and the mobilisation of contaminants present in the soil.

Flash floods can cause widespread destruction, although usually in relatively small areas and environmental damage, especially soil erosion, both on their own and in association with other natural events such as landslides. Fairly common in the Mediterranean and mountain areas, flash floods are a particular danger to people since, as their name suggests, they happen suddenly and with little warning. Diffuse flooding can also have environmental impacts, facilitating for instance the infiltration of polluted runoff into the local aquifers. Flooding caused by storms mainly affects
coastal areas and, by erosion, related ecosystems. It may coincide with high waters in river estuaries (EEA, 2003).

Floods have been the most deadly natural disasters in Portugal during the last century, followed by earthquakes (Ramos & Reis, 2002). Large river floods are caused by heavy rains associated with a westerly zonal circulation that may persist for weeks. The system of dams within the river basin reduces the frequency of flooding, but cannot fully control the river flows. Nevertheless, these floods are not a danger for the human population. In contrast, flash floods are more dangerous and fatal than these large river floods, as demonstrated in 1967 and 1997. They affect the small drainage basins and are caused by heavy and concentrated rainfall, active in the south of the country, in the Lisbon region, Alentejo and Algarve. Deforestation, soil impermeability, chaotic urbanization, building on floodplains, the blockage of small creeks or their canalisation, and the building of walls and transverse embankments along the small creeks all contribute to the aggravation of this kind of flood.

Climate change may cause a further increase in the flood hazard probability and magnitude, whilst it is certain that demographic and economic development is causing a continuous increase in the vulnerability of many floodplain and coastal areas. The Intergovernmental Panel on Climate Change (IPCC) presents a scientific literature based assessment on issues that range from the relationship between climate change and extreme weather and climate events to the implications of these events for society and sustainable development. From the “Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation” (SREX), (IPCC, 2013), the assessment concerns the interaction of climatic, environmental, and human factors that can lead to impacts and disasters, options for managing the risks posed by impacts and disasters, and the important role that non-climatic factors play in determining impacts. Figure 1.1 illustrates the core concepts of SREX. The report assesses how exposure and vulnerability to weather and climate events determine impacts and the likelihood of disasters (disaster risk). It evaluates the influence of natural climate variability and anthropogenic climate change on climate extremes and other weather and climate events that can contribute to disasters, as well as the exposure and vulnerability of human society and natural ecosystems. It also considers the role of development in trends in exposure and vulnerability, implications for disaster risk, and interactions between disasters and development.
Figure 1.1 - The core concepts of SREX (adapted from IPCC, 2012).

The report examines how disaster risk management and adaptation to climate change can reduce exposure and vulnerability to weather and climate events and thus reduce disaster risk, as well as increase resilience to the risks that cannot be eliminated (IPCC, 2012). They concluded that considerable uncertainty remains in the projections of flood changes, especially regarding their magnitude and frequency. There is low confidence (due to limited evidence) in future changes in flood magnitude and frequency derived from river discharge simulations. Projected precipitation and temperature changes imply possible changes in floods, although overall there is low confidence in projections of changes in fluvial floods due to limited evidence and because the causes of regional changes are complex.

The repetitive occurrence of such disastrous floods prompted the investigation of new strategies for flood prevention and protection, with focus on coordinated actions among countries sharing the same river basin. Moreover disaster management for urban areas is a growing priority since anthropomorphic factors such as unplanned urbanization and climate change have amplified the flood disaster risks (Price & Vojinovic, 2008).

Although substantial amounts of money were invested in flood protection and flood mitigation during the past decades the reported damages increased tremendously and continuously. One of the main causes is the change in land use in former flood plains from agricultural utilization to industrial and residential areas (Kenyon et al., 2008; Neuhold & Nachtnebel, 2008).
Flood risk assessment methodologies, using recently developed urban flood models have been applied to estimate likelihood and consequences of flooding effect in highly urbanized areas (Leitão et al., 2013).

During the past centuries, traditional approaches on flood management include structural flood protection measures (river training and restoration), early warning systems and evacuation planning, with the main objective of protecting people from the caprices of nature. The directive 2007/60/EC on the assessment and management of flood risks (EU, 2007) emphasises:

i. Floods have the potential to cause fatalities, displacement of people and damage to the environment, to severely compromise economic development and to undermine the economic activities of the community.

ii. Floods are natural phenomena which cannot be prevented. However, some human activities (such as increasing human settlements and economic assets in floodplains and the reduction of the natural water retention by land use) and climate change contribute to an increase in the likelihood and adverse impacts of flood events.

iii. It is feasible and desirable to reduce the risk of adverse consequences, especially for human health and life, the environment, cultural heritage, economic activity and infrastructure associated with floods. However, measures to reduce these risks should, as far as possible, be coordinated throughout a river basin if they are to be effective.

The main message of this directive is that disaster management should broaden its scope through the integration of disaster risk considerations into sustainable development policies, planning and programmes at all levels, with special emphasis on disaster prevention, mitigation, preparedness and vulnerability reduction.

Figure 1.2 depicts the disaster management cycle which is a widely used frame for flood risk management (Deltares, 2010). It distinguishes three distinct phases in flood risk management: prevention, flood event management and postflood measures. It clearly shows that flood risk management encompasses a wide range of activities and measures, ranging from the traditional flood defence measures, such as dikes and dams, to spatial planning, early warning, evacuation and reconstruction. This reflects the increasing awareness that solutions should be sought in a combination of measures to protect against flooding and to reduce vulnerability.
When preventive measures are not sufficient, flood damage can still be reduced through raised preparedness. Operational flood forecasting systems form a key part of preparedness strategies for flood events by providing early warnings several days ahead, giving flood forecasting services, civil protection authorities and the public adequate preparation time and thus reducing the impacts of the flooding. Many flood forecasting systems rely on precipitation inputs, which come initially from observation networks (rain gauges) and radar (Cloke & Pappenberger, 2009).

Real time flood forecasting is a very challenging issue because it serves as a sound decision support basis for authorities and people affected by these natural events. Hydrologic and river hydrodynamics models are essential elements of fluvial flood forecast systems.

This research work gives an overview of current available options for flood modelling in river basins, from hydrological and hydrodynamic calculations with a one-dimensional river model to detailed flood process representation with one dimensional–two dimensional hydrodynamic coupled models. A specific modelling solution is described and applied in a case study regarding flood forecasting analysis for a set of pre-simulated scenarios and real-time simulations.

### 1.2 Objectives

This research work has as main goal to contribute to development of a hydroinformatics advanced decision support tool for the operational management of floods in a river basin. This IT platform will serve as an early warning system and a means of preparedness for flood events.

Within this main objective the following specific issues were addressed:
Chapter 1  
Towards a Decision Support System for Flood Management in a River Basin

- Set up of hydrological models for a river basin based in Sacramento approach;
- Use of the implemented model combined with a hydrodynamic model in different planning scenarios;
- Integration of the calibrated and validated hydrological and hydrodynamic models in a flood early warning system platform;
- Identification of key variables for flood events within the river basin;
- Integration of a real time meteorological forecasting data in the developed system;
- Flood forecasting based on river hydrodynamics considering the tidal water level as downstream boundary conditions and the river discharges at the upstream boundary;
- Application of the implemented tools to different flood scenarios at river Lima basin to assess different flood management strategies;

1.3 Methodology

The aforementioned objectives have been devised for the construction of a decision support system (DSS) usable for flood management in a river basin scale. This justified the adoption of the case study approach that was applied in the Portuguese river Lima basin.

A wide spectrum of databases and model bases was applied in setting the decision support system.

The main source for data collection (rainfall, water levels and flow rates in rivers and reservoirs) was the Portuguese National Information System for Water Resources (SNIRH). Bathymetry survey information was obtained from previous research works developed at University of Minho (Ferreira, 2010).

The river basin hydrology was studied by means of Sacramento theoretical approach implemented with GIS support, and the river hydrodynamics was simulated using SOBEK software. Models calibration and validation were performed using historical data series of rainfall, river flow discharges and water levels, reservoirs water levels, measured from 1932 to 2012.

This set of hydroinformatic tools was integrated in Delft-FEWS platform to construct the DSS.

Modelling and simulation were performed in the river Lima basin case study. Flood forecasting results (river discharges and water levels) were obtained for different rainfall event scenarios.

The flow chart of the adopted methodology is shown in Figure 1.3.
Figure 1.3 - Methodology flow chart.

1.4 Organization of the dissertation

The outline of this dissertation is as follows.

Chapter 1 describes generically the motivation and scope of the present research work. It also highlights the main objectives and the methodology adopted throughout the dissertation. This is followed by the structure of the manuscript.

Chapter 2 gives a general view of climate changes aspects and their consequences to flood events and discusses capabilities and limitations of different hydroinformatics tools that can be used in hydrologic and hydrodynamic modelling in river and coastal environments. Conceptual hydrologic approach and decision support systems for flood management are also described.
In Chapter 3 a general description of the study area (river Lima basin) is presented where the main interesting issues for modelling are highlighted including the location of meteorological and hydrometric monitoring stations. This chapter also includes the observed data on rainfall, river flow rates and water levels that served as basis for models implementation.

Chapter 4 describes the modelling tools developed and applied in the present work including their theoretical background, numerical details and implementation information. Calibration and validation of models are also included in this chapter.

In Chapter 5 the main assumptions for the development of FEWS-LIMA decision support system are exposed. This chapter presents the platform conception, the configuration of the system and the processes implemented in forecasting flood events.

Chapter 6 describes the application of FEWS-LIMA to the study site, and presents the results obtained and their discussion.

Chapter 7 presents the general conclusion for this work.

Chapter 8 lists by alphabetic order of first author the bibliography referenced throughout the text.
“I know that I know nothing”

Socrates (c.469/470 B.C.-399 B.C.)
CHAPTER 2 STATE OF THE ART

2.1 Overview

The growing world water crisis is in part a failure of human society to be aware of the problem and its possible solutions. This crisis is perceived in different ways. For some it is the conflict between different uses, such as drinking water supply, hydropower generation, and ecological concerns. For others it is learning how to deal with the problems of climate change, whether leading to drought and desertification or more frequent and severe flooding in urban, fluvial and coastal environments. On the other hand the problems of increasingly polluted water resources due to point or diffuse sources from industry and urban wastewater discharges sources seem to be out of control and solutions in many cases are no longer simple to generate or implement.

Integrated water management involves an holistic view of a number of distinct systems which requires a wide range of information, namely scientific and technical information (covering physical, chemical, biological and socio-economic data for the natural system under study), management information (related with the available financial and human resources and planning activities), and public information (integrating a range of stakeholders who have direct interest in the water management process). Processing all this information takes the form of a high dimensional problem, which depends on the availability of efficient means to process required data as well as computational tools for simulation modelling in order to understand the behaviour of complex natural systems and to enable solving problems.

Our ability to model and analyse complex water-based systems is due almost entirely to the development of digital technologies. These have revolutionized the way in which we can reproduce the behaviour of such systems, especially in using graphics to analyse and present data, to track the building of models and to visualize output in ways that replicate images of the real world (Price and Solomatine, 2009). Nevertheless, one must be aware that the results obtained from models (based on well-defined and structured mathematical formulations) are in contradiction with the water-based systems that by definition are non-structured and badly defined.

Simulation models, optimization models, decision support models, databases, expert systems, geographic information systems (GIS), and information and communication technology have been extensively used in solving problems of hydraulics, hydrology and environmental engineering for better management of water-based systems. The coherent integration of these tools provides the
computer based decision support systems that now enter increasingly into the offices of engineers, water authorities and government agencies (Vieira et al., 2012).

### 2.2 Hydroinformatics

The emergence of hydroinformatics can be traced back to developments in computational hydraulics. Abbott (1991), the inventor of the neologism at that time, has defined it as the integration of computational hydraulics and of artificial intelligence, and has identified several generations of modelling activities.

The first generation was characterised by the use of (the first) computers as calculation devices of analytical expressions, i.e., as little more than superior slide rules.

The second generation of modelling appeared since users recognised the value of the sequential, repetitive and recursive modes of operation of their digital machines and turned to finite differences in order to represent and then solve differential equations numerically.

The third generation of modelling developed from about 1970 onwards, when it was recognised the possibility and value of producing software packages for a wide class of similar problems. This enabled resources to be invested on a system that could be used repetitively by a wide range of users. Standards were developed for input and output, preceding future links to databases, GIS and graphical display tools. In turn, the effectiveness of these third generation systems became heavily dependent on “main frame” computers, and the skills and experience of the users.

Since the early 1980s personal computers appeared as serious professional tools, and it was natural for the modelling software packages of the third generation to be ported to them. In turn, the whole mode of operation of the systems aspect of the packages was rapidly improved. This resulted in the modelling systems being used by people who were not computational hydraulics specialists. They demanded high standards of robustness, consistency and ease of use from the software providers, who adopted production means from software engineering and the information technology industry. It meant also that the focus of the developers was on the technology rather than scientific research.

The resulting fourth generation modelling systems have subsequently been transformed through close integration with databases, GIS and sophisticated graphics display tools (Price and Solomatine, 2009).

The birth of hydroinformatics has been identified by Abbott (1996) to have occurred during the transition between the third and fourth generations of modelling. He points out that the revealing
offered by the technology has been made to many thousands of users of fourth generation modelling systems, even if the users are still predominantly specialists in hydraulics, hydrology and water resources employed by different organisations.

The meaning has evolved since. Probably the most consensual definition would be today that Hydroinformatics is about making the best use of information technologies to manage water in the environment. The term “manage” is used here in very wide sense meaning dealing with the whole extent of information and engineering subjects, such as: data collection, measurement, interpretation, and design of river basin management strategies including civil engineering structures, modelling (simulation) of river, groundwater and coastal flows and water quality to forecast natural events (floods) as well as the impacts of human activities. (Pinho et al., 2013).

Hydroinformatics covers the application of information technology applied to the water sector in the widest sense. The continuously increasing speed of computers and increased density of information storage, the increased communication potential through internet and the creative power of scientists have brought us rapidly forward in the way in which water related studies can be executed, currently based upon a much better understanding of underlying physical-chemical and biological processes.

2.2.1 Modelling and simulation

Modelling is at the heart of Hydroinformatics. Models are constructed by the process of conceptualizing the real world system into structural and process objects and abstracting the collection of objects into a feasible system. A hydroinformatics model is designed by the developer who works from his/her own worldview, and particularly for the class of problems that the software package is supposed to address. It does not follow that the user has the same point of view as the developer. Consequently, there are big risks that the user will apply the software package outside the limits for which it was designed. Much is left up to the user concerning how to structure his/her model, what data to select, how to calibrate and validate the model, how to interpret and communicate the results, etc. The decision maker is usually yet a third person, who is even more remote from the modelling process, but intimately concerned with what the model produces in terms of information that will assist in the decision making process.

The application of modelling software tools has brought about radical improvements in our understanding of large-scale water-based systems, such as rivers, lakes, estuaries and coastal waters (Pinho, J.L.S., 2001; Duarte et al., 2001; Pinho et al., 2004; Pinho & Vieira, 2005). The tools have
been extended to include the advection and dispersion of pollutants in the flow, the transport of sediment suspended in the water column and as bed load, the consequences of the water flow for different biological species, the interaction of flow with structures, etc. More emphasis is now being given to the safety and reliability of a given software modelling system as it is of increasing importance for decision making in environmental official policies. In the last decades major efforts have been done to make water quality data bases and modelling tools available for water resources management at a river basin scale. The European Water Framework Directive encourages the use of these tools to investigate the surface water quality status and to anticipate the impact of measures to be implemented in order to achieve a good ecological status by 2015 (European Commission, 2000).

Nowadays a wide infrastructure of hydroinformatics tools is available for modelling and simulation of natural systems enabling a very high potential to be explored and expanded to improve service to society. It comprises: data acquisition and data management techniques; new simulation techniques based upon cognitive sciences and pattern recognition, such as artificial neural networks, data mining and knowledge discovery techniques; evolutionary algorithms; decision support and management systems; forecasting and data assimilation methods; fuzzy logic; cellular automata; integration of systems and technologies; and emerging internet based technologies (Verwey, 2005).

Over the years, several companies and research institutions developed modelling software. The competition is fierce and each software developed has different potentials. A research on some well-known modelling applications was made in order to ascertain their current capabilities. Some software is more mainstream than others, but because of the rivalry and competition from developers, these tools tend to increase in robustness and in wide range of applications offering more confidence and user friendly solutions in benefit of results reliability.

From a wide spectrum of software available for application in surface water systems a comparative study of their characteristics and computing capabilities has been made.

2.2.2 Modeling software – A review

2.2.2.1 POM (Princeton Ocean Model)

POM is a numerical ocean model created by Alan Blumberg and George Mellor around 1977 (POM, 2013). Subsequent contributions were made by Leo Oey, Jim Herring, Lakshmi Kantha and Boris Galperin and others. Institutionally, the model was developed and applied to oceanographic
problems in the Atmospheric and Oceanic Sciences Program of Princeton University, the Geophysical Fluid Dynamics Laboratory of NOAA and Dynalysis of Princeton.

This model is a three-dimensional, primitive equation, time-dependent, free surface, estuarine and coastal ocean circulation model. One apparently unique feature at time it was its imbedded turbulent closure submodel which on the basis of previous studies should yield realistic, Ekman surface and bottom layers. The model has been designed to represent ocean physics as realistically as possible and to address phenomena of 1-100km length and tidal-monthly time scales depending on basin size and grid resolution. The governing equations that are used to simulate all the scenarios as well as the boundary conditions are solved by finite difference techniques.

This model has some great principal attributes. It contains an imbedded second moment turbulence closure sub-model to provide vertical mixing coefficients and this sub-model the vertical coordinate is scaled on the water column depth. There is a horizontal grid that uses curvilinear orthogonal coordinates and an “Arakawa C” differencing scheme. The horizontal time differencing is explicit whereas the vertical differencing is implicit. The latter eliminates time constraints for the vertical coordinate and permits the use of fine vertical resolution in the surface and bottom boundary layers. The model has a free surface and a split time step. The external mode portion of the model is two-dimensional and uses a short time step based on the CFL condition and the external wave speed. The internal mode is three-dimensional and uses a long time step based on the CFL condition and the internal wave speed. Also, there is an complete thermodynamics analysis implemented on this software.

2.2.2.2 DELFT3D

Delft3D (Delft3D, 2013) software comprises several numerical models used to simulate natural environments such as coastal areas, rivers, reservoirs and estuaries. This model allows two-dimensional horizontally and three dimensional applications. It is a high complexity mathematical model and it’s applicable on analysing flows of tides, currents due to wind, river runoff simulations, lakes and bayous, the propagation of tsunamis, hydraulic rebounds, in coastal and fluvial morphodynamics and pollutant transportation analysis as well as in the water temperature changing panorama and salinity gradients.

Delft3D is composed of several modules, where the FLOW module gets greater prominence. Delft3D-FLOW is the hydrodynamic module of Delft3D, which is Delft Hydraulics’ fully-
integrated program for the modelling of water flows, waves, water quality, particle tracking, ecology, sediment and chemical transports and morphology.

The primary purpose of the computational model Delft3D-FLOW is to solve various one, two and three-dimensional, time-dependent, non-linear differential equations related to hydrostatic and non-hydrostatic free-surface flow problems on a structured orthogonal grid to cover problems with complicated geometry. The equations are formulated in orthogonal curvilinear co-ordinates on a plane or in spherical co-ordinates on the globe. In Delft3D-FLOW models with a rectangular or spherical grid (Cartesian frame of reference) are considered as a special form of a curvilinear grid (Kernkamp et al., 2005; Willemse et al., 1986).

The equations solved are mathematical descriptions of physical conservation laws for water volume (continuity equation), linear momentum (Reynolds-averaged Navier-Stokes (RANS) equations), and tracer mass (transport equation) and suspended sediments or passive pollutants. Furthermore, bed level changes are computed, which depend on the quantity of bottom sediments.

Delft3D-FLOW can be used in either hydrostatic or non-hydrostatic mode. In case of hydrostatic modelling the so-called shallow water equations are solved, whereas in non-hydrostatic mode the Navier-Stokes equations are taken into account by adding non-hydrostatic terms to the shallow water equations. A fine horizontal grid is needed to resolve non-hydrostatic flow phenomena.

This powerful computation model can be characterized in great distinguished properties. The grid alignment with complicated boundaries and local grid refinements to meet the needs of resolving finer spatial resolution in various numerical modeling tasks results in an accurate description of geometry. It has application for one and two-dimensional vertically averaged as well as hydrostatic or non-hydrostatic three-dimensional problems. Delft3D-FLOW is a solution technique that allows for solution based on accuracy considerations rather than stability (alternating direction implicit finite difference method). It’s a computationally efficient and robust software that as a computational core and a separate user interface and its extremely efficient coupled with other physical processes via the other modules of the integrated Delft3D modelling system.

**Delft3D-FLOW Applications**

This computational model can be used in a wide range of applications. Delft3D-FLOW can be used for an accurate prediction of the tidal dynamics (water elevation, currents) in estuaries or coastal seas, can be used for an accurate prediction of the density (salinity and/or temperature) driven flow and sediment concentrations can be taken into account with respect to density values. It also can be
used for an accurate prediction of wind driven flow and storm surges and as an accurate prediction of horizontal transport of matter, both on large and small scales.

Other use of this software is the ability to investigate the hydrodynamic impact of engineering works, such as land reclamation, breakwaters, dikes and the impact of hydraulic structures such as gates, weirs and barriers.

Delft3D-FLOW can be used for an accurate prediction of waste water dispersion from coastal outfalls, prediction of thermal stratification in seas, lakes and reservoirs and to describe and quantify the thermal recirculation between discharge and intake points.

Flows resulting from dam breaks can also be accurate predicted as well as small scale current patterns near harbour entrances.

These are just some applications of this software and as can be seen, the possibilities are endless and it’s concluded that the potential of this software is huge.

2.2.2.3 TELEMAC

TELEMAC was developed by the National Hydraulics and Environment Laboratory (LNHE, 2013) of the Research and Development Directorate of the French Electricity Board (EDF-DRD), in collaboration with other research institutes. All the modules of the TELEMAC system have been open sourced since July 2010 and can be downloaded on their official website.

The TELEMAC system comprises several modules including pre-processing, hydrodynamics, sedimentology, water quality, waves, sub-surface flows and post-processing.

Pre-processing is a software module designed to generate a mesh consisting of triangular elements, using bathymetric and/or topographic data.

The Hydrodynamics module consists in two big groups. TELEMAC-2D is designed to perform a hydrodynamic simulation in two horizontal space dimensions. In addition this module can simulate the transport of dissolved tracers. The TELEMAC-3D software is designed to carry out hydrodynamic simulations of flows in three space dimensions and it is able to simulate the transport of tracers and has an library that contains the relevant subroutines for simulating non-cohesive sediment transport. This document is concerned with the implementation of the TELEMAC-3D software.
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Sedimentology module is designed to simulate the transport of sediment through bed load traction and suspension as well as water quality models that able the user to simulate suspended sediment transportation.

Through waves software module it is possible to simulate changes in the features of wave agitation either in a coastal water body or a harbor.

Sub-surface flows module can simulate two or three-dimensional pollutant transport in a subsurface medium.

Finally, the post-processing software processes the information and presents the results within a modern graphic display.

The TELEMAC system is a powerful integrated modelling tool for use in the field of free-surface flows. The various simulation modules use high-capacity algorithms based on the finite-element method. Space is discretized in the form of an unstructured grid of triangular elements, which means that it can be refined particularly in areas of special interest. This avoids the need for systematic use of embedded models, as is the case with the finite-difference method. TELEMAC has numerous applications in both river and maritime hydraulics.

2.2.2.4 MOHID

MOHID is an hydrodynamic model and it was created back in 1985. MOHID Water Modelling System is a modular finite volumes water modelling system written in ANSI FORTRAN 95 using an object oriented programming philosophy, integrating diverse numerical models and supporting graphical user interfaces that manage all the pre- and post-processing (MOHID, 2103). It is an integrated modelling tool able to simulate physical and biogeochemical processes in the water column as well as in the sediments, and is also able to simulate the coupling between these two domains and the latter with the atmosphere.

The MOHID system is composed of several modules which can be divided in three major groups, MOHID Water, Land and Soil.

MOHID Water performs simulations related to hydrodynamic wave propagation, the dispersion phenomena, water quality, sediment transportation and biogeochemical processes. The graphical user interfaces of the MOHID Water Modelling System are a set of programs to pre and post process the input and output data needed by the different numerical programs.
MOHID Land is the newest core executable of the MOHID Water Modelling System. This program is designed to simulate hydrographic basin and aquifers, some classes developed are related with specific processes which occur inside a watershed.

The Module Soil in MOHID solves the Richards equation for Saturated and Unsaturated porous media. This module is used for water flow in porous media. In the present, the hydraulic properties are described using Van Genuchten function. However the model is prepared, if needed, to include any model that describes the relation between water content and pressure head and the relation of conductivity and pressure head.

2.2.2.5 RMA2

RMA2 is a 1D/2D hydrodynamic model using the finite element method. RMA2 was written by Ian King and is maintained by the Army Corp of Engineers Engineering Resource Development Center (ERDC, 2013). RMA2 has been applied to multi-dimensional problems since the mid-1970s. As such, it was one of the first widely used multi-dimensional hydrodynamics engine applied to riverine and estuarine applications.

RMA2 is a two-dimensional depth averaged finite element hydrodynamic numerical model. It computes water surface elevations and horizontal velocity components for subcritical, free-surface flow in two-dimensional flow fields. RMA2 computes a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows. Friction is calculated with the Manning's or Chezy equation, and eddy viscosity coefficients are used to define turbulence characteristics. Both steady and unsteady state (dynamic) problems can be analysed.

RMA2 has been applied to calculate water levels and flow distribution around islands; flow at bridges having one or more relief openings, in contracting and expanding reaches, into and out of off-channel hydropower plants, at river junctions, and into and out of pumping plant channels; circulation and transport in water bodies with wetlands; and general water levels and flow patterns in rivers, reservoirs, and estuaries.

This software is a general purpose model designed for far-field problems in which vertical accelerations are negligible and velocity vectors generally point in the same direction over the entire depth of the water column at any instant of time. It expects a vertically homogeneous fluid with a free surface.
RMA2 is capable of simulate wetting and drying events, providing for a more accurate account of off-channel storage, adjusting for wet and dry by element and account for Marsh Porosity wetlands. The wind stress can be applied uniformly, constant or time-varying over the model domain and as a storm as a time-varying event.

This software provides computational controls such as wet and dry parameters, iteration controls and revisions within a time step. It accepts a wide variety of boundary conditions that can be customized for a better linkage on every data that is initially known.

Besides all of these features, RMA2 has some limitations. This software operates under the hydrostatic assumption meaning accelerations in the vertical direction are negligible. It is two dimensional in the horizontal plane. It is not intended to be used for near field problems where vortices, vibrations, or vertical accelerations are of primary interest. Vertically-stratified flow effects are beyond the capabilities of RMA2. RMA2 is a free-surface calculation model for subcritical flow problems. More complex flows where vertical variations of variables are important should be evaluated using a three-dimensional model such as RMA10.

2.2.2.6 MIKE 21

MIKE 21 is a depth-averaged two-dimensional (2-DH) numerical modelling tool designed to simulate water levels and flows in rivers, estuaries, bays and coastal areas. It can simulate both steady-state (constant) flow conditions or unsteady (time varying) flow conditions in the two horizontal dimensions. This proprietary modelling tool was developed by and can be obtained from DHI Water and Environment in Denmark (DHI, 2013).

MIKE 21 provides the last generation of modelling and resources in the simulation of physical processes, chemical or biological in sea or coastal areas.

MIKE 21 can be considered as a 3 in 1 package. It comprehends three different simulation engines, single grid, multiple grids or a flexible mesh. The classic single grid is easy to set up rectilinear model which has a simple input / output platform. As well as single grid, the multiple grids consist in a rectilinear model but with dynamic grouping enabling the capacity to focus grid resolution. The flexible mesh performs the maximum flexibility grid resolution within the model.

With all these powerful engines, MIKE 21 is capable of innumerous possible applications such as designing data assessments for coastal and offshore structures, optimization of port layout and coastal protection measures, do an analysis of recirculation, desalination and cooling water,
evaluation of environmental impact assessment created by marine infrastructures in many other applications.

Despite all of this wide range of application, MIKE 21 is modular software. This means that the user only buys what he needs. There are a vast number of modules designed for various applications. Focusing on the four major modules available (pre and post processing, hydrodynamics, advection-dispersion and sand transport) can be concluded that there is a variable potential in each one of this modules.

Pre and post processing module provides an integrated environment offering convenient and compatible routines to facilitate the input and data analyses tasks and the presentation of the simulation results.

The hydrodynamics module simulates the variation of flows and water level in response of forcing functions. With the advection-dispersion component, the dispersion and the decay of suspended or dissolved substances can be simulated.

The sand transport module has several formulations for current or wave generated transport, including 2DH description of sediment transport rates. This morphodynamics module is used in optimization of port layouts, stability of tidal inlets, impact of shore protection, as long with many other uses.

MIKE 21 is a highly respected modelling tool that comes with all of the standard hydrodynamic modelling capabilities needed to assess frequency and duration of flooding needs. However, as with all numerical models MIKE 21 is strongly dependent on user specified information including: inflow boundary conditions, tides, channel and floodplain roughness (including ground surface conditions, vegetation, cropping, cultivation patterns), floodplain topographic details, channel bathymetry, characteristics of flow obstructions and other required model parameters such as eddy viscosity and bed friction.

### 2.2.2.7 SOBEK

SOBEK is one and two dimensional modelling software developed by Deltares, and it’s applicable to problems of hydrodynamic modelling in rivers, estuaries or drainage network (Deltares, 2013). SOBEK is also used in flood forecasting, optimization of drainage systems, control of irrigation systems, monitoring the soil water level, river morphology, salt intrusion and surface water quality. It is based on a powerful numerical method that allows obtaining solutions for more complex simulations. The modelling is based on the Saint Venant hydrodynamic equations. It has been
developed - and is being further developed - jointly with Dutch public institutes and governmental organizations, research institutes, universities and private consultants all over the world.

SOBEK gives water managers a high-quality tool for modelling irrigation systems, drainage systems and natural streams in lowlands and hilly areas. Applications are typically related to optimizing agricultural production, flood control, irrigation, canal automation, reservoir operation and water quality control.

SOBEK calculates (easily, accurately and fast) the flow in simple or complex channel networks, consisting of thousands of reaches, cross sections and structures. The user can define all types of boundary conditions, as well as define lateral inflow and outflow using time series or standard formulae. For water quality and environmental problems the water quality module offers almost unlimited possibilities.

The graphic display superimposes the network over a map of the area so the user can see the canals, reservoirs, weirs and pumping stations at a glance. Animation options show the direction of flow through the network and by varying the thickness and colours of selected network elements, all input and computed parameters can be visualized. By clicking on the map the user can draw a network and adjust any detail to suit his needs. The network can also be viewed side-lined. Side view allows watching the water profiles and real-time operation of structures in detail.

SOBEK has some competitive advantages that are important to review:

**Integrated approach**

One software environment for the simulation of problems in the areas of rivers, drainage systems, irrigation systems and sewer systems, while maintaining the application specific user interfaces. This allows for combinations of flow in closed conduits, open channels, rivers overland flows, as well as a variety of hydraulic, hydrological and environmental processes.

**Coupling with 2D overland flow simulation**

SOBEK allows for the combined simulation of pipe-channel and overland flow through and implicit coupling of 1D and 2D flow equations. This makes SOBEK the ideal tool for studying the effects of dam breaks, river flood,s dike breaches, urban flooding, etc.

**Open System**

SOBEK is open to the connection of user-made modules through the specification of data exchange formats and functionalities. This approach allows the inclusion of expertise available at a number of
Institutions and specific procedures applied in a variety of countries to form an integral part of the SOBEK environment.

**Open GIS-like interface**

The Netter module of SOBEK allows for import and export of a range of GIS formats. Apart from creating flexibility to linking SOBEK to the user’s own GIS systems, the Netter layers provide a very fast data access while performing map-based input data editing and post-processing of results.

**Robustness of numerical operations**

SOBEK is equipped with a very robust scheme for the numerical computation of channel flow. At the same time it guarantees mass conservation, even in case of transitions through suddenly varying cross-section shapes. SOBEK combines computations of sub-critical and super-critical flow, at scales selected by the user. It handles flooding and drying of channels without the use of artificial tricks such as the Preissmann slot.

**Numerical Efficiency**

SOBEK has a very efficient numerical solution algorithm, which is based upon the optimum combination of a minimum connection search direct solver and the conjugate gradient method. It also applies a variable time step selector, which suppresses the waste of computational time wherever this is feasible.

**Powerful water quality facilities**

SOBEK is supplied with a water quality processes editor, which contains around 600 processes. It allows the user to combine own sets of processes or to select from predefined sets. One of SOBEK’s powerful water quality functionalities is the determination of the source of water at any time of the year and at any location of the modelled area.

SOBEK consists of several separated modules such as Channel Flow Module, Real Time Control Module and Water Quality Module.

The SOBEK-Rural Channel Flow Module features some great capacities. It works with the complete Saint Venant Equations, including transient flow phenomena and backwater profiles. It models any cross section – open and closed – including asymmetrical profiles. It allows the user to define different sub-sections within a cross section, using alternative resistance formulations and it has an automatic drying and flooding procedure that is 100% mass conservative, which is very relevant for low flows. The sediment transport capacity can be computed and visualized on the network and the effects of wind on water levels can be modelled, by specifying the wind force and
direction as constants or time series. This module interfaces completely with the Water Quality and the Real Time Control Module to provide an integrated model of the water system.

SOBEK-Rural Real Time Control Module enables the user to design an optimal control system for the work process. In Real-time Control, it is possible to define multiple measures (controllers) with different priorities for structures in Water Flow or Water Quality. The most important feature of this module is that it is possible to take into account information from different SOBEK modules. One can define the operation of a weir or pump in Water Flow based on results of the Water Quality or based on rainfall and wind predictions, or on other data. This gives many more possibilities than just using local controllers in Water Flow. The Real Time Control Module has been extended with a reservoir module. This module allows operation reservoirs with multiple outlets using a set of rule curves. The reservoir module distinguishes a flood control curve specifying maximum allowed reservoir levels, a target curve, and a firm storage curve below which desired releases may be reduced according to user-defined hedging rules.

The SOBEK-Rural Water Quality Module is a proven and generally accepted tool to support water quality management and pollution control. The objective of water quality modelling is the computation of the effects of the operation rules applied to the canal system or to identify promising alternatives.

The Water Quality Module is used for a wide range of problems: bacterial pollution, oxygen depletion, eutrophication and the pollution of water and sediments with heavy metals, pesticides and other toxic substances. The associated models range from a very basic to extremely complex. This module operates as an extension of the Channel Flow Module.

2.2.2.8 FlowMaster (Bentley)

FlowMaster is an efficient calculator product for the design and analysis of a wide variety of hydraulic elements, such as pressure pipes, open channels, weirs, orifices and inlets. It is a hydraulic system toolbox it has a lot of different methods to solve a lot of different hydraulic calculi problems. Originally came out able to do simple uniform flow and pipes or pressure flow through a given pipe but over the years, FlowMaster is evolved into just an all variety of very powerful tools that can look at flows and depth in all sorts of different combinations systems. For gravity flow it can handle all types of conducts with different forms and it supports irregular bottoms. Not only does it solve steady state uniform flow, but also solves problems involving gradually varied flow for any free surface flow element (Bentley, 2013).
This is more than just a simple toolbox, and it can solve problems that are impossible to solve manually. In addition, it can work with weirs, orifices, and it can generate rating curves for an all variety of hydraulic structures and recently it is able to solve inlet and gutters calculations.

In FlowMaster, users can perform a pressure pipe design by simply plugging in the known information and it automatically solves the calculation for pipe length, start and stop elevation and pressures, discharge, diameter or roughness.

This toolbox allows users to design and analyze grate, curb, ditch, slotted, and combination inlets. In sag or on grade conditions a continuously or locally depressed gutter can be considered, and water spread and gutter depth for a gutter of pavement section can be calculated.

With FlowMaster, engineers can easily design and analyze channels, ditches, and free surface pipes of any shape including circular, box, elliptical, parabolic, and irregular channels. Under uniform flow, FlowMaster solves for discharge, capacity, normal depth, channel dimensions, slope, or roughness, and lets users compare the results using different friction methods. Gradually varied flow calculations can also be performed for any free surface flow element. Users can generate profile views from the calculated results, and view the points in tabular form.

As previously stated, this software supports weir and orifice modeling considering discharge, weir coefficients and crest, headwater and tailwater elevations. Users can also design rectangular, circular and generic orifice structures accounting for submergence, and produce rating and curve tables.

This toolbox is a great tool to work with these individual components as it is very simple, user friendly and at the same time very powerful calculation software.

2.2.3 Open versus closed source software

Dealing with Hydroinformatics, a continuous discussion point is the question of open source against proprietary software, which is generally provided in the form of compiled executable.

Closed source software can be defined as proprietary software distributed under a licensing agreement to authorized users with private modification, copying and republishing restrictions.

It is a common belief that the closed source or non-free model of software development is “traditional”, and while this is not strictly true, this model has gained such a hold that it makes little difference. In the interest of accuracy, however, it should be pointed out that, in its early days,
computing was an academic pursuit, and software was freely shared among the developer and user communities, which were largely coincident (Stallman, 1998).

Open source software can be defined as software distributed under a licensing agreement which allows the source code (computer code) to be shared, viewed and modified by other users and organizations.

Open source software enables innovation by providing users with the freedom and flexibility to adapt the software to suit, without restriction. However, innovation may or may not be passed on to all users of the software. It is a user’s prerogative whether they wish to share their innovation with any online communities, and users must be actively participating in these communities to become aware of such innovations.

It has been observed that, while the ethical code behind the Free Software movement may suit many, particularly those for whom writing code is a secondary employment or hobby, rather than a primary source of income, not everyone will agree with it. On the other hand, the practical benefits of the Open Source approach, using the same licensing controls as Free Software, have been clearly demonstrated in a number of projects, and it is believed that the Open Source development model has a lot to offer to Hydroinformatics. While it is recognized that not all hydroinformatics software can be open sourced, as current business models would not provide financially for the development of that software, certain aspects of their work, notably the creation of software frameworks, seem to be prime candidates for experimental “open sourcing”.

It’s expected that in the future the difference between open and closed source will be reduced therefore the Hydroinformatics community should be encouraged to experiment Open Source models of software where possible. There are many areas of Hydroinformatics where these models could prove beneficial to the originators of the software and of enormous benefit to the community, the field and the final users of products. Software suppliers should consider whether releasing some of their code as Open Source and encouraging competitors to share in the costs, risks and rewards of its development would not in the long run be financially beneficial. Software purchasers could push suppliers in this direction in order to reap the benefits of openness. It’s believable that Open Source, judiciously applied, could help fulfil our future human responsibilities (Abbott, 1998), as well as generating previously untapped business opportunities. At the same time, it must be careful to remember that Open Source development does not guarantee good software engineering.

In a way of conclusion, when deciding between open source or closed source (proprietary) software, it is critical to first consider the organization’s business internal (resources and capabilities) and
external (stable or evolving) environment, and the level of risk the organization is willing to take. The aforementioned issues can then be used as a guide to make an informed decision between the two.

2.2.4 Hydroinformatics tools for flood forecasting

New communication technologies using Internet have required novel languages and techniques that support elegant models for distributed programming and computing. These models enable Internet and intranet environments to be fully utilized by modellers and extend the capabilities of World-Wide Web (WWW) servers for the purposes of Hydroinformatics. New trends in the development of Hydroinformatics such as collaborative decision support systems, remote modelling (RM) systems, and intelligent agents-based modelling are making strong demand on the Internet.

Flood forecasting is a complex domain where coupling hydroinformatics tools is a critical issue, requiring flexible model integration and many operations necessary to be done in a short time (Verwey, 2005). Since rainfall constitutes the main input for flood models, the description of the spatiotemporal variability of rainfall is a critical issue. Radar rainfall estimates adjusted by rain gauge data can provide accurate point rainfall information (Wang et al., 2013).

Operational forecasting of river flow is becoming increasingly widespread, answering to several objectives such as the provision of early warning of floods to initiate a timely response (Krzysztofowicz et al., 1992; Haggett, 1998; Penning-Roswell et al., 2000; Parker & Fordham, 1996; De Roo et al., 2003), prediction of low flows for navigation (Renner et al., 2009), or water resource predictions to support reservoir operation (Faber & Stedinger, 2001).

2.2.4.1 Delft-FEWS

There are many hydrological and hydraulic models that can potentially be used in operational forecasting, and developments in these result in changing requirements on operational forecasting systems. Additionally the requirements to the use of these models change rapidly due to the increasing availability of real time data from terrestrial networks, from radar and satellite based systems, as well as due to advances in meteorological forecasting. This calls for a flexible approach in establishing sustainable real time decision support systems that can adapt to these changing needs. Rizzoli et al. (2008) advocate abandoning the concept of building monolithic modelling applications in favour of adopting component based modelling frameworks that are constructed from well-defined and documented building blocks. Such an approach was embraced in the
development of the Delft-FEWS (Flood Early Warning System) framework (Werner et al., 2004; Werner & Heynert, 2006). The main purpose of this framework is to provide a platform through which operational forecasting systems can be constructed, and that allows flexibility in the integration of models and data.

Delft-FEWS provides an open shell system for managing forecasting processes and/or handling time series data. Delft-FEWS incorporates a wide range of general data handling utilities, while providing an open interface to any external forecasting model. The modular and highly configurable nature of Delft-FEWS allows it to be used effectively for data storage and retrieval tasks, simple forecasting systems and in highly complex systems utilizing a full range of modelling techniques. Delft-FEWS can either be deployed in a stand-alone, manually driven environment, or in a fully automated distributed client-server environment (Delft-FEWS, 2013).

Delft-FEWS system contains no inherent hydrological modelling capabilities within its code base. Instead it relies entirely on the integration of (third party) modelling components. Since its introduction in its current form in 2002/2003, this system has been applied in several operational flow/flood forecasting centers. Key to its rapid adoption has been the collaborative development process, as well as its ability to build on existing knowledge through integration of existing models and methods where these are available. Both are key factors for the adoption of decision support frameworks within an organization (Argent et al., 1999).

Delft-FEWS operational forecasting platform is quite interesting and innovating. The objective of the system is not to provide forecasting capabilities in the form of hydrological modelling algorithms, but rather to provide the platform through which model codes can be brought to the operational domain. These models can then be linked with data from operational networks, as well as with the advances in related domains such as (probabilistic) meteorological forecasting. The structure of Delft-FEWS includes a data storage layer, a data access layer, as well as several components for importing, manipulating, viewing and exporting data. Although these components provide a range of tools required in using data and models within the operational domain, key to the open concept of the system are the open interfaces that allow integration of external models and algorithms. One of the most important of the open concept is the XML interface layer through which external models can be linked for use in the operational domain. This interface is relatively simple and has been applied in linking numerous models. Most of these are used in operational forecasting centers, with some applied as yet only in the research domain.
The strong focus of using models to provide guidance in the operational forecasting process has been one of leading principles in linking external models and data through simple yet robust and easy to test XML interfaces. Through separating the models that provide the hydrological functionality from the process with which forecasts are made and disseminated, the forecasting methods used at operational forecasting centers can be more flexible. The separation reduces the impact when adapting to changing needs as well as to changing capabilities in models and data, as the operational forecast process will not need to be changed if there are changes to the underlying models. An additional benefit of the open approach is that existing forecasting procedures and models can often be integrated into the operational forecasting domain.

2.3 Hydrologic modelling

2.3.1 Hydrologic cycle and surface runoff

The hydrological studies arose from the need to describe the water balance in watersheds, and to understand the performance of the processes that control the water movement and the impacts of changes in land use on the water quantity and availability (Whitehead & Robinson, 1993). The natural behaviour of the water as their occurrences, transformations and relations with human life, is well characterized by the concept of the hydrological cycle. From the basic stages of the water cycle, surface runoff is considered the most important, since most hydrological studies are linked to the use of surface water and protection from the phenomena caused by its displacement (Villela & Mattos, 1975).

From the total volume of precipitation, part is intercepted by vegetation as the rest part reaches the ground surface. The puddling water in existing depression areas on soil surface begins to occur only from the moment when rainfall intensity exceeds the rate of infiltration, or when the capacity of the water accumulation in the soil is surpassed. Having exhausted the surface retention capacity, water begins to flow (Linsley et al.1975; Luthin, 1973; Pruski & Silva, 1997).

Long prevailed in hydrological studies was a type of assessment based only on two components of the hydrological cycle: the rainfall as the main input parameter, and the runoff as the output parameter, with just a little consideration to the vegetation interception, surface storage and infiltration of water into soil or evapotranspiration phases. However, understanding the set of physical processes that occur in the river basin is essential for interpreting the results obtained and their limitations of appliance to other areas (Mc Culloch & Robinson, 1993).
To better understand the process that describes the runoff is necessary to understand some of the factors leading to its occurrence, such as interception by the canopy and surface storage. The canopy interception is the retaining of a portion of precipitation above the soil surface (Blake, 1972). The volume retained returns to the atmosphere through evaporation. This process affects the basin water balance, tending to cause a reduction in the variation of the flow through the year, and a reduction and delay of peak floods. The quantification of the impact of the vegetation cover on runoff is an important interaction issue because other processes such as, for example, evaporation (Tucci 1998).

![The Water Cycle](image)

**Figure 2.1 - Hydrologic Cycle (NOAA, 2013).**

The importance of water retention by the interception of the vegetation cover has led to the development of various models and empirical conceptualizations to estimate the magnitude of this loss. Empirical models such as the sustained by Horton (1919), Leonard (1961) and Helvey & Patrick (1965), have shown that the interception that occurs in a given period is mainly controlled by the total precipitation and number of precipitation occurrences during that period (Moses & Price, 1999).

The surface storage occurs due to natural and artificial obstructions existent in the basin responsible for part of the rainfall volume (Tucci, 1998). This process is influenced by the soil cover and agricultural practices carried out on the surface (Brakensier & Rawls, 1982). The sum of the amount of rainfall retained and stored in vegetation cover in ground depressions is considered, in relation to runoff as initial losses (DeCoursey, 1980). This sum tends to stabilize the infiltration time and becoming constant (Martins, 1998).
2.3.2 Sacramento hydrologic model: parameters, variables and schematization

The Sacramento Soil Moisture Accounting model (SAC-SMA) is part of the National Weather Service River Forecast System (NWSRFS), which is considered as the standard in flood forecasting models for the United States (Singh & Woolhiser 2002). Although a number of rainfall-runoff models are available within the NWSRFS, SAC-SMA is the primary model used for river elevation and water supply forecasts. The SAC-SMA code is one of many descendants from the Stanford Watershed Model (Singh & Frevert 2006). Research by the National Weather Service during recent years has focused on producing estimates for the SAC-SMA parameter values from known soil properties and remotely sensed data. These \textit{a priori} estimates of the model parameters allow for uncalibrated simulation of watershed scale rainfall-runoff response with distributed versions of the SAC-SMA model (Anderson et al., 2006; Koren et al., 2003, 2004; Smith et al., 2004).

The SAC-SMA model conceptualizes the watershed as an abstracted soil column divided vertically into two storage zones which are filled and emptied to simulate infiltration, percolation, baseflow, and interflow through the watershed. The upper and lower zones represent the infiltration capacity of shallow soils and the underlying aquifer, respectively. Runoff is computed as the net excess volume remaining from precipitation after interception and infiltration have been satisfied. Rates of infiltration and water holding capacities of the zones are represented with conceptual parameters which, while not directly physical, correspond closely to physical values such as void space ratio and saturated hydraulic conductivities (Burnash & Ferral 2002). Figure 2.3 shows a schematic of processes represented by the SAC-SMA model.
The conceptualization of finite volumes filling, draining, and spilling like a collection of interconnected buckets, gives rise to the SAC-SMA model's designation as a “bucket” model. Various parameters govern the rate of filling and spilling as well as the distribution of water in the various upper and lower zone buckets. Although not physical parameters themselves, the Sacramento model parameters can be estimated \textit{a priori} using the assumption that plant extractable soil moisture is related to tension water, and that free water storages relate to gravitational soil water (Koren et al., 2000). Using the ranges of soil properties such as saturated moisture content $\theta_s$, field capacity $\theta_{\text{fld}}$, and wilting point $\theta_{\text{wp}}$ defined in the Soil Survey Geographic (SSURGO) dataset, and based on calibration experience, Anderson et al. (2006) developed a range of acceptable values for eleven of the SAC-SMA parameters as shown in Table 2.1 and a set of state variables (Table 2.2).
Table 2.1 - SAC-SMA parameters and their feasible ranges (Anderson et al., 2006).

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter</th>
<th>Description</th>
<th>Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>UZTWM</td>
<td>The upper layer tension water capacity, mm</td>
<td>10–300</td>
</tr>
<tr>
<td>2</td>
<td>UZFWM</td>
<td>The upper layer free water capacity, mm</td>
<td>5–150</td>
</tr>
<tr>
<td>3</td>
<td>UZK</td>
<td>Interflow depletion rate from the upper layer free water storage, day⁻¹</td>
<td>0.10–0.75</td>
</tr>
<tr>
<td>4</td>
<td>ZPERC</td>
<td>Ratio of maximum and minimum percolation rates</td>
<td>5–350</td>
</tr>
<tr>
<td>5</td>
<td>REXP</td>
<td>Shape parameter of the percolation curve</td>
<td>1–5</td>
</tr>
<tr>
<td>6</td>
<td>LZTWM</td>
<td>The lower layer tension water capacity, mm</td>
<td>10–500</td>
</tr>
<tr>
<td>7</td>
<td>LZFSM</td>
<td>The lower layer supplemental free water capacity, mm</td>
<td>5–400</td>
</tr>
<tr>
<td>8</td>
<td>LZFPM</td>
<td>The lower layer primary free water capacity, mm</td>
<td>10–1000</td>
</tr>
<tr>
<td>9</td>
<td>LZSK</td>
<td>Depletion rate of the lower layer supplemental free water storage, day⁻¹</td>
<td>0.01–0.35</td>
</tr>
<tr>
<td>10</td>
<td>LZPK</td>
<td>Depletion rate of the lower layer primary free water storage, day⁻¹</td>
<td>0.001–0.05</td>
</tr>
<tr>
<td>11</td>
<td>PFREE</td>
<td>Percolation fraction that goes directly to the lower layer free water storages</td>
<td>0.0–0.8</td>
</tr>
<tr>
<td>12</td>
<td>PCTIM</td>
<td>Permanent impervious area fraction</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>ADIMP</td>
<td>Maximum fraction of an additional impervious area due to saturation</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>RIVA</td>
<td>Riparian vegetarian area fraction</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>SIDE</td>
<td>Ratio of deep percolation from lower layer free water storages</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>RSERV</td>
<td>Fraction of lower layer free water not transferable to lower layer tension water</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.2 –SAC-SMA State variables (Anderson et al., 2006).

<table>
<thead>
<tr>
<th>State Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADIMC</td>
<td>Tension water contents of the ADIMP area (mm)</td>
</tr>
<tr>
<td>UZTWC</td>
<td>Upper zone tension water contents (mm)</td>
</tr>
<tr>
<td>UZFWC</td>
<td>Upper zone free water contents (mm)</td>
</tr>
<tr>
<td>LZTWC</td>
<td>Lower zone tension water contents (mm)</td>
</tr>
<tr>
<td>LZFSM</td>
<td>Lower zone free supplemental contents (mm)</td>
</tr>
<tr>
<td>LZFSC</td>
<td>Lower zone free primary contents (mm)</td>
</tr>
<tr>
<td>LZFPC</td>
<td>Lower zone free primary contents (mm)</td>
</tr>
</tbody>
</table>
Understanding all the SAC-SMA parameters and state variables above mentioned it is possible to set up an organizational scheme where the Sacramento hydrological model is more easily explainable and understood.

The Sacramento model has been represented in state space form as a set of differential equations. The representation of the Sacramento soil moisture accounting model makes a number of approximations and simplifying assumptions in order to represent the model in state space form. This model can be written as a system having two inputs, two outputs and six non-negative states. The state space formulation of the Sacramento model is developed in Kitanidis and Bras (1980), and this model is further refined in Bae and Georgakakos (1992). Optimal filtering techniques are applied to the state space model.

The system states are defined as follows:

- \( x_1 \) = upper zone tension water content [mm]
- \( x_2 \) = upper zone free water content [mm]
- \( x_3 \) = lower zone tension water content [mm]
- \( x_4 \) = lower zone primary free water content [mm]
- \( x_5 \) = lower zone secondary free water content [mm]
- \( x_6 \) = additional impervious storage [mm]
The differential equation for additional impervious area water element is given as:

\[
\frac{dx_6}{dt} = 1 - \left( \frac{x_6}{x_3} \right)^m \times u_p - e_u \times \left( \frac{x_1^0}{x_1} \right)
\]  

(2.6)

The differential equation for upper zone free water element is given as:

\[
\frac{dx_2}{dt} = \left( \frac{x_1}{x_1^0} \right)^{m_1} \times u_p \times \left[ 1 - \left( \frac{x_2}{x_2^0} \right)^{m_2} \right] - d_u x_2 - C_1 \times \left( 1 + \epsilon \times y^\theta \right) \times \left( \frac{x_2}{x_2^0} \right)
\]  

(2.2)

The differential equation for lower zone tension water element is given as:

\[
\frac{dx_3}{dt} = C_1 \times \left( 1 + \epsilon \times y^\theta \right) \times \left( \frac{x_2}{x_2^0} \right) \times \left( 1 - p_f \right) \times \left[ 1 - \left( \frac{x_3}{x_3^0} \right)^{m_3} \right] - e_u \times \left( 1 - \left( \frac{x_1}{x_1^0} \right) \right) \times \left( \frac{x_3}{x_1^0 + x_3^0} \right)
\]  

(2.3)

The differential equation for lower zone primary water element is given as:

\[
\frac{dx_4}{dt} = C_1 \times \left( 1 + \epsilon \times y^\theta \right) \times \left( \frac{x_2}{x_2^0} \right) \times \left[ 1 - \left( 1 - p_f \right) \times \left[ 1 - \left( \frac{x_3}{x_3^0} \right)^{m_3} \right] \right] \times \left[ \left( \frac{x_5}{x_5^0} \right) - 1 \right] \times \left( \frac{x_4}{x_4^0} \right) + 1 \right) - d_1 x_4
\]  

(2.4)

The differential equation for lower zone secondary water element is given as:

\[
\frac{dx_5}{dt} = C_1 \times \left( 1 + \epsilon \times y^\theta \right) \times \left( \frac{x_2}{x_2^0} \right) \times \left[ 1 - \left( 1 - p_f \right) \times \left[ 1 - \left( \frac{x_3}{x_3^0} \right)^{m_3} \right] \right] \times \left( 1 - C_2 \times \left( \frac{x_5}{x_5^0} \right) \right) \times \left( \frac{x_4}{x_4^0} \right) - d_1 x_5
\]  

(2.5)
The output $u_c$ from the soil moisture accounting model, referred to as channel inflow per unit time, is given by:

$$u_c = \left( d_u x_2 + \frac{d_i x_4 + d_i^u x_5}{1 + \mu} \right) \times (1 - \beta_1 - \beta_2) + u_p \beta_2 + \left( \frac{x_6 - x_1}{x_3^0} \right) \times u_p \times \left( \frac{x_1}{x_1^0} \right)^{m_1} \times \beta_1 +$$

$$+ \left( \frac{x_1}{x_1^0} \right)^{m_1} \times \left( \frac{x_2}{x_2^0} \right) \times \left( \frac{x_3}{x_3^0} \right) \times \left( 1 - \beta_1 - \beta_2 \right) + \left[ 1 - \left( \frac{x_6}{x_3^0} \right)^2 \right] \times \left( \frac{x_2}{x_2^0} \right) \times \left( \frac{x_1}{x_1^0} \right) \times u_p \times \beta_1$$

The following auxiliary variables ($y$, $C_1$ and $C_2$) are also defined:

$$y = 1 - \frac{x_3 + x_4 + x_5}{x_3^0 + x_4^0 + x_5^0}$$

$$C_1 = d_1^i x_4^0 + d_1^i x_5^0$$

(2.7)
Towards a Decision Support System for Flood Management in a River Basin

Chapter 2

Where,

\[ C_2 = \frac{d_i x_i^0}{C_1} \]

\[ y = \text{lower layer water deficit} \]

\[ C1 = \text{inferior percolation rate} \]

\[ C2 = \text{percentage of percolation water destined to the lower free water reservoir} \]

2.4 Decision Support Systems

A decision support system (DSS) can be defined as an interactive technological solution, flexible and adaptable, especially designed to support decision making in complex management problems, poorly structured, including the assessment of policy measures impacts evaluation, considering different environmental scenarios. These technological solutions, originally developed for financial organizations, have been expanded to the application to water resources management problems (Vieira & Pinho, 2002).

Over the last years, the use of DSS has grown enormously. Partly because of the growing capacity of personal computers, but also because the problems to solve became more complicated. The aim of a DSS is “to support decision making in complex problems by structuring the information and by analyses and evaluation of the effects of different alternatives” (Sprague & Carlson, 1982). The complexity of problems is related to the uncertainty of the behaviour of the system that causes the problem. The uncertainty exists because of lack of knowledge of the system or because of structural uncertainties in the system. Usually there is lack of knowledge on the effects of application of source control measures on a large scale. Decision making for these problems can be supported by structuring the information needed to get a clearer understanding of the problem.

The main structure of a DSS consists of three major components: an interpretation subsystem, a database subsystem and a model base subsystem (Figure 2.1). The database contains all kind of data concerning the problem situation. Some of these data can already be present in the DSS, other data should be added to the database by the user. The model base integrates a set of models used in describing the real world and contains causal relations that give insight in causes and effects of problems faced by the decision maker. Model base uses information from database as input and the output results are sent to an interpretation system. This interpretation system makes it possible to communicate with the user. In different planning scenarios the user can give orders to the DSS and
the DSS can present results through the dialog system. If predefined control measures are available, the user has the ability of reinitialize all the simulation procedures in order to obtain new results.

![General structure of a DSS](image)

**Figure 2.4** - General structure of a DSS (Vieira & Pinho, 2002).

The main features of a DSS are the management, analysis communication, education and library function.

Management function is usually the most important step in a DSS. The results obtained through a DSS will help the user to make a decision on how to solve the problem. This support system will guide the user into a solution, and the results obtained must be as correct as possible so that the user can have full confidence on the results obtained.

The analysis function is the core of a DSS. It gives the user an understanding of a complex problem by structuring the problem and by calculating the effect of other possible solutions. If a model is not as plausible as it should be, the DSS must contain guides and leading figures of similar situations.

Communication and education functions both lead to the same purpose, the ability to help users to understand the problem and to communicate with other people in a clear and simple way. The communication function although simple, can often be the key to solve a problem. The structuring of the results in figures and tables can help the user to get really involved in the situation and can also help to share that knowledge with other people involved in the project. Through the ability to present the results of the analysis in a clear form, it gives the user a huge help in decision making and also leads to a better understanding of the problem.

Library function is the structured information of the model and its database. As easier it is for the user to find relevant information and knowledge in the DSS, more successful the DSS will be.
“The body of the earth is of the nature of a fish... because it draws water as its breath instead of air...”

Leonardo da Vinci (1452 – 1519)
CHAPTER 3  CASE STUDY

3.1 Study area. River Lima basin

The Lima river basin is a Portuguese and Spanish basin with an approximate area of 2450 km$^2$, being about 1140 km$^2$ (46.5 %) located in the Portuguese territory. The average altitude of the Lima River basin is 447 meters. The higher sectors of the basin correspond to Serra da Peneda at the north, 1416 m, and Serra Amarela at the south, with 1361 m. From the Spanish border to its river mouth in Viana do Castelo city, the river Lima is about 67 km long (Figure 3.1). The river longitudinal profile shows three distinct sectors:

- Upstream sector, gently sloping, carved in the plateau surface to the entrance in Portugal, which is around 800 m of altitude;

- Intermediate sector, with an average slope of 1.5%, which corresponds to the mountain area between Alto Lindoso dam and Ponte da Barca town, where the valley is embedded with very steep slopes;

- Downstream sector, with about 35 km long, between Ponte da Barca and Viana do Castelo, with an average slope of about 0.1%, where the valley presents of gentle slopes, particularly downstream of Ponte de Lima’s town.

Ponte de Lima municipality extends over two watersheds: the Neiva river basin and the river Lima basin. The latter crosses the county, running into a wide and stretched valley which associated to the high rainfall and poor permeability of land, is one of the main factors for the occurrence of floods in this region.
In the river Lima basin, the greatest contribution to the formation of floods comes from the runoff generated in the central part of the basin. This fact is due not only to the high rainfall recorded there, but also to the greater ability of this area to generate runoff and the high velocity of the flow (as a result of low permeability, rugged terrain and deep and slotted valleys).

Some reservoirs were built to benefit from the high hydropower potential of the river Lima basin, (Touvedo and Alto Lindoso, in Portuguese territory, and Las Conchas and Las Salas in Spanish territory), whose dams have a significant storage capacity and may be barriers for the formation and propagation of floods. Management of water levels and flows allows to conclude that, the Alto Lindoso dam has an effect of decrease the frequency of occurrence of some flooding, especially the ones with lower return period and/or those occurring at the beginning of the wet periods, when it is expected that the ability to snap the reservoir capacity is greater.

Within river Lima basin, there are some important sites that are relevant not only for social, economic, cultural and historical reasons, but also for understanding the river natural processes. The next paragraphs shortly describe the main characteristics of these sites.

### 3.1.1 Viana do Castelo

Viana do Castelo is a municipality and seat of the district of Viana do Castelo in the northern region of Portugal. The urbanized area of the municipality, comprising the city, has a population of
approximately 36.148 inhabitants, while the municipality includes 91.238 inhabitants (based on 2006 statistics), covering an area of 318.6 km². This location expresses itself as an important mark due to the fact that it’s there that the river Lima’s mouth is located at, and coincides with the downstream open boundary of the one-dimensional hydrodynamic model used in this work (Figure 3.2).

![Figure 3.2 - River Lima's mouth located at Viana do Castelo.](image)

### 3.1.2 Ponte de Lima

The town of Ponte de Lima, located in the central part of the basin, has about 2800 inhabitants and is famous by its medieval heritage and precious architecture (Figure 3.3). A satellite overview of this town can be seen in Figure 3.4. Historically, Ponte de Lima is characterized for being a key spot, in river Lima’s basin, for the occurrence of severe flood events.

![Figure 3.3 – Flood prone historical centre of Ponte de Lima.](image)
3.1.3 Ponte da Barca

Ponte da Barca is a municipality in Portugal with a total area of 182.2 km² and a total population of 13,041 inhabitants (2006) (Figure 3.5). It is a beautiful town that is bathed by river Lima and it is located downstream Touvedo dam, also presenting itself as an important location to this study.
3.1.4 Alto Lindoso dam

Designed in 1983 and built in 1992, Alto Lindoso dam has a huge importance in river Lima flow control, as it is the structure that controls the flow coming from headwaters in Spain. It is the largest and most powerful hydroelectric producer in Portugal with two turbines, six floodgates and two bottom outlets (Figure 3.6).

![Figure 3.6 - Alto Lindoso dam and its reservoir.](image)

The hydraulics characteristics of Alto Lindoso dam are presented in Table 3.1 where $\mu$ states for the contraction coefficient (ratio of the area of the jet by the area of the orifice) and $C_w$ for the lateral contraction coefficient (energy loss in the orifice).
Table 3.1 - Alto Lindoso hydraulics characteristics.

<table>
<thead>
<tr>
<th>Component</th>
<th>Maximum Flow [m$^3$/s]</th>
<th>Dimensions</th>
<th>Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Bed level [m]</td>
<td>Width [m]</td>
</tr>
<tr>
<td>Turbines</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q_{\text{turbinated 1}}$</td>
<td>125</td>
<td>272,65</td>
<td>7,35</td>
</tr>
<tr>
<td>$Q_{\text{turbinated 2}}$</td>
<td>125</td>
<td>272,65</td>
<td>7,35</td>
</tr>
<tr>
<td>Outlets</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q_{\text{bottom outlet 1}}$</td>
<td>200</td>
<td>250</td>
<td>2,00</td>
</tr>
<tr>
<td>$Q_{\text{bottom outlet 2}}$</td>
<td>200</td>
<td>250</td>
<td>2,00</td>
</tr>
<tr>
<td>Floodgates</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q_{\text{discharged 1}}$</td>
<td>460</td>
<td>318</td>
<td>5,95</td>
</tr>
<tr>
<td>$Q_{\text{discharged 2}}$</td>
<td>460</td>
<td>318</td>
<td>5,95</td>
</tr>
<tr>
<td>$Q_{\text{discharged 3}}$</td>
<td>460</td>
<td>318</td>
<td>5,95</td>
</tr>
<tr>
<td>$Q_{\text{discharged 4}}$</td>
<td>460</td>
<td>318</td>
<td>5,95</td>
</tr>
<tr>
<td>$Q_{\text{discharged 5}}$</td>
<td>460</td>
<td>318</td>
<td>5,95</td>
</tr>
<tr>
<td>$Q_{\text{discharged 6}}$</td>
<td>460</td>
<td>318</td>
<td>5,95</td>
</tr>
</tbody>
</table>

3.1.5 Touvedo dam

Touvedo dam (Figure 3.7) is situated 20 km downstream Alto Lindoso dam. Its main function is the production of electricity and regularization of the turbinated flows coming from Alto Lindoso dam. This dam has three floodgates and one turbine. Table 3.2 shows its hydraulics characteristics.

Figure 3.7 – Touvedo dam and its reservoir.
Table 3.2 – Touvedo hydraulics characteristics.

<table>
<thead>
<tr>
<th>Component</th>
<th>Maximum Flow [m$^3$/s]</th>
<th>Dimension</th>
<th>Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Bed level [m]</td>
<td>Height [m]</td>
</tr>
<tr>
<td>Turbine</td>
<td>$Q_{\text{turbinated}}$</td>
<td>26</td>
<td>10,00</td>
</tr>
<tr>
<td></td>
<td>$Q_{\text{discharged1}}$</td>
<td>37</td>
<td>10,10</td>
</tr>
<tr>
<td>Floodgates</td>
<td>$Q_{\text{discharged2}}$</td>
<td>37</td>
<td>10,10</td>
</tr>
<tr>
<td></td>
<td>$Q_{\text{discharged3}}$</td>
<td>37</td>
<td>10,10</td>
</tr>
</tbody>
</table>

3.2 Historical flood events at Ponte de Lima

The historical records of floods at Ponte de Lima are limited, but the first record that has been found dates from 1686. At this date there is an entry in the parish baptism book where the priest wrote that at 28 of September of 1686 “river Lima woke up with the biggest flood that the Man has ever witnessed.

Almost two hundred years later, 1866, another entry book states “In November 1866, river Lima has filled amazingly, invading a large part of the town reaching churches located in the center of the town as well as turning some of its streets into rivers (Figure 3.8).

In 1888, the local newspaper stated that “Our Lima, whose gentleness and good clarity has inspired poets, became muddy of a greatest bravery, and so has forgotten its romanticism and invaded this town as there many years it had done.”

In 1909 there was a major flood in the town of Ponte de Lima being registered the maximum water level in the St. Paul’s tower (Figure 3.9).
Figure 3.9 - Historical Floods information at St. Paul's tower.

In 1939 floods in river Lima caused the collapse of about 30 m guards at Medieval Bridge in Ponte de Lima. On 15 October 1987 there was another flood, causing damages on the historic centre of Ponte de Lima as shown in Figure 3.10.

Figure 3.10 – Picture of Ponte de Lima flood event in 1987.

Historically, at St. Paul’s tower, a label with the information of how high the water level has reached in that flood event is placed. It is impressive to see how high the water level had reached, considering the localization of this Tower in the center of the town.

A more recent look over flood event records in Ponte de Lima, in December 2012 occurred an important event which is registered in Figure 3.11.
3.3 Geographical Information System and data collection

Geographical information systems tool, ArcGIS, was used to create and work the shapefiles of the Portuguese river Lima basin (ESRI, 2013). Figure 3.12 shows this river basin divided into 30 different sub-basins whose processed terrain model was used in building the hydrodynamics and hydrological models (Ferreira, 2010).

![Figure 3.12 - River Lima Sub-basins.](image)

Figure 3.12 shows the location of all the available monitoring stations in the river basin. These stations include active and inactive meteorological and hydrometric stations.
3.4 Data collection

With particular interest for the realization of this work, a survey was made of all the hydrometric and meteorological historical stations within the river Lima basin. This survey was conducted through SNIRH and at this point several difficulties were faced. For both types of stations surveyed, there is the presence of active and inactive stations, and the difficulty faced was the lack of data and its temporal discontinuity. Having this in mind, a screening was performed in a way that the existence of relevant data to this work and its possibility of continuity in time would be minimally acceptable.

To perform the data processing task, which includes data validation and its ordinance, several Visual Basic for Applications (VBA) routines were created. Otherwise it would be a completely unfeasible task to achieve.
3.4.1 Meteorological stations

3.4.1.1 Active Stations

Within river Lima basin, there are sixteen active meteorological stations. In Table 3.3 the active stations are identified and the time series input data available (precipitation) for each of these stations is referred, being shown in Figure 3.14 their spatial distribution. A maximum time interval from 16-05-2002 to 30-09-2012 was used in the present work.

<table>
<thead>
<tr>
<th>Station</th>
<th>Available Input data</th>
<th>Available Input data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aveleiras</td>
<td>01-06-2006</td>
<td>10-02-2010</td>
</tr>
<tr>
<td>Boalhosa</td>
<td>27-05-2003</td>
<td>27-01-2010</td>
</tr>
<tr>
<td>Britelo</td>
<td>01-06-2003</td>
<td>10-02-2010</td>
</tr>
<tr>
<td>Cabana Maior 2</td>
<td>01-06-2003</td>
<td>15-07-2008</td>
</tr>
<tr>
<td>Cabreiro</td>
<td>01-06-2003</td>
<td>02-04-2009</td>
</tr>
<tr>
<td>Casal Soeiro</td>
<td>16-05-2002</td>
<td>30-09-2012</td>
</tr>
<tr>
<td>Geraz do Lima</td>
<td>26-03-2003</td>
<td>30-09-2012</td>
</tr>
<tr>
<td>Lindoso 2</td>
<td>24-03-2006</td>
<td>06-11-2007</td>
</tr>
<tr>
<td>Moreira do Lima</td>
<td>27-05-2003</td>
<td>24-01-2010</td>
</tr>
<tr>
<td>Nogueira</td>
<td>25-03-2003</td>
<td>22-05-2008</td>
</tr>
<tr>
<td>Ponte da Barca</td>
<td>23-01-2003</td>
<td>30-09-2012</td>
</tr>
<tr>
<td>Ponte de Lima</td>
<td>21-01-2003</td>
<td>30-09-2012</td>
</tr>
<tr>
<td>Seixas</td>
<td>02-06-2003</td>
<td>10-02-2010</td>
</tr>
<tr>
<td>Sistelo</td>
<td>03-06-2003</td>
<td>04-02-2010</td>
</tr>
<tr>
<td>Soajo</td>
<td>04-06-2003</td>
<td>09-02-2010</td>
</tr>
<tr>
<td>Tibo da Gavieira</td>
<td>01-06-2003</td>
<td>10-02-2010</td>
</tr>
</tbody>
</table>
The meteorological data of the rainfall precipitation (in mm) are available in an hourly period, regardless of some existing leaps. Figure 3.15 shows the precipitation time series registered in all the active meteorological stations.

**Figure 3.14** - River Lima active meteorological stations.

**Figure 3.15** – Rainfall data series (2002 – 2012) registered in active meteorological stations.
Figure 3.15 – Rainfall data series (2002 – 2012) registered in active meteorological stations (continued).
Figure 3.15 – Rainfall data series (2002 – 2012) registered in active meteorological stations (continued).

3.4.1.2 Inactive Stations

Concerning the meteorological stations that are currently inactive in the river Lima basin, there are eleven different stations identified and characterized in Table 3.4. The geographic position of these stations can be seen in Figure 3.16. A maximum time interval from 01-10-1932 to 30-09-1960 was used in the present work.
<table>
<thead>
<tr>
<th>Station</th>
<th>Available Input data</th>
<th>Earlier entry</th>
<th>Later entry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beleiral</td>
<td></td>
<td>01-01-1939</td>
<td>30-09-1946</td>
</tr>
<tr>
<td>Cabana Maior 1</td>
<td></td>
<td>01-01-1932</td>
<td>15-11-1960</td>
</tr>
<tr>
<td>Candeeira</td>
<td></td>
<td>01-10-1932</td>
<td>31-12-1960</td>
</tr>
<tr>
<td>Choças</td>
<td></td>
<td>01-10-1940</td>
<td>30-09-1960</td>
</tr>
<tr>
<td>Labrujo</td>
<td></td>
<td>01-10-1932</td>
<td>30-09-1960</td>
</tr>
<tr>
<td>Lindoso 1</td>
<td></td>
<td>01-02-1933</td>
<td>01-12-1960</td>
</tr>
<tr>
<td>Lombadinha</td>
<td></td>
<td>01-10-1940</td>
<td>30-09-1960</td>
</tr>
<tr>
<td>Porta Cova</td>
<td></td>
<td>01-10-1940</td>
<td>30-09-1960</td>
</tr>
<tr>
<td>São Sebastião</td>
<td></td>
<td>01-10-1932</td>
<td>30-09-1960</td>
</tr>
<tr>
<td>Souto</td>
<td></td>
<td>01-10-1932</td>
<td>30-09-1960</td>
</tr>
<tr>
<td>Vila Franca</td>
<td></td>
<td>01-10-1940</td>
<td>30-09-1960</td>
</tr>
</tbody>
</table>

For these stations, the meteorological data of the rainfall precipitation is available for different measurement frequencies. For Beleiral, Cabana Maior 1 and Lindoso 1 stations the data time period is daily, whereas for the remaining stations only monthly data exist. This precipitation data is
presented in Figure 3.17 where, similarly to what happened for active stations, lack of some data entries can be observed.

**Figure 3.17 -** Rainfall data series (1932 – 1960) registered in inactive meteorological stations.
3.4.2 Hydrometric stations

3.4.2.1 Active hydrometric stations

Within river Lima basin, there are four hydrometric stations (Ponte da Barca, Ponte de Lima, Alto Lindoso and Touvedo) with relevant measured parameters for this study (Figure 3.18).
Figure 3.18 - Active Hydrometric Stations.

Ponte da Barca station has information on water level and flow rate registered from 13-02-2003 to 29-05-2012, which can be seen in Figures 3.19 and 3.20. Regarding Ponte de Lima 2 station, the unique parameter available for reference is water level, which has been registered from 13-02-2003 to 29-05-2012 (Figure 3.21).

The available information for these two hydrometric stations is based in an hourly time step and has some time leaps.

Figure 3.19 – Water level data at Ponte da Barca.

Figure 3.20 – Discharges at Ponte da Barca.
Alto Lindoso and Touvedo hydrometric stations are used to register the information regarding dams operation from 13-02-2003 to 29-05-2012 (Figure 3.19). There is available historical data for affluent, effluent, and turbinated flow rates as well as the water level records of dam’s reservoir. Figure 3.22 and Figure 3.23 show the available data for Alto Lindoso and Touvedo dams, respectively.

Figure 3.21 - Water level data at Ponte de Lima 2.

Figure 3.22 - Alto Lindoso flow rate and water level data.
3.4.2.1 Inactive Hydrometric Stations

There are only two inactive hydrometric stations with relevant information available for this study. These stations are shown in Figure 3.24.

**Figure 3.24 - Inactive Hydrometric Stations.**
For these two stations, river discharges data information is available. Daily data is available for these gauge stations but presenting considerable gaps for some years. Pontilhão de Celeiros and Ponte de Lima 1 station data are shown in Figures 3.25 and 3.26, respectively.

**Figure 3.25** - Available flow rate data at Pontilhão de Celeiros.

**Figure 3.26** - Available flow rate data at Ponte de Lima 1.
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CHAPTER 4

Modelling Construction and Calibration

“All models are wrong. Some are useful.”

George E.P. Box (1919 – 2013)
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CHAPTER 4 MODELLING CONSTRUCTION, CALIBRATION AND VALIDATION

The software used in the construction of the river basin hydrodynamic and hydrological model was SOBEK whose characteristics were described earlier in this work (section 2.2.2.7). This software package, developed by Deltares is based on a powerful numerical method that allows obtaining solutions for complex simulations. This modelling software is based on the Saint Venant hydrodynamic equations integration by means of a finite difference scheme:

\[
\frac{dA_f}{dt} + \frac{\partial q}{\partial s} = q_{lat} \tag{4.1}
\]

\[
\frac{\partial q}{\partial t} + \frac{\partial}{\partial s} \left( \frac{q^2}{A_f} \right) + gA_f \frac{\partial H}{\partial s} + \frac{gq|q|}{c_s^2} - W_f \frac{\tau_{wi}}{\rho} = 0 \tag{4.2}
\]

where,

- \( Q \) = flow discharge [m\(^3\)/s]
- \( t \) = time [s]
- \( s \) = one-dimensional coordinate [m]
- \( A_f \) = wetted area [m\(^2\)]
- \( g \) = acceleration due to gravity [m/s\(^2\)]
- \( H \) = water level above plane of reference [m]
- \( C \) = Chézy’s coefficient [m\(^{1/2}\)/s]
- \( R \) = hydraulic radius [m]
- \( W_f \) = superficial width [m]
- \( q_{lat} \) = lateral flow [m\(^2\)/s]
- \( \tau_{wi} \) = wind shear force [N/m\(^2\)]
- \( \rho \) = water density [kg/m\(^3\)].

SOBEK software, presents a graphical interface through which all tasks of pre-processing are performed. The spatial discretization of the model was performed on that interface using the map of the river basin as support (in a format compatible with GIS).

4.1 Hydrodynamic model (SOBEK)

4.1.1 Model construction

Model construction was based on different techniques supported by a GIS tool and data, namely aerial photos, topographical and bathymetric data, river flow discharges, and water levels data.

The hydrodynamic model of the river Lima extends from the river mouth at Viana do Castelo to the upstream located Alto Lindoso dam and it comprises the main tributaries. This model was implemented and initially calibrated by Ferreira (2010).
The hydrodynamic model (1DFLOW) is composed by 322 cross sections, 8 bridges, 8 weirs, and 2 dams. A general view of the developed SOBEK model is depicted on Figure 4.1, where those modelling elements are shown.

![Figure 4.1 - SOBEK hydrodynamic model.](image)

Cross sections were defined based on data obtained with bathymetric surveys and satellite topographic data. The model comprises more than 300 different detailed Y-Z type cross sections. Two different cross sections can be seen in Figure 4.2.

![Figure 4.2 – Examples of cross sections in SOBEK environment.](image)
Concerning the bridges, the modelling was performed individually for each one of the arches of the bridges, using the model type "Fixed bed" in which it is necessary to set the bed level, as well as the width of the opening, Figure 4.3.

![Figure 4.3 - Bridges modeling in SOBEK environment.](image)

The two dams (being the most important in the river Lima basin, Alto Lindoso and Touvedo dams), were meticulously modelled in order to integrate all operating hydraulic structures and their characteristics. Floodgates, bottom outlets, and turbines were modelled through orifice nodes in which all the geometric and hydraulics coefficients were defined. Alto Lindoso and Touvedo SOBEK model can be seen in Figures 4.4 and 4.5, respectively.

![Figure 4.4 – Alto Lindoso dam SOBEK model](image) ![Figure 4.5 – Touvedo dam SOBEK model](image)

In the initial version of the model (Ferreira, 2010) the simulation of the rainfall runoff within the basin was implemented considering discharge boundary nodes at rivers upstream locations for all the tributaries. This way it was possible to insert the flow rate originated by the rainfall
precipitation. The updated version considers Sacramento nodes for simulating the hydrological processes.

4.1.2 Model calibration

Although the previous version of the model was calibrated, additional calibration work was carried out in order to improve the model performance.

A new calibration scenario was chosen corresponding to an event that occurred on 23rd and 24th of March 2006. For this event there are records of discharges measured in Ponte da Barca hydrometric station and the water level at Ponte de Lima hydrometric station provided by SNIRH records. To assure the non-existence of any interference in the results derived from the transitional situation between the estimated initial conditions and the conditions recorded, it was adopted a simulation period of 7 days between 00:00 of 20-03-2006 and 23:45 of 26-03-2006 using a time step simulation of 15 minutes. Regarding Ponte da Barca flow rate simulation, the results are shown in Figure 4.6.

![Figure 4.6 - Calibration scenario results at Ponte da Barca.](image)

Once achieved a good approximation to the observed hydrograph for Ponte da Barca, the next step was to simulate the water levels at Ponte de Lima and then compare those results with the historical recorded data for that event (Figure 4.7).
From the results obtained good matching solutions for discharges were achieved and reasonable results for the peak water levels were also attained.

4.2 Hydrologic model (SOBEK)

4.2.1 Model Construction

Hydrologic models are conceptual representations of a part of the hydrologic cycle. They are inextricably linked to the hydrodynamic models, working as an improvement to better simulate the water runoff, infiltration, and evaporation processes that occur in the nature.

For this purpose the SOBEK rainfall-runoff (RR) module was applied. Since this module has to be in real-time linked to the hydrodynamic one, it was defined that both modules worked simultaneously as schematically depicted in Figure 4.8.
From a wide range of different hydrological model approaches, one of the more precise and complex theory is the Sacramento Soil Moisture Accounting Model (SAC-SMA) as previously presented. This model it is fully integrated within SOBEK software, so the hydrologic approach chosen fell to this SAC-SMA.

4.2.1 Sacramento Nodes

As previously stated, river Lima basin has 30 sub-basins. In order to reproduce a real representation of the natural river system it is important to be the most accurate possible in the construction of this model. So, one Sacramento node was implemented for each centroid of all sub-basins.

For this task it was strictly necessary the use of GIS software, ArcGIS: firstly the shapefile, with the correct coordinate system, was inserted in the software, and then using a feature to point tool, the centroids for each one of the 30 sub-basin were created (Figure 4.9).

Once calculated all the centroids for each of the sub-basins it was important to use a way to insert them on SOBEK software, but instead of centroid it should be a node.

Through schematization option it was possible to import the previously created shapefile and then, use as add locations the Sacramento node from RR module. This way worked out on inserting the Sacramento nodes exactly in the centroid position of all river Lima sub-basins (Figure 4.10).
With the Sacramento nodes created it was then necessary to connect them to the river network. It was decided that for a better modelling of river flows, the Sacramento node should be connected to the initial part of the rivers. Therefore, all the boundary nodes linked to the river Lima tributaries, previously created for the hydrodynamic model, were changed to Flow – RR connection on flow connection node. The connection between these last nodes and the Sacramento ones was made through RR-Link linkage as shown in Figure 4.11.

Figure 4.10 - Sacramento nodes insertion in SOBEK.

Figure 4.11 - Sacramento nodes linkage.

Once all connections made, the visual aspect of the hydrologic model is showed in Figure 4.12.

Figure 4.12 - Hydrological model layout.
4.2.1.2 Meteorological stations

Each Sacramento node represents the amount of precipitation that fell in the controlling area of its node. In this case, since this model has one Sacramento node for each of the 30 sub-basins, there must be 30 different precipitation stations.

Since in river Lima basin the available meteorological stations are not located within the sub-basins it must be estimated a rainfall time series for each sub-basin. For this, an interpolation technique based on Thiessen method was used. This method assigns weight at each gauge station in proportion to the catchment area closest to that gauge.

Thiessen method consists on the construction of polygons following some stated rules. The creation of this spatial distribution of the precipitation followed some guidelines. The gauge network was plotted on a map of the catchment area of interest. The adjacent stations were connected with lines and the perpendicular bisectors of each line were constructed (perpendicular line at the midpoint of each line connecting two stations). Then, the bisectors were extended and used to form the polygons around each gauge station. For rainfall quantification, the precipitation measured data at each gauge station was multiplied by the area of each polygon and then summed and divided by the total basin area.

Since for this study active and inactive meteorological stations were considered, two different spatial distributions have been worked out. Thiessen polygons representing the spatial distribution for the inactive and active meteorological stations are shown in Figures 4.13 and 4.14, respectively.

![Figure 4.13 - Thiessen for inactive Meteo Stations.](image)

![Figure 4.14 - Thiessen for active Meteo Stations.](image)

Once the spatial distribution was made, it was then necessary to distribute the rainfall data for each one of the 30 meteorological stations. This task involves a high processing capacity because it is
necessary to check each one of the sub-basins, see which meteorological station contributes to that area of interest and then apply the computation method already explained. In order to optimize this data processing task it were created two different VBA codes, one for the active and another for the inactive meteorological stations.

Both of the VBA codes have the ability to check each one of the sub-basin and understand if that basin have the contribution of one or various rain gauges. If so, the code automatically gets the area of each of the meteorological contribution and then multiplies it for the precipitation data and divides for the sub-basin area.

After process the rain data for all the 30 meteorological stations it was then necessary to insert that information in SOBEK model. SOBEK software saves the rainfall information in a “.bui file”. Again, to streamline this task and get it error free, another VBA code was coded. This VBA code allowed to simply get the worked out precipitation data, and create a “.bui file” with it. These files were automatically created so that SOBEK software could read it. At this phase two different “.bui files” were created: one for the active (16-05-2002 to 30-09-2012) and another for the inactive meteorological stations time period (01-10-1932 to 30-09-1960). In Figure 4.15 the layout of a “.bui file” is showed and in Figure 4.16 it can be seen how SOBEK can read that file.

Inserted all the meteorological information in SOBEK it was then necessary to assign each meteorological station to each Sacramento node. It was also necessary to define in each of the Sacramento nodes, the area of each sub-basin. This could be made manually but since this work had to be made twice, one for each station type, a VBA code was created.
The information regarding Sacramento nodes was saved in “SACRMNTO.3B file”. So, a VBA code that could assign each one of the Sacramento node to its correspondent meteorological station as well as the sub-basin area was coded. The general layout of a “SACRMNTO.3B file” is shown in Figure 4.17 and in Figure 4.18 it is presented that information in SOBEK interface.

At this stage, the Sacramento parameters information was defined as default values. Regarding the evaporation data at the basin, a long term average time series was selected.

4.2.2 Model calibration

Most of the hydrologic models in use today, assume universality in their model structure (Gupta et al. 2003), which means that the structure of the model is expected to work well for any watershed, and by just adjusting the parameter values pertaining to a particular watershed we can simulate the response of that watershed quite effectively. However, many of the parameters are typically not observable or measurable and can only be reasonably estimated by conditioning the model response on the observed output data. The process of adjusting the parameter values so that the model response becomes consistent with the observed watershed response is known as calibration.

The adopted process of the SAC-SMA hydrological model calibration was very complex and high time consuming. As previously stated, SAC-SMA model consists in 16 different parameters. As for this case study none of these parameters values are known, they were obtained for the first time in this work.
For each Sacramento node it is possible to define a different set of parameters values. Since we have 30 different sub-basins, the model calibration process went through the discovery of the most acceptable and real parameters for each sub-basin.

In Figure 4.19 it can be seen this case study site panorama. As observed, the hydrometric gauges are very few, which is a major problem for calibration purposes. Having a look at the current panorama (active stations) apart from the dams, there are only more two gauges: one at Ponte da Barca with flow rates and water levels data; and another at Ponte de Lima with water levels data. So, if the focus of this calibration process was put only on the current situation the only accurate calibration parameters would be the ones of the sub-basins in between the 2 dams, since their affluent and effluent flow rate data are available. Ponte da Barca hydrometric gauge is situated right downstream of Touvedo dam, so there is not any sub-basin contributing from that dam. That said, in the current situation, it would be possible to work on the calibration of the rest of the sub-basins with the data measured at Ponte de Lima gauge with the remind that only water levels data are available. This would create a generalization of SAC-SMA parameters in river Lima basin neglecting river Vez’s sub-basins contribution.

Two inactive hydrometric gauges stations, one located in river Vez and the other located in Ponte de Lima town where discharges historical data are available were also used in this work. Although the discontinuity of data brought some limitations to the study, its availability made possible to use a different approach in the calibration process. In this way, it was possible to calibrate the upstream river Vez sub-basin. At the time when inactive stations were in operation, Alto Lindoso and Touvedo did not exist. Having this fact into consideration, the calibration process was made in two sequential temporal stages: calibration step one for inactive stations panorama; and calibration step two for the current situation.
In the calibration step one, SOBEK model was adapted and Touvedo and Alto Lindoso dams were missed. The purpose of this stage was to calibrate river Vez sub-basin using the hydrometric station at this river, and then all the remaining sub-basins that contribute to river Lima flows.

The aim of calibration step two was to calibrate the model for the present situation with Touvedo and Alto Lindoso dams in operation. The sub-basins located between both of the dams as well as their operational processes (discharged and turbinated flow, effluent flow rate and reservoir water levels) were considered.

4.2.2.1 Calibration step one

The calibration of a SAC-SMA model implies the definition of 16 different model parameters. In SSURGO dataset (Anderson et al., 2006) a range of acceptable values for 11 of those parameters are proposed. These *a priori* estimates are derived from measurements of watershed characteristics, including soil, land use and vegetation and have been shown to provide quite reasonable initial approximations for manual calibration.

Usually the problem of models calibration involves trying to minimize the error between the model response and the observed historical output from the real system by selection of a properly chosen measure, and implementation of a calibration strategy. The strategy adopted for this step is presented in Figure 4.20.
The process started with the hydrograph analysis. A Sacramento estimation of segment parameters methodology is available in SOBEK manual in which 8 out of the 16 parameters can be estimated. Afterwards a parameter sensitivity analysis of parameters with real simulation conditions was performed, using SOBEK model without dams, and an analysis using a VBA code that can reproduce the SAC-SMA operation processes, that was implemented for this work. With this procedure the calibration parameters values were estimated.

From observed rainfall data and runoff records, there is one procedure available to get first estimates for some of the SAC-SMA segment parameters. This procedure is usually applied and works well, provided that the model concepts are applicable and that reliable records are available for some time covering the majority of the range flows. The sequence of parameter estimation follows a guideline provided in SOBEK manual. Firstly and as a mandatory priority, LZPK, LZFP, LZSP and LZFSM parameters must be estimated before the others. To achieve this estimation, a principle of computation of lower zone recession coefficient must be used (Deltares, 2013). In Figure 4.21 the principle used is explained in detail.
The drainage factor LZPK follows from:

\[ K = \left( \frac{Q_{P_{t0+Dt}}}{Q_{P_{t0}}} \right)^{1/Dt} \]  \hspace{1cm} (4.3)

and

\[ LZPK = 1 - K \]  \hspace{1cm} (4.4)

where:
- \( K \) = recession coefficient of primary base flow for the time unit used
- \( Dt \) = number of time units, generally days
- \( Q_{P_{t0+Dt}} \) = a discharge when recession is occurring at the primary base flow rate
- \( Q_{P_{t0}} \) = the discharge \( t \) time units later

If \( Q_{P_{max}} \) represents the maximum value of the primary base flow, then the maximum water content of the lower zone becomes:

\[ LZFPM = \frac{Q_{P_{max}}}{LZPK} \]  \hspace{1cm} (4.5)

Following this procedure, through Figure 4.22 hydrographs it was possible to estimate LZPK, LZFPM, LZSK and LZFSM parameters values.
Figure 4.22 – LZPK, LZFPM, LZSK and LZFSM estimation parameters.

Following the recommended sequence, an estimation of impervious fraction of the basin was performed. PCTIM parameter can be determined from small storms after a significant period of dry weather. Then the volume of direct runoff (observed runoff – base flow) divided by the volume of rain gives the percentage impervious fraction of the basin.

With the support of Figure 4.23 it was possible to calculate the volume of rain, and then get PCTIM parameter estimation.

Figure 4.23 - PCTIM parameter estimation.

The last sequence of the SOBEK manual guideline for SAC-SMA segment parameter estimation is a methodology to estimate the upper zone parameters UZTWM, UZFWM and UZK.

The upper tension storage capacity (UZTWM) represents the depth of water, which must be filled over non-impervious areas before any water becomes available for free water storage. Following the logic of the Curve Number (CN) method (USDA, 1986), where the initial abstraction before rainfall becomes effective is estimated as 20% of the potential maximum retention, the UZTWM becomes:

\[
UZTWM = 50.8(100/CN - 1)
\]
CN values range from 30 to about 90 for rural areas and are a function of the soil type (soil texture and infiltration rate) and land use, type of land cover, treatment and hydrologic or drainage condition. The CN value adopted for the river Lima basin was 80 as this number mimics better the ground cover type and hydrological condition (CPESC, 2013).

The upper zone free water represents that depth of water, which must be filled over the non-impervious portion of the basin in excess of UZTWM in order to maintain a wetting front at maximum potential. This volume provides the head function in the percolation equation and also establishes that volume of water, which is subject to interflow drainage. Generally its magnitude ranges from 10-100 mm. It is not generally feasible to derive the magnitude of the upper zone free water from direct observations, and successive computer runs are required in order to establish a valid depth.

The upper zone lateral drainage rate is expressed as the ratio of the daily withdrawal to the available contents. This factor is not capable of direct observation and must be determined by successive computer runs. Peck (1976) suggests the following approximate procedure assuming that interflow is observed during N consecutive days and that interflow becomes insignificant when it is reduced to less than 10% of its maximum value it follows:

\[
UZK = 1 - 0.1^{1/N}
\]

Values for UZK as a function of N can be read from Figure 4.24. In this study an eight consecutive days period was considered.

![Figure 4.24 - UZK values as a function of N.](image)

Results for 8 of SAC-SMA parameters are presented in Table 4.1 as well as their feasible ranges. Obtained values are in the interval of SSURGO dataset feasible range.
Table 4.1 - SAC-SMA parameter estimation via hydrograph analysis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimation value</th>
<th>SSURGO feasible range</th>
</tr>
</thead>
<tbody>
<tr>
<td>LZPK</td>
<td>0,04</td>
<td>0,001-0.05</td>
</tr>
<tr>
<td>LZFPM</td>
<td>276</td>
<td>10-1000</td>
</tr>
<tr>
<td>LZSK</td>
<td>0,04</td>
<td>0,01-0,35</td>
</tr>
<tr>
<td>LZFSM</td>
<td>230</td>
<td>5-400</td>
</tr>
<tr>
<td>PCTIM</td>
<td>0,044</td>
<td>-----</td>
</tr>
<tr>
<td>UZTWM</td>
<td>15,30</td>
<td>10-300</td>
</tr>
<tr>
<td>UZFWM</td>
<td>30</td>
<td>5-150</td>
</tr>
<tr>
<td>UZK</td>
<td>0,25</td>
<td>0,10-0,75</td>
</tr>
</tbody>
</table>

After this first parameter estimation, the step forward was to insert these values into SOBEK Sacramento nodes that contribute to river Vez. Since only 8 of the 16 parameters (listed in Table 2.1) were estimated, a sensitivity analysis to determine the remaining parameters with a SSURGO feasible range was done following some rules: For each of the un-estimated parameters with a feasible range defined (ZPERC, REXP, LZTWM and PFREE), two simulations were done: one with the lower value and the other with the higher value recommended in SSURGO. These simulations were done using fixed values for the 8 estimated parameters.

As for the other un-estimated parameters (ADIMP, RIVA, SIDE and RSERV) a default value from SOBEK software was applied.

Although the efforts, this sensitivity analysis showed as an inglorious task because it was concluded that in general, changing only one parameter shows no significant changes in the simulated hydrographs and the simultaneous combination of several parameters have greater influence on the final results.

Revealing itself as a very time consuming task and since running numerous SOBEK model simulations was not viable due to time elapsed in each simulation it was decided to perform in this work a highly detailed SAC-SMA model programmed in VBA. Detailed explanation of the basis of this model was already presented in section 2.3.2, and the respective code can be accessed in Appendix I. This approach resulted in a much more fast response in getting results for each parameter, and gave a broader view on the behaviour of these parameters. In Figure 4.25 the VBA SAC-SMA model layout is depicted.
Through the application of the VBA and SOBEK models it was possible to obtain a final combination of the 16 Sacramento calibration parameters for the sub-basins that contribute to river Vez flows. This calibration used a simulation time period of 6 months from 01-01-1960 to 04-07-1960. In Figure 4.26 results of simulated discharges versus observed ones and the square correlation coefficient \((R^2)\) between these two time series are depicted.
Although obtained results may give the impression of a poor calibration, it can be verified that the model is responding according to the available meteorological data. Since the available data is not so reliable and a good model reaction was achieved, it can be concluded that the meteorological data for this time range was not accurate. The calibrated parameters for river Vez’s contributing sub-basins are listed in Table 4.2 from where it can be perceived that all the parameters are within the recommended range values.

**Table 4.2 - Calibrated parameters for river Vez’s contributing sub-basins.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Calibrated value</th>
<th>SSURGO feasible range</th>
</tr>
</thead>
<tbody>
<tr>
<td>UZTWM</td>
<td>160</td>
<td>10–300</td>
</tr>
<tr>
<td>UZFWM</td>
<td>150</td>
<td>5–150</td>
</tr>
<tr>
<td>UZK</td>
<td>0,1</td>
<td>0.10–0.75</td>
</tr>
<tr>
<td>ZPERC</td>
<td>10</td>
<td>5–350</td>
</tr>
<tr>
<td>REXP</td>
<td>2</td>
<td>1–5</td>
</tr>
<tr>
<td>LZTWM</td>
<td>160</td>
<td>10–500</td>
</tr>
<tr>
<td>LZFSM</td>
<td>200</td>
<td>5–400</td>
</tr>
<tr>
<td>LZFPM</td>
<td>250</td>
<td>10–1000</td>
</tr>
<tr>
<td>LZSK</td>
<td>0,05</td>
<td>0.01–0.35</td>
</tr>
<tr>
<td>LZPK</td>
<td>0,01</td>
<td>0.001–0.05</td>
</tr>
<tr>
<td>PFREE</td>
<td>0,04</td>
<td>0.0–0.8</td>
</tr>
<tr>
<td>PCTIM</td>
<td>0,024</td>
<td>-----</td>
</tr>
<tr>
<td>ADIMP</td>
<td>0,2</td>
<td>-----</td>
</tr>
<tr>
<td>RIVA</td>
<td>15,30</td>
<td>-----</td>
</tr>
<tr>
<td>SIDE</td>
<td>0</td>
<td>-----</td>
</tr>
<tr>
<td>RSERV</td>
<td>0,3</td>
<td>-----</td>
</tr>
</tbody>
</table>

This methodology was sequentially replicated in all the other sub-basins that contribute to the location of river Lima 1 hydrometric gauge. For that, river Vez’s contributing sub-basins already used the calibrated Sacramento parameters. In this simulation scenario, a time period of almost 5 months, starting in 06-02-1948 to 24-06-1948 was used, being this period chosen due to the fact that this is the longer time series available. In this period there was the occurrence of a flood peak as well as a recession period. The results for this simulation scenario are shown in Figure 4.27.
The results obtained for Sacramento parameter values in river Lima are not so different from those obtained in the calibration of river Vez (see Table 4.3). That may be explained by the proximity and the homogeneity of soil characteristics within the river Lima watershed.

**Table 4.3** – Calibrated parameters for river Lima’s contributing sub-basins.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Calibrated value</th>
<th>Feasible range</th>
</tr>
</thead>
<tbody>
<tr>
<td>UZTWM</td>
<td>190</td>
<td>10–300</td>
</tr>
<tr>
<td>UZFWM</td>
<td>130</td>
<td>5–150</td>
</tr>
<tr>
<td>UZK</td>
<td>0.15</td>
<td>0.10–0.75</td>
</tr>
<tr>
<td>ZPERC</td>
<td>10</td>
<td>5–350</td>
</tr>
<tr>
<td>REXP</td>
<td>2</td>
<td>1–5</td>
</tr>
<tr>
<td>LZTWM</td>
<td>200</td>
<td>10–500</td>
</tr>
<tr>
<td>LZFSM</td>
<td>200</td>
<td>5–400</td>
</tr>
<tr>
<td>LZFPM</td>
<td>300</td>
<td>10–1000</td>
</tr>
<tr>
<td>LZSK</td>
<td>0.1</td>
<td>0.01–0.35</td>
</tr>
<tr>
<td>LZPK</td>
<td>0.01</td>
<td>0.001–0.05</td>
</tr>
<tr>
<td>PFREE</td>
<td>0.04</td>
<td>0.0–0.8</td>
</tr>
<tr>
<td>PCTIM</td>
<td>0.024</td>
<td>-----</td>
</tr>
<tr>
<td>ADIMP</td>
<td>0.2</td>
<td>-----</td>
</tr>
<tr>
<td>RIVA</td>
<td>15.30</td>
<td>-----</td>
</tr>
<tr>
<td>SIDE</td>
<td>0</td>
<td>-----</td>
</tr>
<tr>
<td>RSERV</td>
<td>0.3</td>
<td>-----</td>
</tr>
</tbody>
</table>

### 4.2.3 Calibration step two

As previously stated, step two of the calibration process has as its main goal the calibration of all the sub-basins that are located in between Alto Lindoso and Touvedo dams. Considering as successful the procedure adopted in calibration step one, the SAC-SMA model of river Lima watershed was calibrated considering the two dams operational processes (reservoirs water levels,
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Luís Vieira  

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turbinated and effluent flow rates) as well as the previously referred sub-basins. The calibration procedure adopted in step two is schematized in Figure 4.28.

![Figure 4.28 - Step two Sacramento calibration strategy.](image)

For calibration of hydraulic structures at dams, an investigation on the historical data of turbinated and effluent flow rates as well as the records of reservoirs water levels was made. All time available records were used for calibration purposes.

Starting with Alto Lindoso calibration, turbinated flow rates was the first operational process to be calibrated. The goal of this calibration is to create orifice opening rules in SOBEK that can reproduce all the historical data of the turbinated flow rates. For that purpose, it was firstly considered a period of simulation with a constant flow rate in order to fill the reservoir to a water level identical to the one defined in initial conditions. The result of this turbinated flow rates calibration is depicted in Figure 4.29.

![Figure 4.29 - Alto Lindoso turbinated flow rate calibration and its correlation coefficient.](image)
Once created the orifice opening rules to simulate the turbined flows for Alto Lindoso, it was then proceeded to the calibration of the discharge flow rates operated by the flood gates. As the sum of turbined flow with discharge flow is equal to the effluent flow rate, the objective of this step was to get the best combined operation rules in order to have a good simulation results for the flow coming from Alto Lindoso. The results of this calibration are shown in Figure 4.29.

Figure 4.30 - Alto Lindoso effluent flow rate calibration and its correlation coefficient.

The reservoir water level benefits from the fact that the incoming flow rate affluent to Alto Lindoso is available through SNIRH records. Good simulation results for volume reservoir and water level were obtained. Figure 4.31 shows the good correlation values reached in this study.

Figure 4.31 - Alto Lindoso reservoir’s water level calibration and its correlation coefficient.

After the successful calibration procedure applied for Alto Lindoso operational conditions processes, a similar methodology was replicated to Touvedo dam. Figures 4.32, 4.33 and 4.34 depict calibration results for turbined flow, effluent flow and reservoir’s water level, respectively.
These results are illustrative of a good model performance after a correct definition of the structures opening rules, a proper discretization of the model and its calibration parameters (orifices flow coefficients).

Following the defined strategy, the calibration of the sub-basins existing in between both dams was the next task. Since the affluent and effluent flow rates historical data from the existing hydrometric gauges in both dams are available, this calibration process took a different approach. The calibration of the intermediate contributing sub-basins was performed considering that the effluent flow rate
from Alto Lindoso dam subtracted by the affluent flow rate in Touvedo is equal to the precipitation contribution of those sub-basins.

The methodology for the calibration of the existing sub-basins in between Alto Lindoso and Touvedo dam followed exactly the same procedure already explained in calibration step one. It was done primarily a hydrograph analysis and then a sensitivity analysis using as support SOBEK model and SAC-SMA VBA model. The calibration scenario data started from the events occurred in 21-04-2006 until 19-08-2007. Figure 4.35 shows the results obtained in this process.

![Figure 4.35- Sub-basins comprehended between dams calibration results.](image)

As observed in step one, the results obtained shows that the model is responding correctly with the available precipitation data inputted by the meteorological stations. Sacramento parameters obtained are not very distant from the ones already achieved in previous calibration processes as shown in Table 4.4.
Table 4.4 - Calibrated parameters for the existing sub-basins in between dams.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Calibrated value</th>
<th>Feasible range</th>
</tr>
</thead>
<tbody>
<tr>
<td>UZTWM</td>
<td>170</td>
<td>10–300</td>
</tr>
<tr>
<td>UZFWM</td>
<td>150</td>
<td>5–150</td>
</tr>
<tr>
<td>UZK</td>
<td>0.15</td>
<td>0.10–0.75</td>
</tr>
<tr>
<td>ZPERC</td>
<td>10</td>
<td>5–350</td>
</tr>
<tr>
<td>REXP</td>
<td>2</td>
<td>1–5</td>
</tr>
<tr>
<td>LZTWM</td>
<td>230</td>
<td>10–500</td>
</tr>
<tr>
<td>LZFSM</td>
<td>230</td>
<td>5–400</td>
</tr>
<tr>
<td>LZFPM</td>
<td>350</td>
<td>10–1000</td>
</tr>
<tr>
<td>LZSK</td>
<td>0.1</td>
<td>0.01–0.35</td>
</tr>
<tr>
<td>LZPK</td>
<td>0.01</td>
<td>0.001–0.05</td>
</tr>
<tr>
<td>PFREE</td>
<td>0.04</td>
<td>0.0–0.8</td>
</tr>
<tr>
<td>PCTIM</td>
<td>0.024</td>
<td>-----</td>
</tr>
<tr>
<td>ADIMP</td>
<td>0.2</td>
<td>-----</td>
</tr>
<tr>
<td>RIVA</td>
<td>15,30</td>
<td>-----</td>
</tr>
<tr>
<td>SIDE</td>
<td>0</td>
<td>-----</td>
</tr>
<tr>
<td>RSERV</td>
<td>0.3</td>
<td>-----</td>
</tr>
</tbody>
</table>

Finalized all the complex Sacramento hydrological model calibration process, it must be stressed that this procedure revealed itself as a very tricky and time consuming task to achieve a good parameter combination for each one of the sub-basins.

4.2.4 Model validation

Model validation is a process of evaluating the calibrated model using a different period of analysis. For this validation, the same event used with the hydrodynamic model was used. This situation corresponds to a flood event that occurred on 23rd and 24th of March 2006 and the simulation period considered 7 days comprised between 00:00 of 20-03-2006 and 23:45 of 26-03-2006. The simulation time step used was of 15 minutes. The results of the validation simulation scenario are again focused on two different locations. Firstly it was studied the river discharge behaviour at Ponte da Barca’s hydrometric station, and after the water levels measured at Ponte de Lima’s weir.

To evaluate the goodness of fit between observed river discharges, water levels and simulated outputs, the $R^2$ correlation coefficient was used to compare simulated and measured values. Figures 4.36 and 4.37 show these simulated and measured values.
The results obtained were very encouraging, since the simulated event is very similar with the registered one. One aspect that is very important to refer is that the flood peak was perfectly simulated, giving confidence in the results obtained for flood periods simulation.
"Prediction is very difficult, especially if it’s about the future."

Nils Bohr (1885 – 1962)
CHAPTER 5    FEWS-LIMA PLATFORM

5.1 Flood forecasting

Floods and droughts are naturally occurring phenomena that in most parts of the world can never be fully avoided. With growing numbers of people and capital investments in areas prone to floods and droughts worldwide, the potential losses increase even more. Traditional measures attempt to avoid damages and focus on usually high capital investments in physical infrastructure, such as dams, reservoirs, raising river embankments and various other river engineering works. The risk however can never be fully eliminated. Consequently additional measures like early warning systems and event management are required to minimize the risk of damage caused by these hydrological events.

A warning system is generally a set of processes that are interconnected through an important timeline whose components are depicted in Figure 5.1.

![Figure 5.1 - Warning system timeline.](image)

Hydrological and meteorological data collected by real-time monitoring systems provide the basic information needed for warning feeding. Warnings should be sufficiently reliable and be provided in time to allow effective responses by the competent authorities. Although warnings can be directly issued on the basis of observed data, hydrological forecasting can increase the lead time in which adequate responses can be given. Forecasting can provide additional information to the authorities on coming events and allows a prompt and effective response allowing far less impact on society. Thus hydrological forecasting constitutes a precious tool for early warning and preparedness for critical flood events.

The development of hydrological forecasting and warning systems is an essential element in regional and national hydrological strategies, and has gained high priority in many countries especially in the realm of flood forecasting. Recent developments in numerical weather prediction, radar data, and on-line meteorological and hydrological data collection have resulted in an
increasing focus on data import and processing especially in the flood forecasting domain. In conjunction with progresses in database development, hydrological and hydrodynamic model development, and on-line data availability, the challenges for developing a modern hydrological forecasting and warning system are found in the integration of large data sets, specialised modules to process the data, and open interfaces to allow easy integration of existing modelling capacities.

5.2 FEWS-LIMA

5.2.1 Introduction

The development of flood early warning systems is an essential element in regional and national flood alert strategies. The key elements of a forecasting system operating in a real time environment are:

- Real time data acquisition for observed meteorological and hydrological conditions;
- Hydrologic and hydrodynamic models for simulation;
- Meteorological conditions forecasting;
- Updating and data assimilation.

Figure 5.2 illustrates the structure of a flood warning system.
Recent developments in weather forecasting, radar data and on-line meteorological and hydrological data collection, require for an increasing focus on data import and processing within a FEWS platform. The challenges for developing a modern FEWS system are found in the integration of large data sets, modules to process the data and integrate various existing models. FEWS-LIMA system has been developed for the river Lima basin with a sophisticated collection of modules designed for building a FEWS customised to the specific requirements of this river Lima. Details on FEWS-LIMA development are explained in the next paragraphs.

### 5.2.2 Platform conception

The first step in the creating of a FEWS system consists on analysing the case study and understanding how the system will work. All the functioning processes as well as the way in which the data source will be gathered and inserted must be decided. Figure 5.3 presents how FEWS-LIMA works out as an all-in-one tool.

![FEWS-LIMA conceptualization](image)

**Figure 5.3 - FEWS-LIMA conceptualization.**

UGrib is a meteorological forecast service that allows instant and fully customizable access to global weather forecast data. Within a user friendly interface it is possible download and view weather data right on a desktop (Grib, 2013). Through this service, it is possible to download a “grib file” of one selected area. “Grib” is the format used by the world meteorological institutes to
transport and manipulate weather data and is the foundation of the forecasts we see around us in our daily life. The actual “Grib” data file is produced by Global Forecast System (GFS) and it is updated every 6 hours (runtime + 5 hours). This service provides a 7-days forecast system with 3 hour time step on a resolution of 0,5º by 0,5º.

ArcGIS software works as a support to insert all the geographical and topographical data on FEWS-LIMA region and map layers. With this support it is possible to successfully include river Lima shapefiles as well as all hydrologic and meteorological stations within their exact location.

SNIRH database served as the source of all FEWS-LIMA historical data. Existing available data for all the considered meteorological and hydrometric stations were thoroughly inserted in order to get a sustainable archive data for all simulations in river Lima basin system.

SOBEK hydrodynamic and hydrological successfully calibrated models play the essential role as the core of FEWS-LIMA system. The models are runned through a SOBEK adapter that is a tricky operational conversion process which gives the user an independent way to execute the models since it’s not necessary to use SOBEK software itself.

FEWS-LIMA was created with all the aforementioned components constituting a platform able to provide information on the hydrodynamics characteristics within the river Lima basin. This platform was built so that the river hydrodynamics conditions of the river were the most approximately as possible to the reality. This way the FEWS-LIMA is outlined to do every day at 00:00 a simulation with data registered at that time in order to recreate the best initial conditions. This simulation creates a "restart file" which is a file filled with the most recent simulated results obtained for the system. To perform a forecast procedure, the model will read this “restart file” and then start the simulation considering those results as initial conditions. Warm state is defined as the river state generated in this previous forecasting run, that is, the set values taken from the initial system conditions (“restart file”).

The forecast procedure estimates the discharge and water levels at specified locations up to seven days. To explore the uncertainties it also allows the user to explore the effects of uncertain rainfall forecasts on the water levels and discharges.

5.2.3 User interface

Delf-FEWS operates with a very clean and fresh Graphical User Interface (GUI). As an open-source platform, it can be fully personalized in terms of visual or operative functions. The first recommended step was to insert all the river Lima shapefiles as well as all the hydrometric and
meteorological stations locations. Both of these procedures were made by editing map layers and locations files. The procedures of importing the locations information was done compiling that information in “.dbf” files with the correspondent location coordinates and then assigning those files within the location configuration file. In Figure 5.4 an excerpt of “LocationSets.xml” is depicted. The shapefiles are located at /MapLayerFiles folder and then correctly allocated in the map layers configuration files.

![Diagram](image.png)

**Figure 5.4** – “LocationSets.xml” configuration file (excerpt).

With all the locations and shapefiles inserted, the first step of building a FEWS is complete. In Figure 5.5 FEWS-LIMA end user layout screen is depicted. The layout screen can also be fully customised so that the preferences of startup locational focus or the initial zoom can fit the needs of the user.
5.2.4 Workflows

DELFT-FEWS uses workflows to define logical sequences of running forecast modules. The workflow itself simply defines the sequence with which the configured modules are to be run. There is no inherent information or constraints within the workflow about the role that the module has in delivering the forecasting requirement.

Workflows may contain calls to configured module instances, but may also contain calls to other workflows. In the workflowDescriptors configuration described in the so called Regional Configuration section, the properties of the workflows are defined.

All workflows are defined in the Workflows section of the configuration. Each workflow will have the same structure and must adhere to the same schema definition. Workflows are identified by their name, which are registered to the system through the workflowDescriptors configuration in the Regional Configuration section.

5.2.4.1 Historical data insertion

Importation of the historical data available in SNIRH records, for all the hydrometric and meteorological stations followed a simple procedure. Firstly it was necessary to gather all the data and then create two different “.xml files”: one with all the meteorological data, and the other with all the hydrometric data. In these files all the data grouping with the respective stations was already
defined. Note that both of these files must comply with a XSD (XML Schema Definition). In general, a schema is an abstract representation of an object’s characteristics and relationship to other objects. A XSD represents the interrelationship between the attributes and elements of an XML object (for example, a document or a portion of a document). To create a schema for a document, it structure must be analysed, defining each structural element as it’s found. Figure 5.6 shows a small portion of how these “.xml files” look like.

![Figure 5.6 – “.xml file” with historical data (excerpt).](image)

After creating these two files with all historical data, it was then necessary to add them to FEWS-LIMA platform. For doing this task, it was used the ImportTelemetry ModuleInstanceId. This module reads the “.xml files” with the historical data, and then imports them to the platform database, enabling the user to actually see the information using the Time Series display grid as presented in Figures 5.7. Figure 5.8 shows a short sample of the ImportTelemetry module. Imported data should be carefully validated before proceeding with forecasting. The generally large amount of data that is usually imported requires that validation is done, at least partly-automatically by the system, only warning the user when pre-set criteria are not met. Standard imported data is checked for missing values, outliers and unlikely gradients in time.
5.2.4.2 UGrib

UGrib workflows allow the user to perform two different tasks. The first one is to be able to use UGrib application inside FEWS-LIMA and visualize the meteorological forecast for a specified spatial grid, which includes river Lima basin. The second is a more operative task that consists of reading the meteorological data and then importing it to Time Series display grid, as well as to write
that forecast information inside the SOBEK “.bui file” and in one “.xml file”. Doing this, with one “click” the forecast information is available for FEWS-LIMA to process it.

A workflow was created in order to be able to read “.grb files” information inside FEWS-LIMA interface. This workflow automatically downloads the “.grb file” correspondent to river Lima spatial location, and then shows the forecast in the platform. Note that, as already mentioned, Grib service only provides a resolution of 0.5º by 0.5º, which in this case covers most of all river Lima basin. This workflow was developed in XML and then connected to all the system descriptors files. Figure 5.9 shows UGrib forecast layout.

Within the second task UGrib workflow performs three processes. In the first process UGrib works as an importer and writer of data. To import the precipitation forecast, firstly this data must be read. As “grib files” are binary, their reading is not easy. An existing application Degrib (NOAA, 2013) is able to read these files but to get this application to work within prompt command line a “batch file” was coded. This “batch file” calls Degrib and executes the commands to export the wanted precipitation data for river Lima basin. In Appendix II more information on this code is given. Once exported from “grib files”, this data is automatically imported to FEWS-LIMA Time Series display grid (Figure 5.10).
The second process of this workflow is to write the data in the “.bui file”. For this process, a more elaborated script had to be programmed. This script, “Update_BUI.exe” was coded in Visual Basic, using .NET framework. “Update_BUI.exe” reads the decoded data from “grib files” and then writes it in the exact date and time place in the “.bui file”. Details of the code are available in Appendix III. This script has the ability to overwrite existing data. That is, for instance, if it reads forecast data for 7 days today, and if tomorrow another precipitation forecast is used, then the script automatically rewrites the data, updating the “.bui file”. So, with this second process it is possible to automatically create and archive precipitation data, got from UGrib forecast service. In Figure 5.11 excerpts of both codes can are presented.

Figure 5.10 – Precipitation forecast in FEWS-LIMA display grid.

Figure 5.11- Batch Degrib and Update_BUI.exe codes (excerpts).
The third and final task of this workflow consists in reading the “.bui file” previously updated and then automatically create an “.xml file” with all of its contained data. This file, “rain_forecast.xml” will be used as an input for the SOBEK adapter. Again, a conversion application programmed in Visual Basic was built for that specific purpose.

5.2.4.3 SOBEK adapter

To perform the operation of running SOBEK via “batch file” it is necessary to create a hierarchy of configuration files that allows the SOBEK software to be fully operational. Inside the adapter directory, it must be present a /bin folder with “SBKbatch.exe” and “SBKbatch.ini”. These two files are the core files of the adapter.

In other folder /Lima there are six sub-folders with critical configuration files for this adapter. In the /Defaults folder all the information regarding wind and evapotranspiration for this model is found. Within /Input folder there is available the precipitation “.xml file”, as on the /Output folder all the outputs coming from SOBEK will be saved. In /Logs folder a log for all the operations performed by SOBEK are also saved. This way there is a control of which tasks were successfully achieved and if not, an error message will be available giving more precise information on how to fix it. /States folder is where all the “restart files” are kept on. A /.lit” folder with the SOBEK model for this case study must also be present. In the root of this directory, “SOBEK_Adapter.xml” and “run.bat” can be found.

“SOBEK_Adapter.xml” is the control configuration file for the adapter. In this file, all the configurations are done. It’s a very customizable control center that allows the user to program the orders on how this adapter must run. This file must comply to “sobekAdvancedBatch.xsd”, and a general view of its potentialities and possible operational options can be seen in Figure 5.12. It is in this file, that the output configuration for the SOBEK simulation results is defined. As for this procedure, it is possible to filter the exact locations where is desired to know the results. For this work, it was configured that all the results should be automatically converted in FEWS Published Interface (PI) files.

Executing “run.bat” file, “SBKbatch.exe” is started with its own informal standard for configuration information (SBKbatch.ini) and with the operational rules that are defined in “SOBEK_Adapter.xml”.
In FEWS-LIMA, it was defined that the processing activity should be preceded by a pre-processing phase, where a “restart file” should be created every 00:00 hour. Therefore, two different Sobek...
adapter workflows were created. The first, performs the pre-processing task and the second the forecast procedure using the “restart file” created in pre-processing phase as initial conditions information.

For both of these workflows, and since it was necessary to create an interface where the user should choose the date and time for the start and end of the simulation period, two different applications were programmed. The first application is relative to the pre-processing workflow and automatically edits the SOBEK files informing that a “restart file” must be created as well as the simulation start/end period. The second application was programmed to be used in the forecast workflow. With it, SOBEK is informed of the simulation start/end period and that no “restart file” should be created. These applications were coded in Visual Basic within .NET framework, and are depicted in Figures 5.13 and 5.14.

![Pre-processing workflow user interface](image1.png)

**Figure 5.13** - Pre-processing workflow user interface.

![Forecast workflow user interface](image2.png)

**Figure 5.14** - Forecast workflow user interface.

Once inserted the simulation time period, SOBEK simulation in batch is started. Figure 5.15 shows how is the visual interface when running SOBEK inserted in FEWS-LIMA platform. The time needed for the simulation run is exactly the same as in the SOBEK interface, since the core processor is the same.
5.2.4.4 Import results

As referred, SOBEK forecast workflow exports the results into one “Output.xml file”. This file saves all the results for all the parameters for the desired locations indicated in the adapter configuration file. This file is already in PI format which makes the import task easier.

To import the results to FEWS-LIMA system it was created “Import_PI” workflow. This workflow imports the results using the TimeSeriesImportRun module and it is configured in a way that when running this workflow all the results available in “Output.xml” are imported to FEWS-LIMA database and are available to be consulted in Time Series display grid.

5.2.4.5 Scheduled run

FEWS-LIMA is outlined to perform automatically every day at 00:00 a simulation with data registered at that time in order to recreate the best initial conditions. For that, scheduled run workflow was programed. This workflow starts every day at 00:00 through WorkflowTestRun configuration module. When executed, scheduled run workflow calls “DailyRun.bat” application that automatically informs FEWS-LIMA of the current date, which will work as the end time of the simulation period being the day before considered as the start time of it. This way, a “warm state”
of the river conditions is created every single day. “DailyRun.bat” was programmed in Visual Basic, using .NET framework. In Figure 5.16 the layout of the “DailyRun.bat” start is depicted.

![Figure 5.16 – Scheduled run workflow start.](image)

Once all the workflows are successfully programmed and fully operational, FEWS-LIMA is ready for use. Figure 5.17 shows FEWS-LIMA final layout where the aforementioned workflows are displayed.

![Figure 5.17 – FEWS-LIMA workflows layout.](image)
"An ocean traveller has even more vividly the impression that the ocean is made of waves than that it is made of water"

Sir Arthur Stanley Eddington (1882 – 1944)
CHAPTER 6 RESULTS AND DISCUSSION

6.1 Rainfall events

The performance of the Decision Support System created for the river Lima basin was verified for past rainfall events, using a backcasting approach to four events occurred in the years 2006, 2010, and 2011. In addition, a forecasting event was also considered in order to show the applicability of this methodology in future situations demonstrating the strength of the FEWS-LIMA platform.

The backcasting approach consisted on travelling to specific dates in the past and then to perform a 7 days simulation time period using the rainfall data measured in the meteorological stations as the forecasting data. Since river flow rates and water levels at those time periods are available in Ponte da Barca and Ponte de Lima, a “validation” process of the backcasting approach was possible.

As referred on Chapter 3, there are records of flow rates in Ponte da Barca town and water levels in Ponte de Lima town. The week periods for performing the backcast simulations were chosen from the Ponte da Barca’s flow rates hydrograph. The historical data of river flow rate measured at Ponte da Barca town is shown in Figure 6.1 where the 4 peak events used for flood situations are highlighted.

![Figure 6.1 – Time series (2003 – 2011) of flow rate measured at Ponte da Barca town.](image)

The rainfall event considered for flood forecasting was adopted from the Portuguese official meteorological service information for the week 2013.10.14 – 2013.10.21. This rainfall event scenario was obtained from the UGrib service.
All these scenarios were developed in order to anticipate flow rates and water levels in the river Lima. The results obtained in this way were after compared against the minimum water level value of 4 meters in Ponte de Lima’s weir which historically configures a flood situation in this town.

Table 6.1 shows the rainfall event scenarios considered in this study.

<table>
<thead>
<tr>
<th>Rainfall event</th>
<th>Simulated results</th>
<th>Flow rate (Ponte da Barca)</th>
<th>Water level (Ponte de Lima)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backcast:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2006.03.20 – 2006.03.27</td>
<td>BC1</td>
<td>BC1</td>
<td></td>
</tr>
<tr>
<td>2006.11.20 – 2006.11.27</td>
<td>BC2</td>
<td>BC2*</td>
<td></td>
</tr>
<tr>
<td>2010.01.01 – 2010.01.07</td>
<td>BC3</td>
<td>BC3*</td>
<td></td>
</tr>
<tr>
<td>2011.01.03 – 2011.01.10</td>
<td>BC4</td>
<td>BC4</td>
<td></td>
</tr>
<tr>
<td>Forecast:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013.10.14 – 2013.10.21</td>
<td>FC</td>
<td>FC</td>
<td></td>
</tr>
</tbody>
</table>

*Note: results not validated due to lack of measured values.

### 6.2 Results for river flow rates in Ponte da Barca

For each of the considered scenarios the selected rainfall events were used as input data for Sacramento hydrological model combined with the hydrodynamic model. FEWS-LIMA acting as the overall system integrator executed the connection of all the involved elements of modelling. Results for river flow rates at Ponte da Barca are described in the next paragraphs.

Figures 6.2 and 6.3 show the results obtained for river flow rate at Ponte da Barca in scenario BC1. The results obtained for river flow rate at Ponte da Barca in scenario BC2 are shown in Figures 6.4 and 6.5. In Figures 6.6 and 6.7 the results obtained for river flow rate at Ponte da Barca in scenario BC3 are depicted. Figures 6.8 and 6.9 present the results obtained for river flow rate at Ponte da Barca in scenario BC4. As for the forecasting scenario (FC), the obtained results are shown in Figure 6.10.
6.2.1 Backcasting rainfall events

Figure 6.2 – Scenario BC1. River discharge at Ponte da Barca.

Figure 6.3 - Scenario BC1. Correlation coefficient.
Figure 6.4 - Scenario BC2. River discharge at Ponte da Barca.

Figure 6.5 - Scenario BC2. Correlation coefficient.
Figure 6.6 - Scenario BC3. River discharge at Ponte da Barca.

Figure 6.7 - Scenario BC3. Correlation coefficient.
Figure 6.8 - Scenario BC4. River discharge at Ponte da Barca.

Figure 6.9 - Scenario BC4. Correlation coefficient.
6.2.2 Forecasting rainfall events

Figure 6.10 - Scenario FC. River discharge at Ponte da Barca.

6.2.3 Discussion

The results obtained for river discharges at Ponte da Barca allow the following considerations:

- For the backcast scenarios a high correlation between the simulated and observed values has been achieved in the 7-days simulation time period.
- The best fitting results for backcast scenarios was found in BC1 when it was registered the highest flow rate value.
- The correlation coefficient in the flood peak situations is apparently higher than for the periods before and after the occurrence of those events. This suggests that FEWS-LIMA has better performance in flood peak events than in other river hydrodynamics situations.
- The good performances achieved with FEWS-LIMA DSS in all the backcasting scenarios allow confidence enough to trust in the results obtained for the forecasting scenario (FC).
6.3 Results for river water levels in Ponte de Lima

For each of the considered scenarios the selected rainfall events were used as input data for Sacramento hydrological model combined with the hydrodynamic model. FEWS-LIMA acting as the overall system integrator executed the connection of all the involved elements of modelling. Results for river water levels at Ponte de Lima are described in the next paragraphs.

Figures 6.11 and 6.12 show the results obtained for river water levels at Ponte de Lima in scenario BC1. The results obtained for river water levels at Ponte de Lima in scenario BC2 and BC3, respectively, are shown in Figures 6.13 and 6.14 in which there is no registered historical water levels data. Figures 6.15 and 6.16 present the results obtained for river water levels at Ponte de Lima in scenario BC4. Figure 6.17 shows the results obtained for the forecasting scenario (FC).

6.3.1 Backcasting rainfall events

![Figure 6.11 - Scenario BC1. River water level at Ponte de Lima.](image-url)
Figure 6.12 - Scenario BC1. Correlation coefficient.

Figure 6.13 - Scenario BC2. River water level at Ponte de Lima.
Figure 6.14 - Scenario BC3. River water level at Ponte de Lima.

Figure 6.15 - Scenario BC4. River water level at Ponte de Lima.
6.3.2 Forecasting rainfall events

Figure 6.17 - Scenario FC. River water level at Ponte de Lima.
6.3.3 Discussion

From the results obtained for water levels in Ponte de Lima following considerations can be drawn:

- For the backcast scenarios in which water levels measurements are available (BC1 and BC4) high correlation between the simulated and observed values has been achieved in the 7-days simulation time period.

- The best fitting results for backcast scenarios was found in BC1 when the lower water level in those two scenarios was registered.

- The correlation coefficient in the flood peak situations is apparently higher than for the periods before and after the occurrence of those events. This suggests that FEWS-LIMA has better performance in flood peak events than in common river hydrodynamics.

- Rainfall event scenario BC1 provided the highest correlation coefficients for water level in Ponte de Lima and river flow rate at Ponte da Barca. This suggests that FEWS-LIMA has better performance in flood peak events than in other river hydrodynamics situations.

- For the highest river flow rate measured at Ponte da Barca, 798 m$^3$/s (BC1), it is observed a correspondent water level in Ponte de Lima of 6.01m. Conversely, the highest water level in Ponte de Lima (6.45m) was observed when the river flow discharge in Ponte da Barca was 595 m$^3$/s (BC4). These findings suggest the influence of upstream dams flow regulations and/or the natural flow contribution of the tributary river Vez.

- The good performances achieved with FEWS-LIMA DSS in all the backcasting scenarios allow confidence enough to trust in the results obtained for the forecasting scenario (FC).
“All things are from water and all things are resolved into water.”

Thales (c. 624 B.C. – c. 546 B.C.)
CHAPTER 7  CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

This research work aimed to build a decision support system platform for flood forecasting in a river basin. The created tool leads to prediction of hydraulic variables, namely river discharge and water levels which are critical for flood management in a river basin.

Since meteorological forecast data (mainly precipitation) is available, a hydroinformatics tool like that one developed in this work is of valuable help not only for flood forecasting but also for flood nowcasting. Actually, good and accurate meteorological information obtained from sophisticated means can be effectively used in combination with decision support systems for flood protection in basins and urban environments contributing for establishing early warning systems for the sake of safety and security of people and economic goods.

In this work a platform, FEWS-LIMA, developed in DELFT-FEWS environment was successfully applied in the case study of the Portuguese river Lima basin. This platform integrates hydrological and hydrodynamic models that work together in predicting river hydraulics variables such as water levels and flow rates. These predictions use rainfall time series as input data that can be obtained from meteorological forecasting services.

In this way FEWS-LIMA will work as a user friendly tool in forecasting flood events serving as a powerful help in flood management at a river basin scale.

Although FEWS-LIMA has the ability to simulate results for every single reach segment of all river Lima and its tributaries, in this work only flow rates at Ponte da Barca and water levels at Ponte de Lima were predicted.

Rainfall historical data were used in different rainfall events scenarios for backcasting simulations in order to demonstrate the accuracy of the modelling processes. In these practical situations it was verified that the results obtained have good adherence to the actually measured hydraulic parameters.

Once finished the models calibration and validation the platform can be applied for accurate flood forecasting. This possibility allows better control and management of floods in river Lima helping to protect the historical towns that are within its basin.
7.2 Future work

Based on the results obtained in this research work further efforts and future improvements may include:

- Implementation of 2D/3D modelling for simulating hydrodynamics in estuarine and coastal environments.
- Implementation of a Real Time Control module.
- Further tests and simulations in different operational conditions in upstream dams of river Lima.
- Application of a water quality module to simulate the river water quality status.
- Improvement of FEWS-LIMA to a fully automated distributed client-server environment.
“Success is stumbling from failure to failure with no loss of enthusiasm.”

Winston Churchill (1874 – 1965)
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CHAPTER 8 REFERENCES


Faber, B.A.; and Stedinger, J.R. (2001) Reservoir optimization using sampling SDP with ensemble streamflow prediction (ESP) forecasts, J. Hydrol., 249, 113-133.


“We never know the worth of water till the well is dry.”

Thomas Fuller (1608 – 1661)
APPENDIX I – SACRAMENTO VBA MODEL CODE

Option Explicit

'   Número de variáveis de entrada
Dim nv_in As Integer
'   Variáveis de entrada
Dim xm() As Double
'   Número de variáveis de estado
Dim nv_st As Integer
'   Variáveis de estado
Dim x() As Double
'   Número de parâmetros do modelo
Dim np As Integer
'   Parâmetros do modelo
Dim pmod() As Double
'   Integração
Dim t As Double
Dim t0 As Double
Dim deltat As Double
Dim tf As Double
'   Parâmetros RK
Dim k1() As Double
Dim k2() As Double
Dim k3() As Double
Dim k4() As Double
'   Funções
Dim frk() As Double
'   Variáveis de saída
Dim uc As Double
Dim uer As Double
Dim somavar As Double
'   Variável auxiliar
Dim y As Double
'   Contadores
Dim i As Integer, j As Integer
Dim xvar() As Double
Dim uparc1, uparc2, uparc3, uparc4, uparc5 As Double

Sub rk()

'   Aquisição dos valores presentes na folha de Excel
Call initt

'   Imprimir o cabeçalho e os primeiros valores
Sheets("Resultados").Cells(1, 1) = "Iteração"
Sheets("Resultados").Cells(1, 2) = "t"
Sheets("Resultados").Cells(1, 3) = "uc"
Sheets("Resultados").Cells(1, 4) = "uer"
Sheets("Resultados").Cells(1, 12) = "Soma Variáveis"
Sheets("Resultados").Cells(2, 1) = 0
Sheets("Resultados").Cells(2, 2) = t

uc = (pmod(6) * x(2) + (pmod(7) * x(4) + pmod(8) * x(5)) / (1 + pmod(12))) * (1 - pmod(13) - pmod(14)) + xm(1) * pmod(14) + ((x(6) - x(1)) / pmod(3)) * xm(1) * (x(1)) / pmod(11) + pmod(15) * pmod(13) + xm(1) * (x(1)) / pmod(11) + pmod(15) * (x(2) / pmod(2)) + pmod(16) * (1 - pmod(13) - pmod(14)) + (1 - (x(6) / pmod(3)))
^2) * (x(2) / pmod(2)) ^ pmod(16) * (x(1) / pmod(1)) ^ pmod(15) * xm(1) * pmod(13)
Sheets(“Resultados”).Cells(2, 3) = uer
uer = xm(2) * x(1) / pmod(1) + xm(2) * (1 - x(1) / pmod(1)) * (x(3) / (pmod(1) + pmod(3)) + xm(2) * (1 - x(1) / pmod(1)) * (x(6) / (pmod(3) + pmod(1)))
Sheets(“Resultados”).Cells(2, 4) = uer
somavar = uc * deltat + uer * deltat + xm(1) * deltat
Sheets(“Resultados”).Cells(2, 12) = somavar
'Stop
For i = 1 To nv_st
    Sheets(“Resultados”).Cells(1, 4 + i) = “x” & i
    Sheets(“Resultados”).Cells(2, 4 + i) = x(i)
Next
Sheets(“Resultados”).Cells(1, 5 + nv_st) = “y”
y = 1 - (x(3) + x(4) + x(5)) / (pmod(3) + pmod(4) + pmod(5))
Sheets(“Resultados”).Cells(2, 5 + nv_st) = y
ReDim k1(1 To nv_st), k2(1 To nv_st), k3(1 To nv_st), k4(1 To nv_st)
j = 1
Do
    t0 = t
    For i = 1 To nv_st
        x0(i) = x(i)
    Next
    ' k1
    Call fun
    For i = 1 To nv_st
        k1(i) = frk(i)
    Next
    ' k2
    t = t0 + deltat / 2
    For i = 1 To nv_st
        x(i) = x0(i) + deltat / 2 * k1(i)
    Next
    Call fun
    For i = 1 To nv_st
        k2(i) = frk(i)
    Next
    ' k3
    t = t0 + deltat / 2
    For i = 1 To nv_st
        x(i) = x0(i) + deltat / 2 * k2(i)
    Next
    Call fun
    For i = 1 To nv_st
        k3(i) = frk(i)
    Next
    ' k4
    t = t0 + deltat
    For i = 1 To nv_st
        x(i) = x0(i) + deltat * k3(i)
    Next
    Call fun
    For i = 1 To nv_st
        k4(i) = frk(i)
Next
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For i = 1 To nv_st
    x(i) = x0(i) + deltat / 6 * (k1(i) + 2 * k2(i) + 2 * k3(i) + k4(i))
    xvar(i) = deltat / 6 * (k1(i) + 2 * k2(i) + 2 * k3(i) + k4(i))
Next

' Cálculo das variáveis de saída

uparc1 = (pmod(6) * x(2) + (pmod(7) * x(4) + pmod(8) * x(5)) / (1 + pmod(12))) * (1 - pmod(13) - pmod(14))
' Stop
uparc2 = x(1) * pmod(14)
' Stop
uparc3 = ((x(6) - x(1)) / pmod(3)) * x(1) * (x(1) / pmod(1)) ^ pmod(15) * pmod(13)
' Stop
uparc4 = x(1) * (x1) / pmod(1) ^ pmod(15) * (x(2) / pmod(2)) ^ pmod(16) * (1 - pmod(13) - pmod(14))
' Stop
uparc5 = (1 - (x(6) / pmod(3)) ^ 2) * (x(2) / pmod(2)) ^ pmod(16) * (x(1) / pmod(1)) ^ pmod(15) * x(1) * pmod(13)
' Stop
uc = uparc1 + uparc2 + uparc3 + uparc4 + uparc5

' Stop

uer = x(2) * x(1) / pmod(1) + x(2) * (1 - x(1) / pmod(1)) * x(3) / (pmod(1) + pmod(3)) + x(2) * (1 - x(1) / pmod(1)) * (x(6) / (pmod(3) + pmod(1)))
somavar = xvar(1) + xvar(2) + xvar(3) + xvar(4) + xvar(5) + xvar(6) + uc * deltat + uer * deltat

' Imprimir os valores calculados
Sheets("Resultados").Cells(2 + j, 1) = j
Sheets("Resultados").Cells(2 + j, 2) = t
Sheets("Resultados").Cells(2 + j, 3) = uc
Sheets("Resultados").Cells(2 + j, 4) = uer
Sheets("Resultados").Cells(2 + j, 12) = somavar
For i = 1 To nv_st
    Sheets("Resultados").Cells(2 + j, 4 + i) = x(i)
Next
y = 1 - (x(3) + x(4) + x(5)) / (pmod(3) + pmod(4) + pmod(5))
Sheets("Resultados").Cells(2 + j, 5 + nv_st) = y

t = t0 + deltat
If t > tf Then
    Exit Do
Else
    j = j + 1
End If
Loop
End Sub

Sub init()

' Apagar os valores da folha Resultados
Sheets("Resultados").Select
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Cells.Select
Selection.ClearContents

Sheets("Modelo").Select

' Variáveis de entrada
nv_in = 2
ReDim xm(1 To nv_in)
For i = 1 To nv_in
    xm(i) = Cells(4 + i, 2)
Next

' Variáveis de estado
nv_st = 6
ReDim x0(1 To nv_st), x(1 To nv_st), xvar(1 To nv_st)
For i = 1 To nv_st
    x(i) = Cells(8 + i, 2)
Next

' Parâmetros do modelo
np = 19
ReDim pmod(1 To np)
For i = 1 To np
    pmod(i) = Cells(16 + i, 2)
Next

' Integração
t = 0
tf = Cells(38, 2)
deltat = Cells(39, 2)

End Sub

Sub fun()

' Contador
Dim k As Integer
' Variáveis auxiliares
Dim c1 As Double
Dim c2 As Double

y = 1 - (x(3) + x(4) + x(5)) / (pmod(3) + pmod(4) + pmod(5))
c1 = pmod(7) * (pmod(4) + pmod(5))
c2 = pmod(7) * pmod(4) / c1

' Vetores
ReDim frk(1 To nv_st) As Double
ReDim x_x(1 To nv_st - 1) As Double

For k = 1 To nv_st - 1
    x_x(k) = x(k) / pmod(k)
Next

' Definição das funções
frk(1) = (1 - x_x(1) ^ pmod(15)) * x_x(1) - x_x(2) * x_x(1)
frk(2) = x_x(1) ^ pmod(15) * x_x(1) * (1 - x_x(2) ^ pmod(16)) - pmod(6) * x(2) -
c1 * (1 + pmod(9) * (y) ^ pmod(10)) * x_x(2)
frk(3) = c1 * (1 + pmod(9) * (y) ^ pmod(10)) * x_x(2) * (1 - pmod(11)) * (1 -
x_x(3) ^ pmod(17)) - x(2) * (1 - x_x(1)) * x(3) / (pmod(1) + pmod(3))
frk(4) = c1 * (1 + pmod(9) * (y) ^ pmod(10)) * x_x(2) * (1 - (1 - pmod(11)) * (1 -
x_x(3) ^ pmod(17))) * ((c2 * x_x(3) - 1) * x_x(4) + 1) - pmod(7) * x(4)
frk(5) = c1 * (1 + mod(9) * (y) ^ mod(10)) * x_x(2) * (1 - (1 - mod(11)) * (1 - x_x(3) ^ mod(17))) * (1 - c2 * x(5)) * x_x(4) - mod(7) * x(5)  
frk(6) = (1 - (x(6) / mod(3)) ^ 2) * (1 - x_x(2) ^ mod(16)) * x_x(1) ^ mod(15) * x_m(1) - x_m(2) * (1 - x_x(1)) * (x(6) / (mod(3) + mod(1)))

End Sub
APPENDIX II – BATCH DEGRIB CODE

::Script to read a GRP into a PRB, using degrib
:: For degrib information see: http://www.nws.noaa.gov/mdl/degrib/
:: The script needs the file structure:
:: \degrib
:: \GRB
:: \OUT
:: \TMP
::
:: When executed ALL files in the OUT and TMP directory will be deleted.

@ECHO OFF
cls
::Delete all output files
echo A limpar ficheiros anteriores
del .\OUT\*_.txt
del .\TMP\*_.prb
del .\TMP\*_.tmp

::Cycle all GRB files
echo.
for %%A in (\GRB\*_.grb) do ( 
    set GRB_FILE=%%~nA 
    call :process_grp
)
go to:CleanTemp

::Process the .GRB file
:process_grp
    echo Converter : %GRB_FILE%.grp
    call :process_degrib
    call :process_filter
    echo Output : %GRB_FILE%.out
    call :process_output
    goto:eof

::Build PRB file from .GRB
::==============================================================================
================
:process_degrib
.\degrib\bin\degrib.exe -in .\GRB\%GRB_FILE%.grb -P -pnt 42,-8.5 -Csv -Unit m -out .\TMP\%GRB_FILE%.prb
go to:eof

::Filter only APCP
::==============================================================================
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:process_filter
Findstr /c:"APCP" .\TMP\%GRB_FILE%.prb > .\TMP\%GRB_FILE%.tmp
go to:eof

::Transform the output
::==============================================================================

Luís Vieira
:process_output
for /f "tokens=*" %%A in (.\TMP\%GRB_FILE%.tmp) do (  
    set THE_LINE=%%A
    call :process_line
)
go to:eof

:process_line
for /f "usebackq tokens=4,5" %%G in ('%THE_LINE%') DO (  
    set T1=%%G
    set T2=%%H
    call :echo_line
)
go to:eof

:echo_line
>>."\OUT\%GRB_FILE%.txt echo %T1:~0,4%/%T1:~4,2%/%T1:~6,2% %T1:~8,2%:%T1:~10,2% %T2%
go to:eof

:CleanTemp
del .\TMP\*.prb
del .\TMP\*.tmp

:TheEnd
::Clear variables
set T1=
set T2=
set THE_LINE=
set GRB_FILE=

::End
echo Ficheiros Gerados
APPENDIX III – UPDATE_BUI.EXE CODE

Imports System.Collections.Generic
Imports System.Diagnostics
Imports System.IO
Imports System.Linq
Imports System.Text
Imports System.Threading.Tasks

Namespace UpdateBUI
    Class Program

        Private Shared Function simulateArgs() As String
            Dim basePath As String = "C:\Users\LuisVieira\Documents\Programa"
                'string basePath = "C:\Users\LuisVieira\Documents\Programa";
            Dim buiFile As String = basePath & "LIMAFORE.BUI"
            Dim delftFile As String = basePath & "Delft_3b.ini"
            Dim settingsFile As String = basePath & "Settings.dat"
            Dim rainFile As String = basePath & "rain_forecast.xml"
            Dim runBatDir As String = basePath
            Dim runBatFile As String = "run.bat"
            Dim outputDir As String = basePath & "OUT"
            Dim meteoDir As String = basePath
            Dim args() As String = New String() { "-M", outputDir, meteoDir }
            Return args
        End Function

        Private Shared Sub Main(args As String())
            ' * ARGS:
            '   * -B "<path to bui>" [BUI update]
            '   * -R "<path to Delft_3b.ini>" "<path to Settings.dat>" "<only path
            to run.bat>" "<run.bat file name>" [restart file]
            '   * -S "<path to Delft_3b.ini>" "<path to Settings.dat>" "<only path
            to run.bat>" "<run.bat file name>" [simulate]
            '   * -D "<path to Delft_3b.ini>" "<path to Settings.dat>" "<only path
            to run.bat>" "<run.bat file name>" [daily run]
            '   * -F "<path to bui>" "<path to rain_forecast.xml>" [actualizacao
de ficheiro XML]
            '   * -M "<path to txt files>" "<path to Meteo.xml dir>" [geracao
            ficheiro Meteo.XML]
            '   * -H [ajuda]
            ' TODO :
            '   args = simulateArgs();

            'Check for args
            If args.Length = 0 OrElse args(0).ToUpper().Equals("-H") Then
                'Error. The BUI file must be provided
O programa tem de ser executado com argumentos. Comando:

> UpdateBUI «OPTIONS»

Opções:

- B '<path to bui>'
- R '<path to Delft_3b.ini> '<path to Settings.dat>' '<only path to run.bat>' '<run.bat file name>'
- S '<path to Delft_3b.ini> '<path to Settings.dat>' '<only path to run.bat>' '<run.bat file name>'
- D '<path to Delft_3b.ini> '<path to Settings.dat>' '<only path to run.bat>' '<run.bat file name>'
- F '<path to bui> '<path to rain_forecast.xml>'
- M '<path to txt files> '<path to Meteo.xml dir>''

'Exit

End If

'Log the arguments

For Each arg As String In args
    Console.WriteLine(arg)
Next

'Read Args. Infinite loop

Dim a As Integer = 0
While True
    If args(a).ToUpper().Equals("-B") Then
        'BUI Update
        a += 1
        If args.Length < a Then
            Console.WriteLine("ERRO. A localização do ficheiro BUI tem de ser fornecida.")
            'Exit
            Return
        End If
        Dim buiFile As String = args(a)
        doBuiUpdate(buiFile)
    ElseIf args(a).ToUpper().Equals("-R") Then
        If args.Length < (a + 3) Then
            Console.WriteLine("ERRO. A localização dos ficheiros Delft_3b.ini e Settings.dat tem de ser fornecida.")
            'Exit
            Return
        End If
        a += 1
        Dim delftFile As String = args(a)
        Dim settingsFile As String = args(a)
        a += 1
        Dim runBatDir As String = args(a)
        a += 1
        Dim runBatFile As String = args(a)
        'restart
        doRestartOrSimulate(delftFile, settingsFile, runBatDir, runBatFile, "Restart_File FEWS-LIMA, LuisVieira")
    ElseIf args(a).ToUpper().Equals("-S") Then
        Dim runBatFile As String = args(a)
        a += 1
        Dim runBatFile As String = args(a)
        'restart
        doRestartOrSimulate(delftFile, settingsFile, runBatDir, runBatFile, "Restart_File FEWS-LIMA, LuisVieira")
If args.Length < (a + 2) Then
    Console.WriteLine("ERRO. A localização dos ficheiros Delft_3b.ini e Settings.dat têm de ser fornecidas.")
    'Exit
    Return
End If
a += 1
Dim delftFile As String = args(a)
a += 1
Dim settingsFile As String = args(a)
a += 1
Dim runBatDir As String = args(a)
a += 1
Dim runBatFile As String = args(a)

'Do Restart or Simulate
doRestartOrSimulate(delftFile, settingsFile, runBatDir, runBatFile, "Simulate FEWS-LIMA, LuisVieira")
ElseIf args(a).ToUpper().Equals("-D") Then
    If args.Length < (a + 3) Then
        Console.WriteLine("ERRO. A localização dos ficheiros Delft_3b.ini e Settings.dat têm de ser fornecidas.")
        'Exit
        Return
    End If
    a += 1
    Dim delftFile As String = args(a)
a += 1
    Dim settingsFile As String = args(a)
a += 1
    Dim runBatDir As String = args(a)
a += 1
    Dim runBatFile As String = args(a)

    'DAILY RUN
    doDailyRun(delftFile, settingsFile, runBatDir, runBatFile, "Simulate FEWS-LIMA, LuisVieira")
ElseIf args(a).ToUpper().Equals("-F") Then
    If args.Length < (a + 2) Then
        Console.WriteLine("ERRO. A localização dos ficheiros BUI e rain_forecast.xml têm de ser fornecidas.")
        'Exit
        Return
    End If
    a += 1
    Dim buiFile As String = args(a)
a += 1
    Dim forecastFile As String = args(a)

    'Forecast
    doForecast(buiFile, forecastFile)
ElseIf args(a).ToUpper().Equals("-M") Then
    If args.Length < (a + 2) Then
        Console.WriteLine("ERRO. A localização dos ficheiros TXT e Meteo.xml têm de ser fornecidas.")
        'Exit
        Return
    End If
    a += 1
    Dim txtDir As String = args(a)
a += 1
```vbnet
Dim meteoXmlDir As String = args(a)

'Export to XML
doMeteoXML(txtDir, meteoXmlDir)
Else
  Exit While
End If

a += 1
If args.Length <= a Then
  Exit While
End If
End While
End Sub

Private Shared Function getFormatedDate(dt As DateTime) As String
  Return dt.Year.ToString() & "/" & dt.Month.ToString() & "/" & dt.Day.ToString() & ";00:00:00"
End Function

Private Shared Sub doRestartOrSimulate(delftFile As String, settingsFile As String, runBatDir As String, runBatFile As String, windowTitle As String)
  'Validate Files
  If Not File.Exists(delftFile) Then
    Console.WriteLine("O ficheiro Delft_3b.ini não foi encontrado.")
    Return
  End If

  If Not File.Exists(settingsFile) Then
    Console.WriteLine("O ficheiro Settings.dat não foi encontrado.")
    Return
  End If

  If Not File.Exists(runBatDir & "\" & runBatFile) Then
    Console.WriteLine("O ficheiro run.bat não foi encontrado.")
    Return
  End If

  Dim df As New DatesForm(windowTitle)
  df.ShowDialog()

  If df.getCancel() Then
    'Canceled
    Return
  End If

  Dim begin As DateTime = df.getInicio()
  Dim [end] As DateTime = df.getFim()

  Dim lines As String()
  'Read, Update and Write the Delft_3b.ini
  lines = System.IO.File.ReadAllLines(delftFile)
  lines(106) = "StartTime='" & getFormatedDate(begin) & ";00:00:00'
  lines(107) = "EndTime='" & getFormatedDate([end]) & ";00:00:00'
  System.IO.File.WriteAllLines(delftFile, lines)

  'Read, Update and Write the settings.dat
  lines = System.IO.File.ReadAllLines(settingsFile)
```
lines(43) = "BeginYear=" & begin.Year.ToString()
lines(44) = "BeginMonth=" & begin.Month.ToString()
lines(45) = "BeginDay=" & begin.Day.ToString()
lines(46) = "BeginHour=0"
lines(47) = "BeginMinute=0"
lines(48) = "BeginSecond=0"
lines(49) = "EndYear=" & [end].Year.ToString()
lines(50) = "EndMonth=" & [end].Month.ToString()
lines(51) = "EndDay=" & [end].Day.ToString()
lines(52) = "EndHour=0"
lines(53) = "EndMinute=0"
lines(54) = "EndSecond=0"

System.IO.File.WriteAllLines(settingsFile, lines)

' Run the bat
' Start the child process.
Dim p As New Process()
' Redirect the output stream of the child process.
p.StartInfo.WorkingDirectory = runBatDir
p.StartInfo.UseShellExecute = False
p.StartInfo.FileName = runBatDir & "\" & runBatFile
p.Start()
Dim output As String = p.StandardOutput.ReadToEnd

Private Shared Sub doDailyRun(delftFile As String, settingsFile As String, runBatDir As String, runBatFile As String, windowTitle As String)
' Validate Files
If Not File.Exists(delftFile) Then
    Console.WriteLine("O ficheiro Delft_3b.ini não foi encontrado.")
    Console.WriteLine("»» " & delftFile)
    Return
End If

If Not File.Exists(settingsFile) Then
    Console.WriteLine("O ficheiro Settings.dat não foi encontrado.")
    Console.WriteLine("»» " & settingsFile)
    Return
End If

If Not File.Exists(runBatDir & "\" & runBatFile) Then
    Console.WriteLine("O ficheiro run.bat não foi encontrado.")
    Console.WriteLine("»» " & runBatFile)
    Return
End If

Dim drf As New DailyRunForm(windowTitle)
drf.ShowDialog()

If drf.getCancel() Then
    ' Canceled
    Return
End If

Dim begin As DateTime = drf.getInicio()
Dim [end] As DateTime = drf.getFim()

Dim lines As String()
' Read, Update and Write the Delft_3b.ini
lines = System.IO.File.ReadAllLines(delftFile)
lines(106) = "StartTime='" & getFormatedDate(begin) & ";00:00:00'
lines(107) = "EndTime='" & getFormatedDate([end]) & ";00:00:00'
System.IO.File.WriteAllLines(delftFile, lines)

'Read, Update and Write the settings.dat
lines = System.IO.File.ReadAllLines(settingsFile)

lines(43) = "BeginYear= " & begin.Year.ToString()
lines(44) = "BeginMonth= " & begin.Month.ToString()
lines(45) = "BeginDay= " & begin.Day.ToString()
lines(46) = "BeginHour= 0"
lines(47) = "BeginMinute= 0"
lines(48) = "BeginSecond= 0"
lines(49) = "EndYear= " & [end].Year.ToString()
lines(50) = "EndMonth= " & [end].Month.ToString()
lines(51) = "EndDay= " & [end].Day.ToString()
lines(52) = "EndHour= 0"
lines(53) = "EndMinute= 0"
lines(54) = "EndSecond= 0"

System.IO.File.WriteAllLines(settingsFile, lines)

'Run the bat
' Start the child process.
Dim p As New Process()
' Redirect the output stream of the child process.
p.StartInfo.WorkingDirectory = runBatDir
p.StartInfo.UseShellExecute = False
p.StartInfo.FileName = runBatDir & "\" & runBatFile
p.Start()
Dim output As String = p.StandardOutput.ReadToEnd
End Sub

Private Shared Sub doBuiUpdate(buiFile As String)
Dim curDir As String = Directory.GetCurrentDirectory()
Dim searchDir As String = curDir & "\OUT"

'Validate OUT dir and BUI file
If Not File.Exists(buiFile) Then
    Console.WriteLine("O ficheiro BUI não foi encontrado.")
    Return
End If

If Not Directory.Exists(searchDir) Then
    Console.WriteLine("A directoria de ficheiros a ler não foi encontrada.")
    Return
End If

'read the OUT dir, looking for *.out files
Dim di As New DirectoryInfo(searchDir)
Dim fi As FileInfo() = di.GetFiles("*.txt")

'Validate how many out files?
If fi.Length = 0 Then
    'No files
    Console.WriteLine("Não existem ficheiros para ler.")
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Private Shared Sub doForecast(buiFile As String, forecastFile As String)
' Validate Files
If Not File.Exists(buiFile) Then
    Console.WriteLine("O ficheiro BUI não foi encontrado.")
    Return
End If

If File.Exists(forecastFile) Then
    'Delete the old forecastFile
    File.Delete(forecastFile)
End If

'Create Writer
Dim w As New XMLWriter(forecastFile)

'Read BUI
Dim lines As String()
Dim line As String
Dim cols As String()
'Read
lines = System.IO.File.ReadAllLines(buiFile)

For h As Integer = 0 To 29
    Dim refDate As New DateTime(2013, 9, 27, 0, 0, 0)

    'Create the header
    w.writeHead(h + 1)

    'Write the details
    For l As Integer = 46 To lines.Length - 1
        line = lines(l).Substring(2)
        line = line.Replace(" ", "~")

        'Split the line
        cols = line.Split("~")
        If cols.Length <> 30 Then
            Exit For
        End If

        w.writeEvent(refDate, cols(h))

        'Next date/time
        refDate = refDate.AddHours(3)
    Next

    w.endHeader()
Next

w.endXml()
End Sub

Private Shared Sub doMeteoXML(txtDir As String, meteoXmlDir As String)
' Validate Files

Return
End Sub
If Not Directory.Exists(txtDir) Then
    Console.WriteLine("A directória de ficheiros TXT não foi encontrada.")
    Return
End If

If Not Directory.Exists(meteoXmlDir) Then
    Console.WriteLine("A directória do ficheiro Meteo.MXL não foi encontrada.")
    Return
End If

If File.Exists(meteoXmlDir & "/Meteo.xml") Then
    'Delete the old forecast file
    File.Delete(meteoXmlDir & "/Meteo.xml")
End If

Dim firstDate As String = ""
Dim firstTime As String = ""
Dim lastDate As String = ""
Dim lastTime As String = ""
Dim events As New List(Of String)()
Dim fileRead As Boolean = False

'String[] files = Directory.GetFiles(txtDir, ".TXT");
Dim files = Directory.GetFiles(txtDir, ".TXT").OrderByDescending(Function(d) New FileInfo(d).CreationTime)

'Only the first file is used. The first is most recent one
For Each file__1 As String In files
    fileRead = True
    Dim outLines As String() = System.IO.File.ReadAllLines(file__1)
    Dim li As LineItem
    Dim first As Boolean = True
    Try
        'Read TXT and build event list
        For Each line As String In outLines
            'Break line
            li = New LineItem(line)

            If first Then
                first = False
                firstDate = li.getDate()
                firstTime = li.getTime()
            End If

            lastDate = li.getDate()
            lastTime = li.getTime()

            'Build event line : <event date="2013-10-14" time="09:00:00" value="0.040" flag="2"/>
            events.Add(li.eventLine)
        Next
    Catch ex As Exception
        Console.WriteLine("Ocorreu um erro na leitura do TXT : «" & file__1 & "»")
        Console.WriteLine("A mensagem de erro é :")
        Console.WriteLine(ex.Message)
    End Try
End If
Return
End Try

Exit For
Next

If Not fileRead Then
    Console.WriteLine("Não existem ficheiros TXT para ler.")
    Return
End If

'Create Writer
Dim w As New XMLMeteoWriter(meteoXmlDir & "/Meteo.xml")

Dim locations As String() = New String(17) {}
later
locations(1) = "Aveleiras"
later
locations(2) = "Boalhosa"
later
locations(3) = "Britelo"
later
locations(4) = "CabanaMaior2"
later
locations(5) = "C abreiro"
later
locations(6) = "CasalSoeiro"
later
locations(7) = "GerazdoLima"
later
locations(8) = "Lindoso2"
later
locations(9) = "MoreiradoLima"
later
locations(10) = "Nogueira"
later
locations(11) = "PonteBarca"
later
locations(12) = "PontedeLima"
later
locations(13) = "PontedeLima"
later
locations(14) = "Seixas"
later
locations(15) = "Sistelo"
later
locations(16) = "Soajo"
later
locations(17) = "TiboGavieira"

For i As Integer = 1 To 17
    w.writeHeader(locations(i), firstDate, firstTime, lastDate, lastTime)
    For Each eventString As String In events
        w.writeEvent(eventString)
    Next

    w.endHeader()
    Next
    w.endXml()
End Sub
End Class
End Namespace