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Effect of climate change on the hydrological regime of navigable water courses in Belgium

Sub report 7
Development of a framework for flexible hydrological modelling

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Effect of climate change on the hydrological regime of navigable water courses in Belgium

Sub report 7 – Development of a framework for flexible hydrological modelling

Tran, Q. Willems, P.; Pereira, F.; Nossent J.; Mostaert, F.

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Abstract

The recent studies by Vansteenkiste et al. (2011, 2012a and 2012b) have shown that the potential hydrological impacts caused by climate change scenarios for Belgium have high uncertainty. For a given climate scenario, the quantitative impact results on the hydrological extremes and overall water balance strongly depend on the selected hydrological model. However, there is a wide variety of existing hydrological models which are now available with different levels of complexity. Therefore, it is necessary to analyze the model structure uncertainty affecting the impact results. An ensemble approach is recommended, where different plausible model structures are tested and inter-compared.

To make such approach feasible in an operational context, an innovative flexible framework is developed and proposed in this study. The framework starts from the multi-model / multi-process ensemble concept, which provides the ability to pinpoint the uncertainties related to hydrological modelling, including the selected model structure, in impact investigations such as climate change or land use change or other types of scenario investigations. This framework, moreover, contains some advantageous aspects, namely the data based approach, the flexibility in model components (hydrological processes) and equations, the spatial implementation, the flexibility in spatial resolution, the model calibration approach for various spatial scales and the flexibility for future extension.

Several well-known lumped and distributed prevailing hydrological models and modelling systems (platforms) were reviewed and presented in order to define the most basic or common hydrological processes that should be implemented in the proposed concept. The popular approaches for presenting hydrological connectivity inside catchments are as well listed. Moreover, PCRaster in Python programming language with its great functionality for spatio-temporal environmental modelling was selected as the platform for the proposed framework.

Three lumped models (i.e. NAM, PDM and VHM) were translated into Python language within the PCRaster environment. The converted scripts were then applied to the case study of the Grote Nete catchment, using the same inputs and model parameters as in the report of Vansteenkiste et al. (2012a). The performance of the translated scripts was evaluated by comparing the simulation results to those from the existing Matlab scripts. The comparisons done for the NAM, PDM and VHM lumped conceptual models have shown a perfect match, which indicates the potential for further implementation of the proposed concept in PCRaster. A distributed version of the NAM model was built and recalibrated for the same catchment to show the possibility for spatial implementation in PCRaster. A concrete work phase is made where the flexible modelling framework, including the flexible approaches for spatial calibration or disaggregation and hydrological spatial linking (explicit versus non-explicit), is implemented and applied for (climate change) impact analysis for a number of catchments.

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1 Introduction

The global climate is changing. This was observed in Belgium by many recent studies (Baguis et al., 2008; Baguis et al.; 2009; Ntegeka and Willems, 2008; Ntegeka et al., 2010), in which the changes in the amount and variability of precipitation and evapotranspiration were believed to have important impacts on the hydrological systems. As a consequence, the hydrological regime of runoff and water availability are directly affected. To investigate the climate change impact on water resources in Belgian catchments, many researches have been carried out during recent years (Boukhris et al., 2008; Ntegeka et al., 2008; Baguis et al., 2009; Van Hoey et al., 2012; Vansteenkiste et al., 2012a, 2012b; 2012c). These studies made use of a common methodology to estimate the potential effect of climate change on Belgian hydrological systems. It is based on climate scenarios and related quantile perturbation method to transform (perturbed) historical meteorological series (i.e. rainfall, evapotranspiration series) into potential future series. The current and perturbed series for different climate change scenarios were employed as inputs in hydrological models which were calibrated and validated using historical records. The simulation results are subsequently analyzed by comparing them with the selected reference.

The climate change impact results obtained by Vansteenkiste et al., (2012a, 2012b) have shown that the current Belgian climate scenarios and related hydrological impacts have high uncertainty. Next to a predicted potential increase in river peak flows, a clear decrease is expected for the low flows, resulting in water availability risks. Their results at the same time also have indicated that for a given climate scenario, the quantitative impact results on hydrological extremes and overall water balance strongly depend on the selected hydrological model.

In the context of the wide variety of existing hydrological models, it is often thought that it is necessary to find the most suitable one for climate change impact assessment on hydrological characteristics, etc. and for a specific study area (Flanders - Belgium in this case). Vansteenkiste et al. (2011; 2012a; 2012b; 2012c), however, indicated that different models might produce good results and that it might be very difficult to select a single “best” model. Therefore, an ensemble approach was recommended, which is already commonly applied in meteorology and climate science, where different plausible models or model assumptions are applied, inter-compared and combined. In this way, the impact of the model uncertainty on the climate change and other types of impact results can be quantified. Vansteenkiste and his colleagues (2012c) demonstrated this by applying two approaches of deterministic rainfall-runoff or hydrological modelling: lumped conceptual and spatially distributed process-based modelling. The lumped conceptual models have the benefit of very limited computational times, which has clear benefits in some applications. The latter models have more detailed descriptions of the different spatially variable hydrological processes. The studies also have shown that these more detailed descriptions may lead to strong differences in the simulated impact of climate scenarios on the low runoff flows during dry seasons. The more detailed models have, however, the disadvantages of much longer calculation times and overparameterization. The latter issue may cause high uncertainty in the parameter calibration, hence as consequence, lead to high uncertainty in the impact results.

Therefore, for impact analysis in water management, the use of a single model may lead to unreliable predictions. Hence, it is significantly necessary to develop a modelling system that allows:

- Different model structures and underlying model assumptions to be tested;
- Impact results from different structures to be inter-compared;
- Application of an ensemble approach for a range of plausible model structures;
- Flexibility, not only in the process components or process detail, but also in the spatial resolution;
- Selecting and applying the most appropriate model detail, taking required spatial detail, accuracy and related computational time into account.

This report discusses the selection and development of a framework and modelling system that meets these needs. The report is organized into five chapters. The first chapter re-organizes the recent studies of Vansteenkiste et al. (2011, 2012a, 2012b), where an overall review on lumped and distributed modelling approaches that are popularly used for Belgian catchments was provided. Other existing approaches or modelling environments, which were not mentioned in their recent reports, but are believed to be worthy investigating in the context of this continuation study, are reviewed in the second chapter. The next chapter introduces the proposed flexible modelling framework, which allows a flexible and modifiable model structure. First tests with this framework, which makes use of the existing open-source modelling package PCRaster in Python are presented in the fourth chapter. These tests allowed fine-tuning of the proposed framework and came up with a final proposal and work plan for continuation of the development of a flexible hydrological modelling tool in the last chapter.

2 Overview of recent studies

Depending on the modelling approach, the deterministic hydrological models can be classified into lumped and distributed models (Chow, 1988; Abbott and Refsgaard, 1996; Beven, 2001). Lumped models schematize the whole studied system as a single unit, which means they are often not able to take into account the spatial variability of the hydrological processes over the large basin domain. Their parameters, estimated by taking the average values of characteristics of the catchment, are usually immeasurable. On the other hand, distributed models discretize the catchment into a spatial grid, which allows them to incorporate spatial variables such as topography, land use and soil characteristics. Thus, they are supposed to describe the hydrological system more accurately and more realistically. However, due to the higher complexity of spatially distributed models and the huge number of model parameters (parameters need to be specified for each grid cell), the calibration procedure creates huge difficulties; the so-called problem of over-parameterization or equifinality of different parameter sets. This might produce higher uncertainty in the impact results by these models.

A review on both lumped conceptual models and physically based, spatially distributed models and their applicability in climate change impact investigation (and also land use impact investigations) has been done by Vansteenkiste et al. in their recent researches (2012a; 2012b; 2012c). The lumped conceptual rainfall-runoff models they investigated were NAM, PDM and VHM, whereas MIKE SHE and WetSpa were chosen as two distributed models. All of these models were used to analyze hydrological impacts, especially for extreme high and low flows, due to climate change for a Belgian medium scale catchment: the catchment of the two rivers Grote Nete and Grote Laak. The models were calibrated by using identical meteorological and other inputs, and by applying a consistent step-wise manual calibration procedure. The simulation results were analyzed to assess the influence of the applied hydrological model structure and the complexity of the process description on the simulated variables. A brief summary of these models and the main conclusions from that study are provided hereafter.

2.1 Lumped conceptual models

The conceptual rainfall-runoff models studied by Vansteenkiste et al. (2012a) , i.e. NAM, PDM and VHM are represented by storage elements and transport – routing – units, however with various formulations (linear or non-linear) and model structures. The number of model parameters that need to be calibrated against the observed records depends on the number of applied processes and descriptions.

The NAM model continuously accounts for the moisture content in different and mutually interrelated storages, namely: snow storage, surface storage, lower (root zone) storage and groundwater storage. In the NAM concept, the lower root zone storage is the central process of the model. Its relative soil moisture content controls linearly the different sub-flows. The model outputs are overland flow, interflow and baseflow. The overland flow is routed by using two linear reservoirs in series while other components are routed through a single linear reservoir. The sum of these three sub-flow component is the total flow. The NAM model structure is represented in Figure 1 (DHI, 2007).

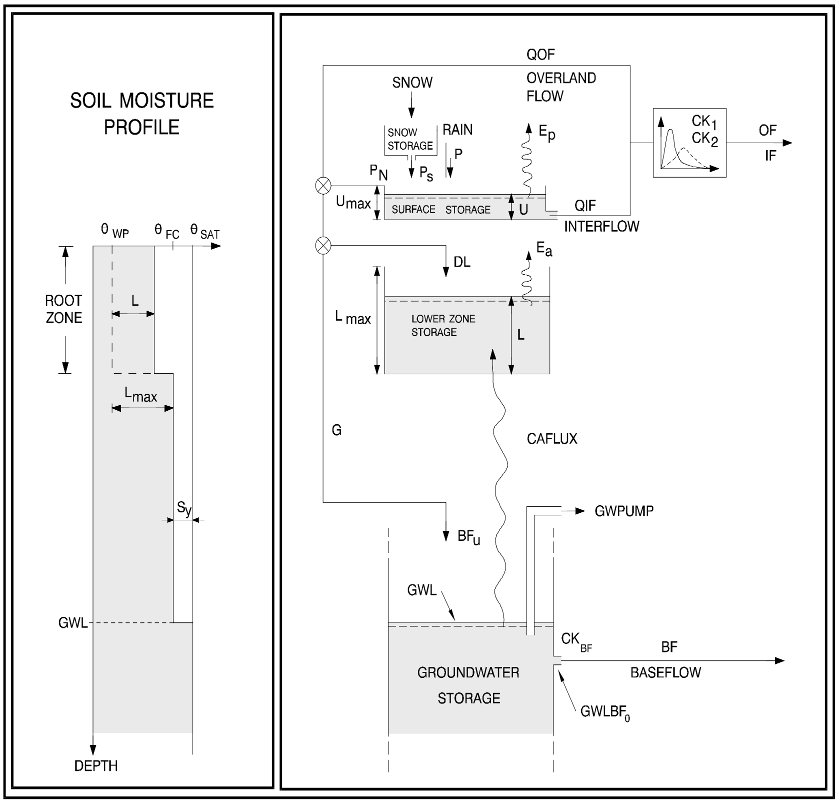


Figure 1– NAM model structure (DHI, 2007)

Differently, PDM (Probability Distributed Model) considers the catchment as a collection of soil moisture reservoirs with different storage capacity. A probability distribution is used to describe the spatial variation of the storage capacity over the catchment. The PDM model offers a range of options for the probability distribution, however, a Pareto or truncated Pareto distribution is often used in practice.

The common PDM model consists of three major components, which are: a probability distributed soil moisture storage for separation of direct and subsurface runoffs, and two storages components for transforming the separated runoffs into surface runoff and baseflow. Two linear reservoirs in series are used to route the surface flow while a cubic non-linear storage routing function is applied for the groundwater discharge. Both outflows are the model outputs and their sum forms the total discharge at the catchment outlet (Moore, 1985). The structure of the widespread applied PDM model can be seen in Figure 2 below.

The NAM model requires to calibrate at least 9 main empirical parameters but for PDM model, there are five more parameters needed for calibration.

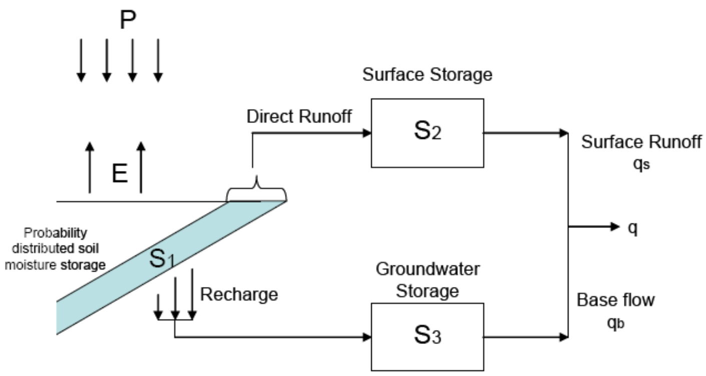


Figure 2 – PDM model structure (Moore, 2007)

The last studied lumped conceptual model was VHM (Willems, 2000, 2011). In fact, VHM is not a model in the classical sense (with a fixed model structure), but an approach to identify or build, and to calibrate a lumped conceptual model structure in a case-specific data-based way. The model identification and calibration approach starts from a generalized lumped conceptual model structure (Figure 3). It is built up by four storage elements, which stand for the soil moisture storage, the groundwater storage, the surface water storage and the unsaturated zone storage. These elements are filled by precipitation fractions. The three latter storages will transform the precipitation contributions into sub-flows by using reservoir models.

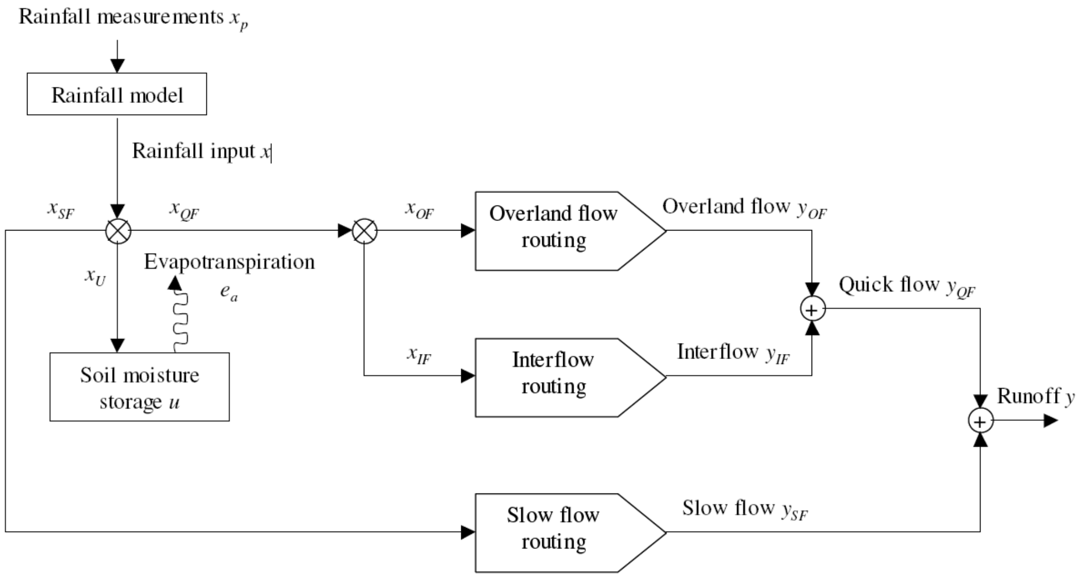


Figure 3 – VHM model structure (Willems, 2011)

The basic philosophy of the VHM approach is that only model components and parameters are incorporated that can be identified from the data. In this way, a parsimonious model structure is obtained. Although the final model structure depends on the specific case-study, for the Grote Nete application by Vansteenkiste et al. (2012a) and for many other catchments in Flanders where the VHM approach has been applied so far, a model structure is obtained with about (in fact at least) 12 parameters. The most important model component is the soil water storage model, which has to be calibrated first. The appropriate storage function, which can be described by a simple linear equation or a more complex (e.g. exponential) relation of relative soil moisture, is selected in a data-based way by plotting the storage fraction of precipitation versus the soil water state. The calibration procedure demands the prior sub-flow filtering and extraction of nearly independent events for high and low flow extremes, which can be done by using the Water Engineering Time Series PROcessing (WETSPRO) tool of Willems (2009). The linear reservoir approach is tested firstly as the most parsimonious model for routing of the sub-flows, i.e. overland flow, interflow and baseflow. More complex routing methods can be used if necessary. Depending on the catchment specific conditions and the data, the VHM model can take into account the effect of antecedent rainfall and therefore it is able to describe the infiltration excess next to the saturation excess.

An inter-comparison of these three lumped conceptual models is given in Table 1

Table 1 – Inter-comparison between the three lumped conceptual models (Vansteenkiste et al., 2012a)

Modules and components	PDM	NAM	VHM
Main principle	Soil storage capacity distribution	Soil moisture content	Rainfall fractions
Soil water model			
Soil water storage	- Exponential (Pareto)	- Linear	- Linear - Exponential
Overland flow processes	- Infiltration excess - Saturation excess	- Saturation excess	-Infiltration excess -Saturation excess
Recharge	- function of soil and groundwater storage - function of groundwater storage - splitting direct runoff	- function of soil storage (directly)	- function of soil storage (indirectly)
Sub-flow routing			
Overland flow	2 reservoirs	1 or 2 reservoirs (with same/ different constants)	1 or more reservoirs (same constants)
Interflow	-	1 reservoir	1 reservoir
Baseflow	1 reservoir (non-linear)	1 reservoir (linear)	1 reservoir (linear)

2.2 Spatially distributed models

Despite the fact that lumped conceptual models are traditional and common methods in the context of climate change impact investigation, their simplified modelling structure has limitations when representing the real hydrological processes (Beven, 1989; Grayson et al., 1992; McDonnell, 2003). The distributed models, which are more complex and detailed in model structure are supposed to produce more realistic descriptions of the hydrological processes. The MIKE SHE and WetSpa models are two examples selected by Van Hoey et al., (2012) in order to examine how the distributed models assess the impacts of climate change, and how they differ from the lumped conceptual models.

MIKE SHE, a product of DHI, is a comprehensive model which is based on SHE - the European Hydrological System (Abbott et al., 1986a, 1986b). It consists of different modules for simulating water, sediment and water quality. The water movement module is considered as the most important one, which simulates the water cycle over the whole basin, including four processes: evapotranspiration, overland flow, unsaturated soil water, and groundwater flow. The evapotranspiration process, calculated using empirically derived equations (Kristensen and Jensen, 1975) is divided into evaporation from canopy and soil surface; the water – consumption and transpiration of plant. The overland flow is simulated either by a finite difference method with diffusive wave approximation of the Saint-Venant equations or by semi-distributed approach using an empirical and conceptual relationship between water depth and surface detention. The movement of water in the unsaturated zone is assumed to be only vertical and it is majorly influenced by the soil moisture state, the evapotranspiration rate and the recharge rate to the groundwater. The last module, i.e. saturated water flow or groundwater flow can be simulated by using the Darcy equation in a 3-D groundwater flow model or linear reservoir method. The interactions between groundwater and surface flow as well as the channel flow are operated by the MIKE 11 model, another product of DHI. The structure of the MIKE SHE model is illustrated in Figure 4

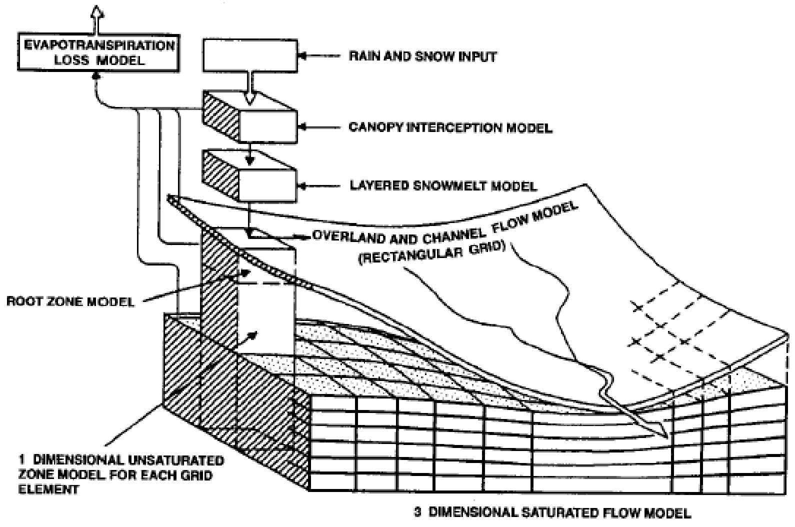


Figure 4 – Schematic representation of the water movement module of MIKE SHE (Singha et al., 1999)

While MIKE SHE has a fully physically based structure, WetSpa (Liu and De Smedt, 2004) is an intermediate conceptual – physically based model. Its name is the acronym for Water and Energy Transfer between Soil, Plants and Atmosphere. The model was applied in some catchments in Belgium, such as Barebeek and the Grote Nete basins. Most of its hydrological processes are simulated using a distributed and physically based approach, but some of them are described in a lumped and more conceptual way. The WetSpa model divides the catchment into a grid and calculates continuously the water balance for each cell. The similar hydrological processes as in MIKE SHE are simulated but with other equations. Instead of using the empirical equations, the evapotranspiration is formulated based on the relationship between potential evapotranspiration, vegetation type, stage of growth and soil moisture content (Thornthwaite and Mather, 1955). A potential runoff coefficient, which depends on land cover, soil type, slope and magnitude of rainfall and antecedent soil moisture, is applied to calculate the surface runoff and infiltration rate. The gravity is assumed as the only driving force of percolation, which is estimated by Darcy's law. The interflow or shallow subsurface lateral flow is controlled by soil characteristics and is modelled by Darcy's law and kinematic wave approximation. However, the groundwater flow is calculated in a less detailed way as it uses only a simplified lumped linear reservoir and is characterized by groundwater storage and its recession constant. All processes are worked out at point-scale, except for the groundwater flow. A cell – structure of the model is shown in Figure 5

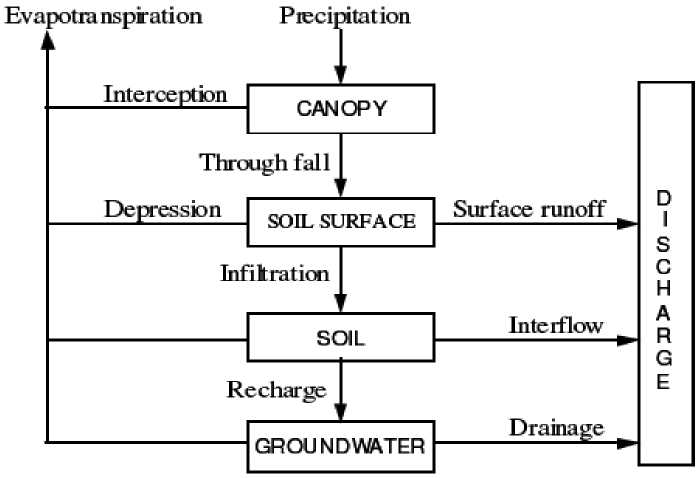


Figure 5 – Structure of the WetSpa model processes at a pixel cell level (Liu and De Smedt, 2004)

2.3 Comparison of lumped and distributed models in climate change assessment

The five models discussed in the previous sections (i.e. NAM, PDM, VHM, WetSpa and MIKE SHE) have been inter-compared in the context of climate change impacts in order to examine the uncertainty due to the model structure on the impact results. All models were successful to capture the flow dynamics with high efficiencies for both the winter and summer flows. Similarly, total and sub-flow cumulative volumes were well described. The high and low extremes and their distributions also matched well with the observations for the calibration and validation periods. The simpler models (i.e. conceptual models), which have less parameters could be calibrated more easily and in general produced better performance for both calibration and validation periods. However, differences in some simulation outputs were observed between the models. The NAM model tended to underestimate the interflow changes due to the rainfall changes, which was different from other models. In contrast, the PDM model performed unlikely from other models in predicting high flows at high rainfall intensities. The latter was explained by the Pareto distribution that is representing the distribution of storage depth over the whole catchment, leading to a power relation of the quick flow runoff coefficient versus the catchment averaged soil moisture state. These deviations of both models might cause differences (errors?) in the climate change impact simulations. For VHM, it was noted that this model – after a careful calibration for the Grote Nete – Grote Laak catchment, simulated the baseflow responses stronger than the other models. For the distributed models, no noticeable deviations were found. However, the sensitivity of model calibration requires further investigation. Also further analysis is required to determine the model structure effects on the catchment runoff simulations.

Vansteenkiste et al. (2012c) concluded that the direction and magnitude of the climate change impacts might be predicted with high confidence based on the success of the calibration and validation for winter high flows and summer low flows of all five models. They came to a broad agreement on the hydrological changes under changed climatic conditions associated with the scenarios. For high flows, a similar trend in peak flow changes was found but with high uncertainties in the absolute values for the changes. These uncertainties were found to be more related to the climate scenarios than due to the model structures. For low flows, a clear decreasing trend was predicted up to the year 2100; again with large uncertainty in the flow impact magnitude by the climate scenarios and by the model structures. In particular, the MIKE SHE model, which contains a three dimensional groundwater sub-model, simulated different low flow impact results. The strong simplification of the groundwater component in the other models might lead to inability of these models to simulate the baseflow changes accurately, especially during the dry summer seasons. Also between the other models, clear differences in impact results were obtained for the low runoff flows; with largest differences between the NAM and WetSpa models. It was concluded that the low flow impact simulation is much more sensitive to the hydrological model structure than the impacts on high flow. A well-defined or flexible model structure could be a solution to better understand or provide more complete information (including the influence of the model structure uncertainty) on the hydrological impact results of climate scenarios.

3 Literature review of other modelling approaches

Since there is a large number of existing hydrological models, this inventory only aims to introduce several existing modelling frameworks/software that may be applicable or that could support the development of the proposed framework and tool for flexible hydrological modelling. The review in this chapter is limited to software that either is now widely applied in practice or has been developed for water management analysis purposes. Moreover, some prevailing approaches for spatial linking between distributed grid cells are also investigated in order to include the spatial information in the framework as expected. Finally, two popular programing platforms which are suitable to support the development of the envisaged tool are also reviewed. It is believed that these software packages are worth having a deep review due to their distinct characteristics in the context of the current study.

3.1 Structure integrated models

The models described in the two upcoming sections, the GSFLOW model and the SWAT with MODFLOW model, were shortly reported by Vansteenkiste et al. (2011). Only the main information on both models is summarized in this inventory.

3.1.1 GSFLOW

GSFLOW (Groundwater and Surface-water FLOW model) was developed by integrating the PRMS - U.S. Geological Survey Precipitation – Runoff Modelling System (Leavesley et al., 1983) and the MODFLOW - USGS Modular Groundwater flow model (Harbaugh, 2005). The GSFLOW model has been applied before at the Department of Hydrology and Hydraulic Engineering of the Vrije Universiteit Brussel.

The model requires data on topography, land use, soil, meteorological series and pumping well observations and models the following hydrological zones: surface, soil, unsaturated and saturated zones. It discretizes the catchment into a network of homogeneous hydrological response units (HRUs). GSFLOW can work with a daily or storm time scale. The individual sub-models (i.e. the PRMS model and the MODFLOW model) are calibrated separately first. The rainfall-runoff model PRMS describes the watershed as a series of four reservoirs according to the aforementioned hydrological zones and takes the sum of the responses from these reservoirs as the total discharge. The calibration of the GSFLOW model is mainly based on a set of parameters controlling the flow rates between the different sub-models.

This model is useful to analyze the interactions between the surface and groundwater components. Moreover, instead of using a lumped reservoir for the groundwater (as is done in the lumped conceptual models NAM, PDM, VHM), the three dimensional model MODFLOW allows to simulate groundwater flow in a spatially detailed and process based way.

3.1.2 SWAT with MODFLOW

The Soil and Water Assessment Tool, which is well-known as SWAT is a semi-distributed hydrological model and was developed by Arnold et al. (1993). It is a physically based model, consisting of eight major components namely weather, hydrology, soil temperature and properties, plant growth, nutrients, pesticides, bacteria and pathogens and land management. The model divides the catchments into multiple sub-watersheds and further sub-divides them into the HRUs. Moreover, SWAT is often used for water quality purposes. In Belgium, studies in the framework of water quality modelling using SWAT were carried out by Van Griensven and Bauwens (2005), Vandenberghe et al. (2005, 2006, 2007) and Cools et al., (2007).

Furthermore, Jeong et al., (2010) have modified the algorithms for infiltration, surface runoff, flow routing, impoundments, and lagging of surface runoff to enable the capacity of simulating a sub-hourly time interval. The time step can range down to one minute. The evapotranspiration, soil water contents, baseflow and lateral flow are still estimated hourly and are then distributed to each selected time step. This recent development of SWAT was tested on a small watershed and reasonably reproduced stream flow hydrograph under multiple storm events (Jeong et al., 2010). A better performance for a 15-min simulation in comparison with a daily simulation was recorded, especially on high flows. Therefore, this modified version was said to be a promising tool for hydrology and non-point source pollution assessment studies.

Another problem of SWAT is the difficulty in simulating the low flows due to the use of a lumped groundwater component resulting in a loss of distributed information. Therefore, an idea of combining SWAT with the MODFLOW groundwater 3D model was introduced (Perkins and Sophocleous, 1999; Kim et al., 2008). An example of a schematic diagram of the surface water model SWAT combined with the groundwater model MODFLOW is shown in Figure 6

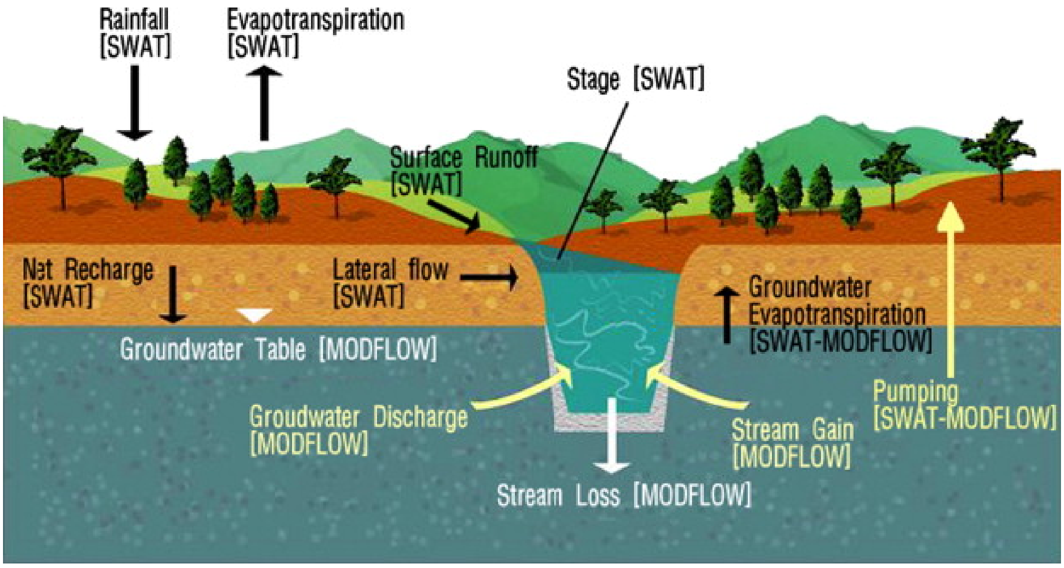


Figure 6 – Schematic diagram of combined SWAT with MODFLOW model (Kim et al., 2008)

After the sub-hourly simulation capability is carefully examined and the model is coupled with MODFLOW for the groundwater component computation, SWAT is a good choice for simulating different hydrological processes in watersheds with various land uses.

3.1.3 HEC - HMS

HEC-HMS or the Hydrologic Modelling System is a package product of the Hydrologic Engineering Centre of the U.S. Army Corps of Engineers (USACE). It is a replacement of HEC-1 (watershed hydrology), which exists since 1967. HEC-HMS has been popularly applied for operating reservoirs for flood reduction purpose on a daily basis.

The program was designed to simulate the rainfall-runoff processes of a dendritic drainage basin and to deal with a wide range of hydrological problems in many different geographic areas. It can be used for various purposes such as water supply in a large river basin, flood hydrology, small urban runoff and natural watershed runoff. Its resulting hydrographs can be assessed directly or combined with other programs for studies of other aspects.

HEC-HMS is considered as a generalized modelling system that allows representing many different watersheds. A watershed model has the structure as shown in Figure 7 below. The functions of continuous soil moisture accounting and reservoir routing operations were added as well.

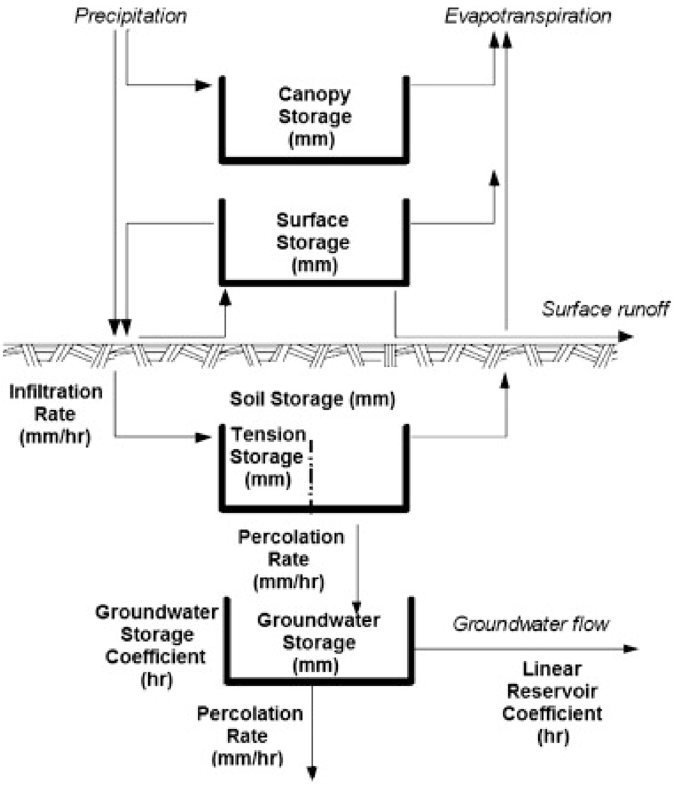


Figure 7 – HEC – HMS model structure

The HEC-HMS model is expected to further develop for providing solutions for water erosion and sedimentation transport. Being supported by a national federal agency, HEC-HMS became very popular, especially in the U.S. and hence it has been improved frequently. Although it was constructed for the U.S. Army Corps of Engineers, the model package and documentations and the mentioned information are available for free download at the website http://www.hec.usace.army.mil/software/hec-hms/.

3.1.4 CRASH

The Catchment Resources and Soil Hydrology (CRASH) is a conceptual, continuous, daily, catchment scale rainfall-runoff model (Marechal and Holman, 2005). It has been developed with the purpose of being applied in ungauged catchments.

CRASH is used to transform the rainfall into river discharge using the pre-existing UK datasets of soil, land use and weather. Therefore, the spatial variability of soil properties and land use is taken into account in the catchment representation. In CRASH, studied catchment is divided into sub-catchments. Each sub-catchment was further divided into response units (or primary objects) according to the identification of soil groups, the spatial distribution of the soil and land use map. The hydrological properties of soils were grouped and parameterized using the Hydrology of Soil Types (HOST) classification.

For each response unit, both infiltration excess and saturation excess processes are simulated. Water flow between soil layers can be simulated using the capacitance approach, which is based on classifications of

HOST. The simulated total flow is calculated by summarizing the output components of each response unit, i.e. the interflow from soil water storage, the baseflow from groundwater storage and the overlandflow from the infiltration excess and saturation excess. Figure 8 below shows the structure of the CRASH model from the primary unit to the conceptualized representation of the whole catchment.

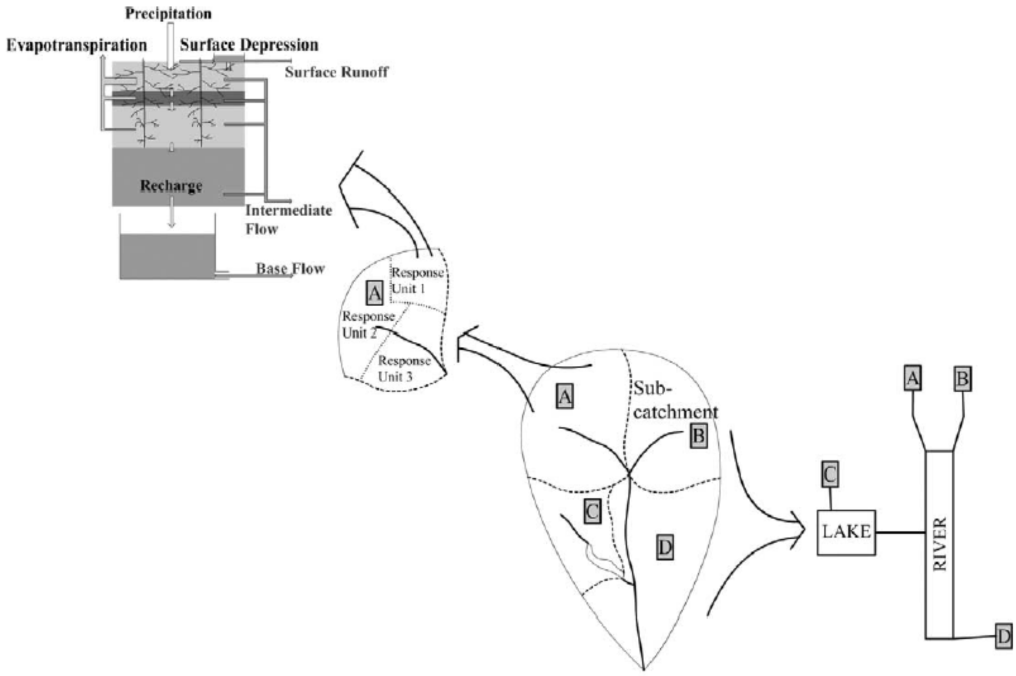


Figure 8 – Structure of the CRASH model (Marechal and Holman, 2005)

Calibrated HOST parameters are only available for the UK. Therefore, applications with the CRASH model are mainly limited to UK catchments. It is necessary to build up a consistent framework for national soil hydrological classification before applying the model in other regions. Regardless of these disabilities, the CRASH model is still worth studying.

3.1.5 CLASSIC

CLASSIC or Climate and Land use Scenario Simulation In Catchments was initially introduced by Naden and his colleagues in 1993 to investigate the impact of climate and land use change on the flood response of large catchments in England and Wales (approximately 10000 km^2).

In this model, the spatial distribution of catchments and climatic data are represented by using a semi-distributed model. The model allows to incorporate GIS data and other grid-based data. Moreover, an important feature of CLASSIC is the introduction of a nested calibration, which ensures the spatial consistency of the simulated flows for sub-catchments. By applying this method, the model parameters are selected appropriately for both the whole catchment and the sub-catchments. Furthermore, the model parameter sets can be used to simulate the flow at the ungauged areas within the large studied catchment or for similar catchments. In addition, the wide range of spatial and temporal scales is another advantage of the model. Flow simulations with a daily and hourly time scale and with a range of grid sizes from 5 km to 40 km and for the smaller catchments down to 200 km^2 have been studied (EUROTAS, 2000).

There are three major modules of CLASSIC: (1) a soil water balance model, which calculates the effective rainfall; (2) a drainage module to compute the water movement between land surface and open water stream network; and (3) a channel routing module. The power of the CLASSIC model is its modular structure, which gives possibility to replace or add alternative modules such as actual evaporation component or snowmelt modules (Crooks and Naden, 2007). Its structure is illustrated in Figure 9.

The two first models run within a grid based framework with the climatic and land use variables (the red rectangle in Figure 9). The aggregation of grid outputs provides the total flow at the outlet of the catchment. Moreover, the formulation of the drainage model allows to route separately the components of total flow from three different sources (permeable soils, semi-permeable soils and impermeable surfaces or urban). Therefore, they can be represented by separate hydrographs.

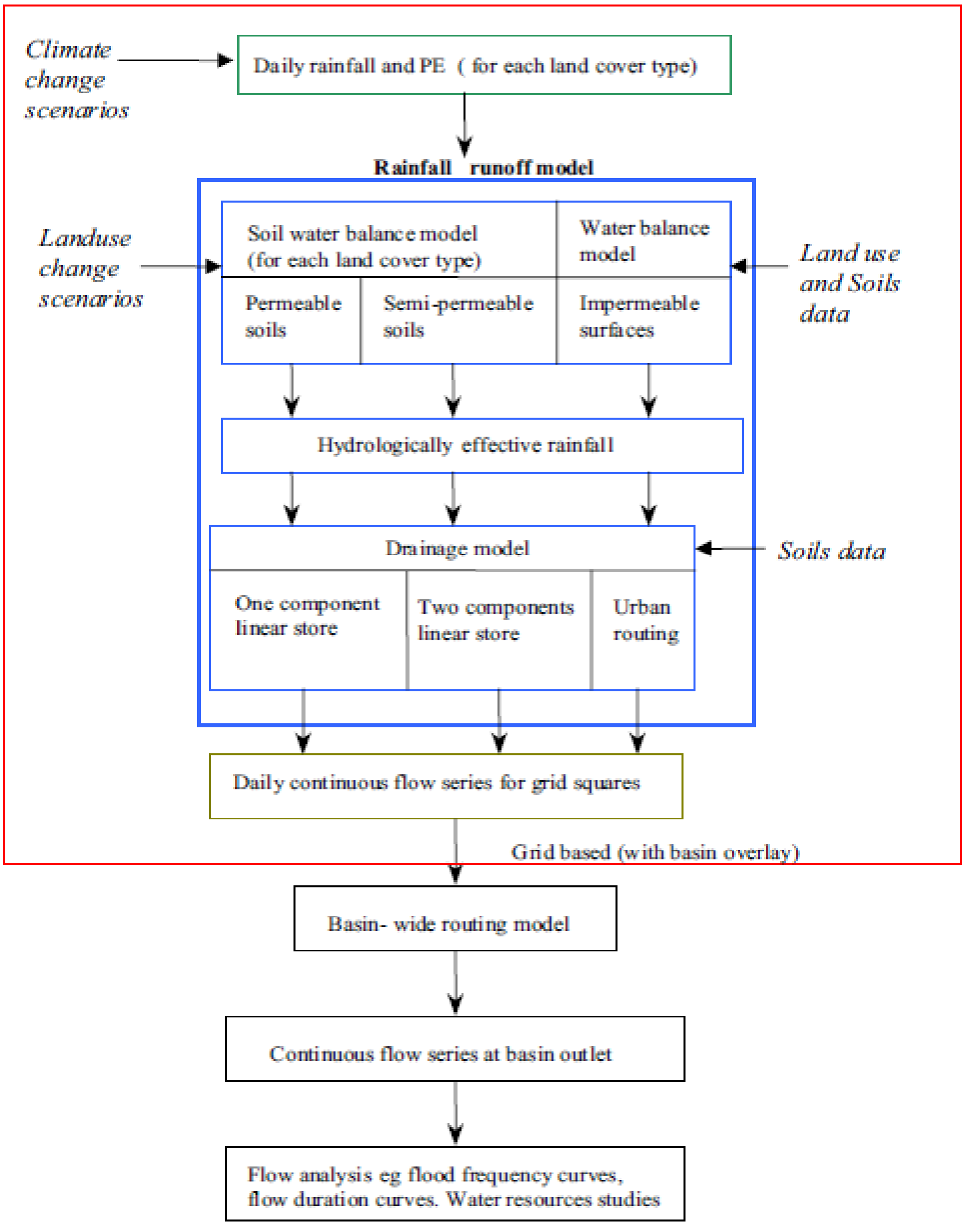


Figure 9 – Schematic structure of CLASSIC model (Crooks and Naden, 2007)

The CLASSIC model has been tested for three catchments of the River Thames, Severn and Ouse in England and Wales (Crooks and Naden, 2007). Moreover, it was examined in the framework of the EUROTAS project for the Thames catchment with several different climate change scenarios (EUROTAS, 2000). The simulated results have demonstrated that the structure of CLASSIC provides a robust framework that can be applied for a wide range of spatial scale and different types of catchments.

3.1.6 HBV – 96

The well-known semi-distributed conceptual rainfall-runoff model HBV (Bergström, 1976; 1992) has been used in more than 30 countries all over the world. In HBV, the catchment is divided into sub-basins. According to altitude, lake area and vegetation, it continues dividing these sub-basins into hydrological zones. Although it was designed for a daily time step, smaller intervals can also be implemented. The model will separately simulate the runoff for sub-basins and then sum up the results as the catchment runoff output. An improvement of HBV, which was named HBV-96, has been developed by the Lindström et al. (1997). They aimed to make use of spatially distributed data to perform significantly better and to be more physically reasonable.

The original HBV consists of six major subroutines namely: input (meteorological data) integration, snow accumulation and snowmelt, evapotranspiration, soil moisture accounting procedure, runoff response and routing between sub-basins. The model structure is presented schematically in Figure 10.

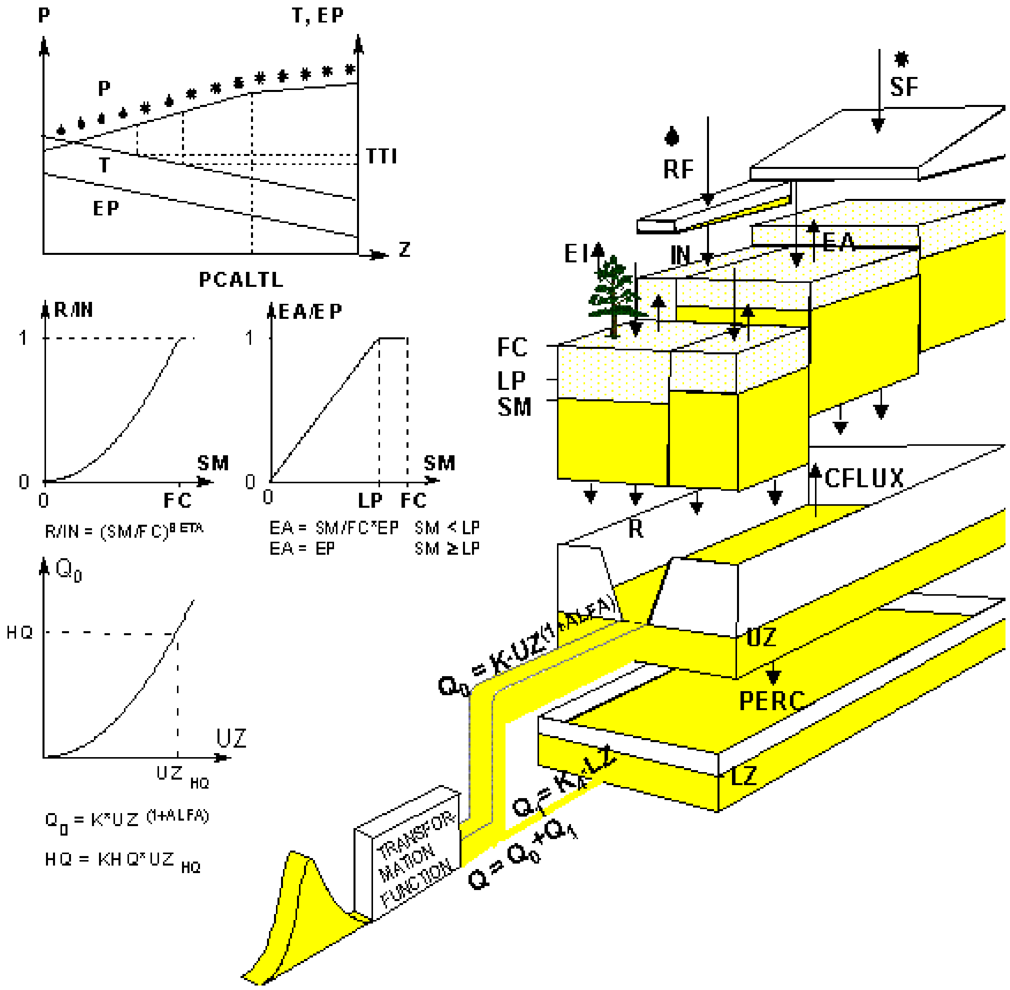


Figure 10 – Schematic structure of HBV – 96 (Lindström et al., 1997)

The upgraded HBV-96 model also uses the basic model routines of the original version. It divides the catchment into sub-basins using the digitized standard drainage basins of the Swedish Meteorological and Hydrological Institute. Hence, the spatial resolution corresponds to around 40 km^2, although other resolutions still can be used. This improvement offers space for an integration of spatially distributed field data such as GIS data or satellite images. The areal meteorological series interpolation and evapotranspiration computation were improved in order to minimize the estimation error. A more advanced distribution routine for the snow accumulation in each elevation zone was introduced in HBV-96 to produce a more realistic description and a possibility to compare with remote sensing data. A simple interception model for the forested area was included in the new version.

The soil moisture accounting routine of the model is based on an assumption of a statistical distribution of storage capacities in a basin. It is considered as the main part of the HBV model for controlling the runoff generation. The excess water from the soil zone is transformed to the runoff by means of the response function. It was compounded of two layers, which are represented by a non-linear (for the upper zone) and a linear (for the lower zone) reservoir. The simulated discharges from these zones will result in the quick and slow flows.

HBV-96 has been examined for seven test basins and showed improvements for both the calibration and verification periods. It was chosen to transfer its code to another programming language (i.e. Python) to be able to couple or integrate with other model codes within a single system or framework. This is one of the reasons why the HBV-96 model became a popular and famous rainfall-runoff model.

3.1.7 LGSI

The Lowland Groundwater – Surface water Interaction or LGSI model was developed by Van der Velde et al. (2009). It is a lumped conceptual model that uses a normal distribution of groundwater heads to simulate discharges. This helps to prevent losing all spatial information of the catchment when using an average groundwater head. The model has been examined with two catchments in the Netherlands. The results showed that LGSI produced more promising results for one (smaller) catchment (Wanders et al., 2011).

The main process of the LGSI model is the water balance where the change in storage is related to the change in groundwater depth distribution. This relation is calculated by a unique relation between the average groundwater depth and the standard deviation of groundwater depth. The statistical groundwater depth distribution is used to determine the storage of three components of the model, i.e. the storage in saturated zone, the storage in the unsaturated zone and the surface water storage. Overlandflow occurs and fills in surface storage when the groundwater head exceeds the surface. The total output of the LGSI model is composed of overlandflow, groundwater flow, direct runoff (from precipitation which falls onto water open surface) and discharge through drains. Figure 11 below shows the structure of the water balance model of LGSI.

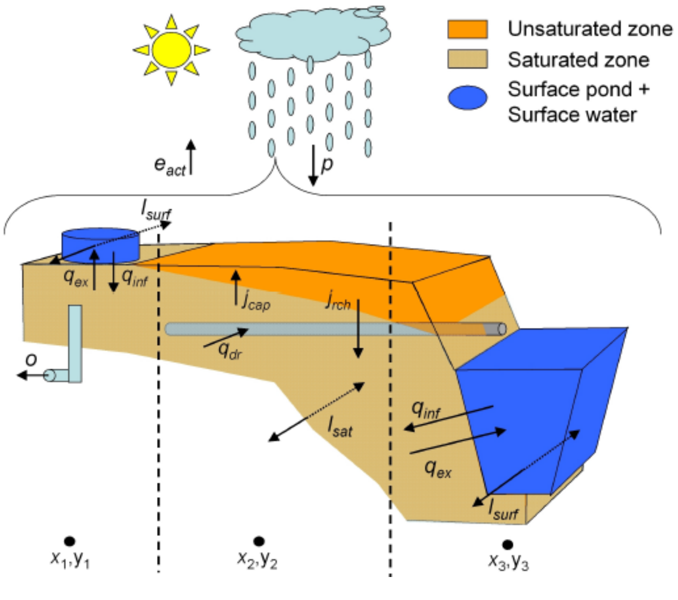


Figure 11 – The water balance model describes fluxes at the point-scales (Van der Velde et al., 2009)

Nevertheless, the relationship between the average groundwater depth and its standard deviation cannot be produced using only the discharge data. Therefore, a groundwater head measurement or a spatially distributed groundwater model (e.g. MODFLOW or MIPWA) is necessary in order to prevent large equifinality problems common to models of groundwater-surface water interactions (Beven, 2001).

3.1.8 INCA

INCA (Integrated Nitrogen in Catchments) is a relatively new semi-distributed model, introduced by the Aquatic Environments Research Centre of University of Reading, UK (Limbrick et al., 2000). Although it was initially created to assess multiple sources of nitrogen in catchments, it has been used as a rainfall runoff model to investigate the potential impacts of several determined climate change scenarios on the hydrological flow regime of the Kennet River catchment (Limbrick et al., 2000; Wade et al., 2002). The INCA model is built up by three components. The first sub-model is the Meteorological Office rainfall and evapotranspiration system, which generates the daily hydrologically effective rainfall (the fraction of precipitation that contributes directly to the catchment runoff) and the daily soil moisture deficits (SMDs). Together with the average temperature observation, they are the input requirements of the model. The second component is to calculate the effects of land cover, land uses and topography on the flow.

A semi-distributed approach is applied to identify and incorporate the dynamics and characteristics of each sub-catchment into the whole basin. The final component is used to simulate the flows through a set of storages in the soil and groundwater reactive zones. However, despite of the advantage of allowing to incorporate GCM output scenarios, the similar drawback of the coarse time step limits is applicable. Moreover, the calibration process for the Kennet River case study showed that INCA tended to simulate maximum flows better than minima. Especially, INCA was occasionally recorded to calculate poorly the low summer flows but it was said to perform better the rapid baseflow response to sudden recharge.

3.1.9 Concluding remark

The models described above mainly focus on one existing model implemented as a single script or on the integration of different hydrological scripts into a single framework. All of them are worth to investigate more deeply due to their specific advantages such as their extension to spatial distribution or the ability to simulate ungauged catchments or to deal with climate change and land use change impact assessment, or their popularity. They might produce similar or even better performance for Belgian catchments than the five models studied by Vansteenkiste et al. (2012a, 2012b, 2012c). In this context, it is important to stress here that the use of single / “closed” models have the disadvantage that it is not possible to have only “one model structure” for all problems, all situations and all the catchments. To perform a better analysis, an ensemble approach with different models is recommended, especially when the models are applied for scenario analyses (such as the study of the impacts of climate change). This is, however, difficult to perform (unpractical) with different models. It would be easier to bring different models in a similar model structure and platform. This can be done, given that similarities in the basic model components can be found in the reviewed different model structures: the meteorological components, the storage components, the splitting components and the routing components. These components are also present in the five models reported by Vansteenkiste et al. (2012a, 2012b). Therefore, they will be also considered as the core (main) modules of the generalized hydrological model structure in the proposed concept (see chapter 4).

3.2 Open-source software

Since the above mentioned models were developed in classical programming environments, most of them are closed source software. This means that the model codes are prevented from being modified. It also reduces the flexibility of the model structures since it minimizes the possibilities to access or change the original codes such as adding, moving or replacing the alternative components. Moreover, the flexibility in choosing various levels of complexity is also often limited.

In order to provide users more freedom to modify model structures as desired, more flexible frameworks or dynamic environments are needed. In these frameworks, a variety of physical processes can be described by one or several modules in their library. According to Leavesley and his colleagues (1996), for hydrological studies, such of that library is required to describe the processes of the hydrological cycle including precipitation, temperature, evapotranspiration, soil moisture accounting, solar radiation, impervious area, interception, infiltration, overland flow, subsurface flow, groundwater, channel flow, reservoir routing, sediment and snow. Moreover, these frameworks contain a model interface to enable interactions between various sub-models, allowing to use the output from one module as the input of others. A final dynamic model is developed by coupling the most appropriate modules together to develop the most optimal application(s) for a given situation (Shultz, 2007). The complexity of the model depends on the number of applied modules, the amount of variables and the different selected mathematical equations. If a suitable existing solution is not found in the library, alternative algorithms can be produced by the users themselves. Users are able to adjust the representation of the catchments, or the hydrological processes based on the available data and specific purposes. Such frameworks are often created on an open coding environment and released as (free and) open source software which gives chances for sharing resources, knowledge and costs (Vansteenkiste et al., 2011). Several examples of such flexible-dynamic environments and/or frameworks are introduced in the following paragraphs.

3.2.1 PCRaster and PCRaster extension in Python

PCRaster (Van Deursen, 1995), created by the Department of Physical Geography of Utrecht University is a free collection of software aiming at the development and deployment of spatio-temporal environment models such as geographical, hydrological or ecological models. Moreover, the construction of dynamic models or stochastic models or data assimilation can also be done within PCRaster. In general, the supported languages of PCRaster do not require much experience in programming for researchers to create their models themselves. Users can construct the models using supported scripting languages including PCRcalc (a core calculator of PCRaster) and Python (see below). PCRaster owns a large set of model building blocks and analytical functions for manipulating raster GIS maps. However, the package lacks of typical GIS functions since it was not developed to be a full-grown raster GIS. Therefore, it is recommended to combine the PCRaster with a raster GIS by employing converting libraries. A detailed description of the modelling package can be found at its website (http://pcraster.geo.uu.nl/) or in the thesis of Van Deursen (1995).

Many hydrological models have been converted or created by using PCRaster. Examples are the KIDS model (Hörmann et al., 2007), Bridge Event And Continuous Hydrological model – BEACH (Sheikh et al., 2009), the distributed Tracer aided catchment model - TAC^{D} (Uhlenbrook et al., 2004), etc. They show the advantages of the PCRaster environment because they allow calculating spatially distributed variables using spatial databases such as satellite maps or GIS data. Hence, it is possible to investigate the added values of this additional spatial information and their spatial resolution.

To improve the efficiency of scripts written in PCRaster, its team of developers has introduced an extension of Python, a noticeable coding language for dynamic modelling system. With the **PCRaster Python Extension**, users are able to develop models in Python language next to the original environmental modelling language. Figure 12 shows an example of the different steps in the development of a spatio-temporal dynamic model in the PCRaster Python Extension.

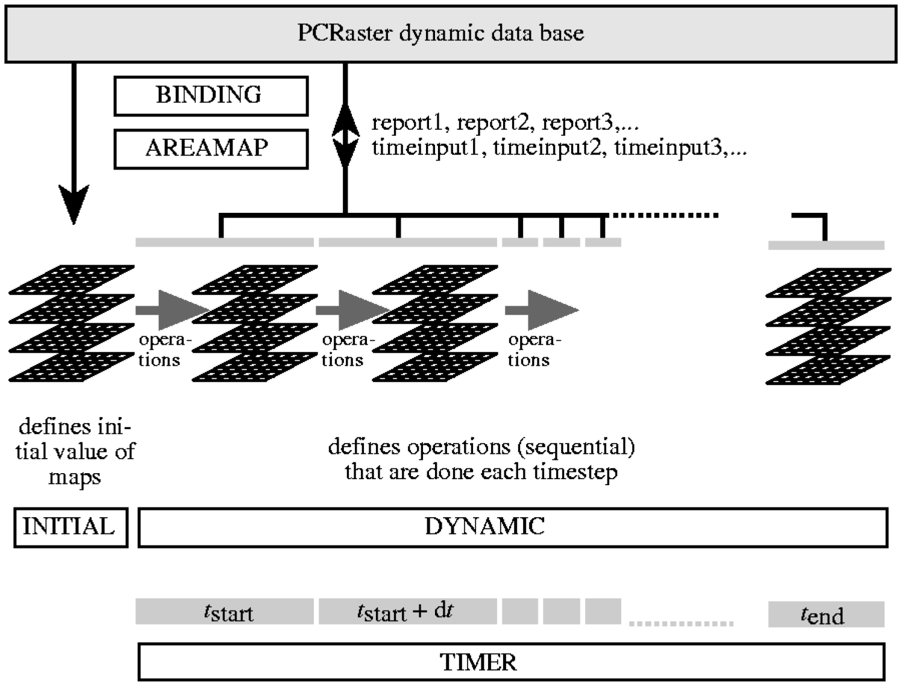


Figure 12 – Steps to develop a spatio-temporal model in PCRaster using Python language

Python is popular with the software developers for control and management building due to its simplicity of writing extension code, the third party libraries for visualization, data assessment and the database assess management. As its implementation is under open source license and since it is compatible with almost every computer operating system, it gathers a large community of developers and users, who contribute and share scripts online. The WetSpa-URBAN model described below highlighted the advantages and the flexible ability of Python and its extension.

WetSpa-URBAN is an improvement of WetSpa (see section 2.2) aiming at a more accurate representation of the urban water cycle. It was developed to hydrologically analyze urbanized and semi-urbanized catchments. Being a fully distributed model, it is able to generate more precise runoff hydrographs at interested points of the catchment as well as it offers a chance to assess the impacts of land use changes or the effects of the impervious surface variations in both rural and urban areas. The model has been ameliorated into a new version called **WetSpa-OO** (Salvadore, 2012) by (1) adding an improved hydrodynamic solver, (2) the use of the PCRaster-MODFLOW library (Schmitz et al., 2009), (3) an empirical module for water flow into pipes, (4) an uncertainty analysis module and (5) a combination with a land use change model. WetSpa-OO is a fully distributed, physically based and object oriented hydrological model, which was converted into Python. It was further developed by making use of the “modelling framework prototype”, which helps in the calculation order and in the data exchange between components. The conceptual model structure of WetSpa-OO is represented in Figure 13.

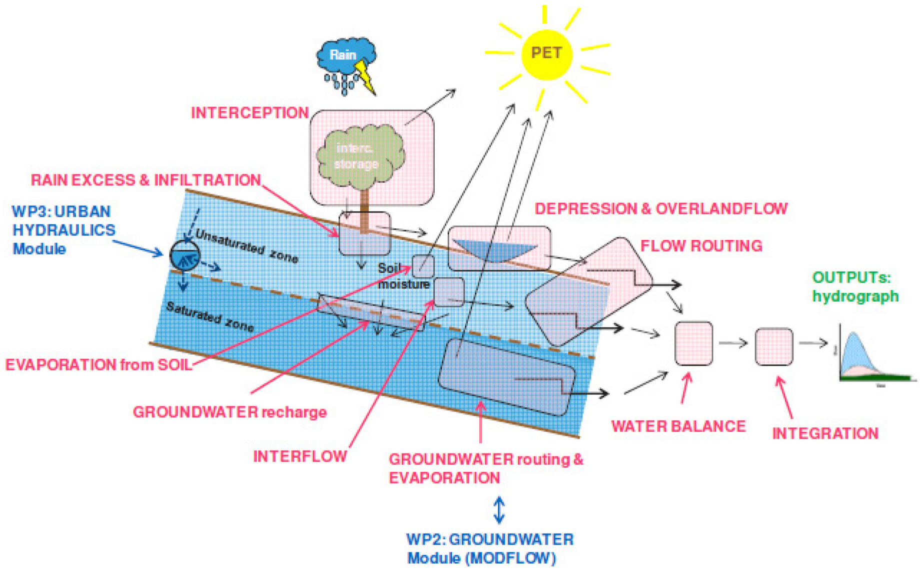


Figure 13 – Conceptual scheme of the physical processes by the WetSpa-OO model (Salvadore, 2012)

The GIS pre-processing of WetSpa-OO is performed by using the PCRaster functionalities. It also employs the PCRaster MODFLOW module, which is physically based for groundwater component. A land use change model named "Ruimtemodel", which has been developed by the Flemish Institute for Technological research (VITO) is coupled to the WetSpa-OO to investigate the impact of land use change, especially the increase of impermeable surface on water resources. However, the development of the model is still in progress. The detailed information on the model and its improvement can be found in preliminary reports of Salvadore (2012).

Similar to PCRaster Python Extension, the **Catchment Modelling Framework** (CMF) was constructed in the Python language by Kraft et al. (2011). According to his study (Kraft, 2012), CMF based model consists of three components: a water network, a spatial context and a solver as can be seen in Figure 14. Users are able to attach the extra water storage with a variety of flux connections equations. The model is run with a creating time loop. A time increment is applied by most of the sub-solvers.

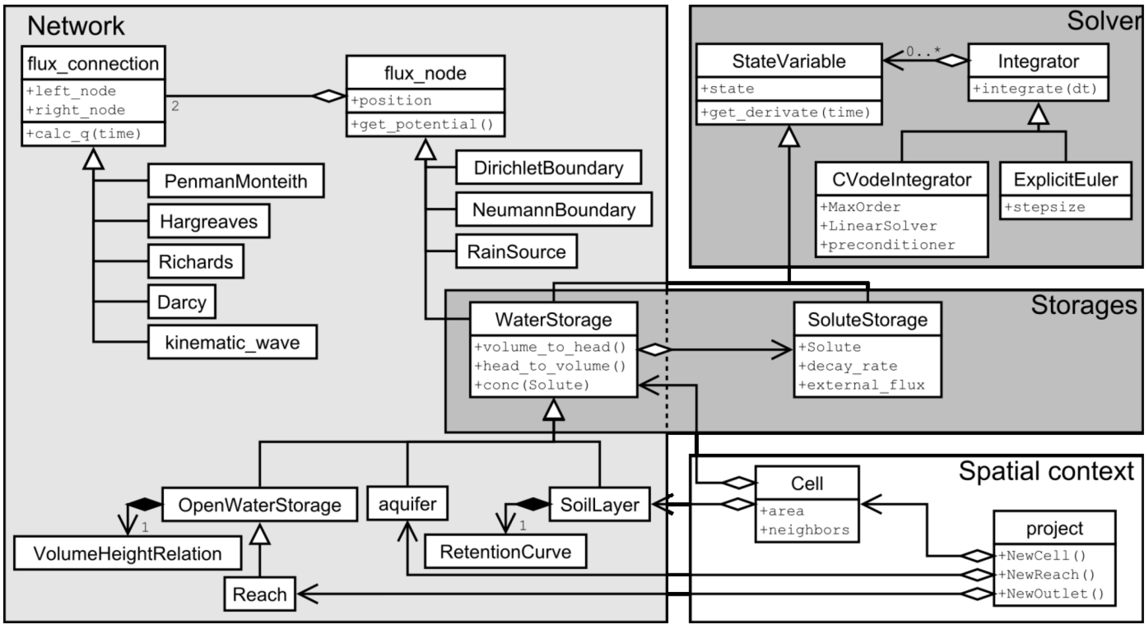


Figure 14 – CMF design concept (Kraft et al., 2011)

A fully distributed and connected flux model and a lumped model were created by the author using the CMF objects. Their structures are illustrated as in the Figure 15 below. It showed the ability of the framework to scale not only the spatial dimension of modeled catchments but also to adjust the model complexity up to the studied purpose and applied scale.

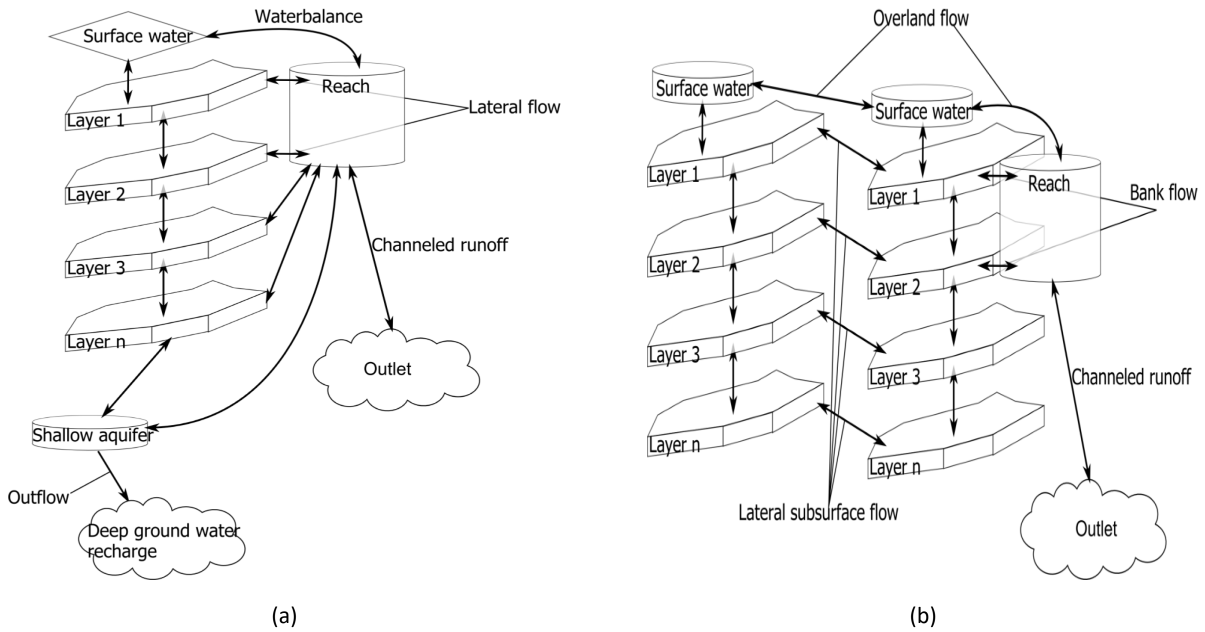


Figure 15 – Structures of lumped (a) and distributed (b) models built based on the CMF Framework (Kraft, 2012)

3.2.2 OPENSTREAMS

Another open modelling system for hydrological purposes is OpenStreams, developed by the company Deltares. The system offers users a tool to create integrated hydrological models by providing the building blocks including complete models or components of models. The main goal of OpenStreams is to be a collection of hydrological models and modules that can work independently. However, these components can be linked together through standards or even by linked interfaces. Different models and parts of models written in different programming languages such as PCRaster Python Extension, C++, FORTRAN or C# are combined together within the system. Moreover, OpenStreams is expected to be used easily by researchers with a simple command-line interface or with a directly model API (Application programming Interface). Different from other frameworks, OpenStreams links its components by taking control over the model as the highest commander. This can be done only when the provided APIs of components accepts a higher level of control.

A test case for the Rhine River basin upstream of Dutch border has been carried out by the project team (Schellekens et al., 2012). The first component (sub-model) was the WFLOW rainfall runoff model, a distributed version of HBV-96 model, which has been implemented in PCRaster Python Extension. WFLOW is a part of the OpenStreams project. It performs as a toolkit for distributed hydrological models within the system. WFLOW with a low level API and abilities to link to other framework (e.g. OpenMI, OpenDA…) is able to be a part of other larger modelling systems. The second component was a MODFLOW model of the Rhine basin with a spatial resolution of 1x1 km. The last one was RTC-Tools model for lake Constance. RTC-Tools is an open source, modular toolbox aiming to work with real-time control of hydraulic structures. It is another product of Deltares. A simple link was made, in which the HBV lower zone (in WFLOW model) was switched off and MODFLOW was used instead to simulate the groundwater. It is ensured that both sub-models used the same river network and drainage level. Flow in the kinematic wave routine of the distributed HBV-96 model was diverted to the RTC-Tools model as a connection between RC-Tools with the other model components. The schematic structure of the linkage between MODFLOW and WFLOW (distributed HBV-96) model is shown as below.

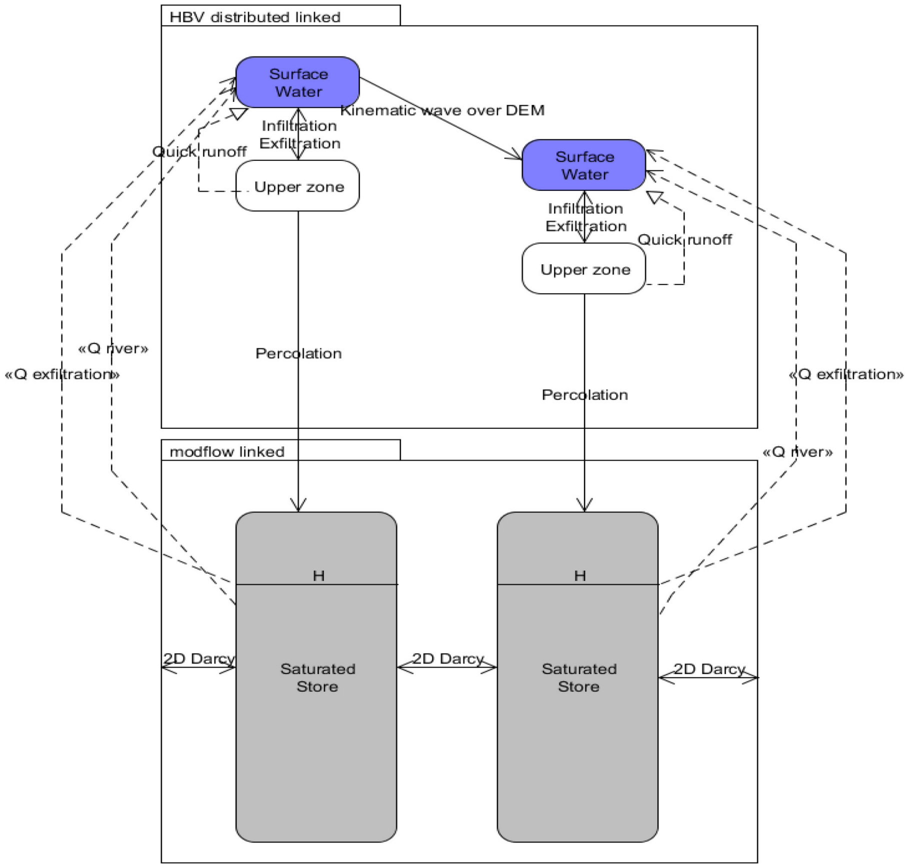


Figure 16 – Diagram of linkage between the MODFLOW model and the distributed HBV model

OpenStreams is expected to undergo rapid development due to its transparent and flexible structure offering researchers and modellers an easy and rapid approach to construct their own model. More information on the OpenStreams project and developed components can be found on its homepage (http://publicwiki.deltares.nl/display/OpenS/Home).

3.2.3 Concluding remark

Since the proposed flexible hydrological modelling concept would provide as much as possible freedom for users to identify the structures according to their interests and the applications, the modelling framework should be also open to access and modify. Therefore, the open software is the most suitable selection for implementing the proposed concept. Next to that, the open source software as well brings more benefits that the “closed” market software is not able offer. For instance, knowledge and resources sharing exchanges can be done easily, costs for repeating existing researches can be saved, the improvement and adaptation of hydrological models for new insights or knowledge can be conducted without any authorization difficulty.

Moreover, PCRaster in Python with its great support for spatio-temporal environment modelling and its (large) increasing user community is an ideal choice to construct the proposed framework. Obviously, some implementation tests need to be carried out first in order to confirm the possibility of the use of this package.

3.3 Spatial linking

PCRaster in Python allows easy extension of lumped models to spatially distributed models. For such spatially distributed modelling, the spatial linking is an indispensable module to represent the flux interaction between the linked grid cells. The rainfall-runoff flows computed using a certain hydrological structure or a set of runoff production functions are generated in every grid cell or delineated sub-area of the catchment. Afterwards, the grid flows need to be routed to the neighbouring cells or directly to the outlet of the catchment. In distributed models, this procedure can be done in two ways: *source-to-sink* and *grid-to-grid* (cell-to-cell). The source-to-sink models simulate flow at the catchment outlet by translating runoffs from the source areas directly to the outlet location. In contrast, grid-to-grid (or cell-to-cell) models redirect the produced runoffs from a grid-cell to another grid-cell over a predefined area. This type of models calculates flows (or subflows) for all cell outlets based on sequential procedure in a spatially distributed way. Both approaches are described hereafter in more details.

3.3.1 Source-to-sink (S2S) approach

The source-to-sink approach is most used for the lumped models. However, it can be also applied for distributed hydrological modelling to simulate river flow at the catchment outlet as well as to represent the distributed nature of runoff formation and translation through the catchment system. The approach employs a routing scheme that takes the distributed runoffs, which are generated from every grid cell (source) or response unit of the catchment, and directs them to the outlet cell (sink), without any estimation of flows at intermediate locations (Figure 17). It means that the flows are routed from grid to grid implicitly (not explicitly, as in the grid-to-grid models). Moreover, travelling time (recession time) has to be introduced in the method to account for the differences between runoff source locations. The source-to-sink routing method can be applied to the total runoff flow, but also to the individual runoff subflows (Figure 18).

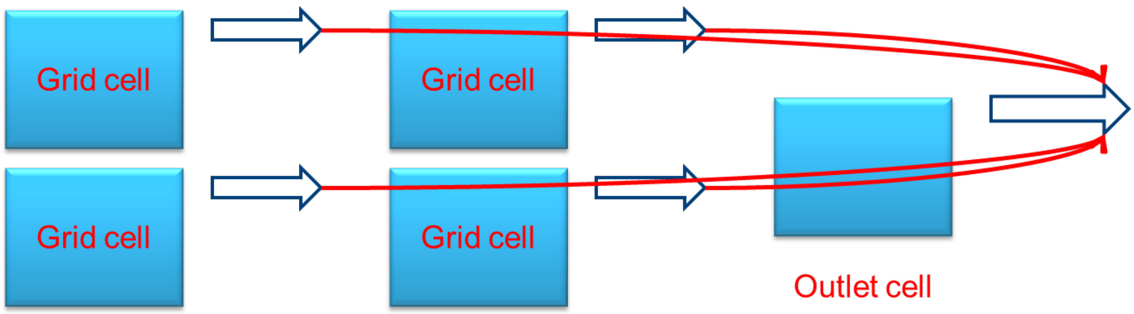


Figure 17 – Schematic representation of the source-to-sink concept, applied to total runoff from grid cell

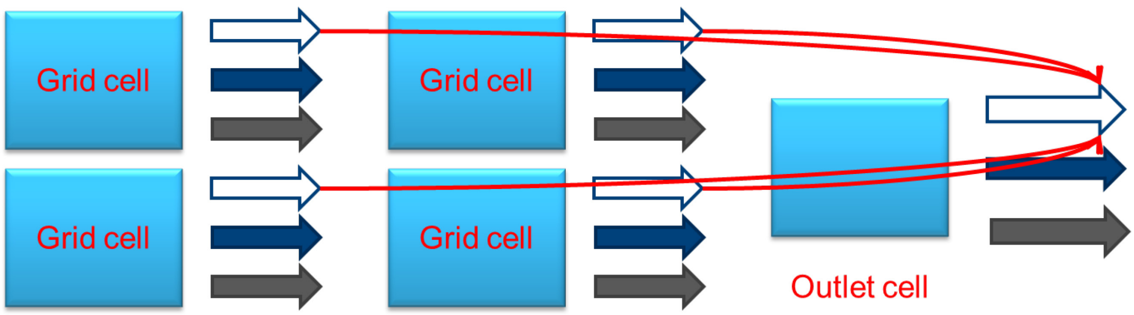


Figure 18 – Schematic representation of the source-to-sink concept, applied to runoff subflows from grid cell

Runoff accumulation

The runoff accumulation can be considered as the simplest approach to route runoffs from distributed cells over the whole catchment area to the outlet cell (Figure 19). The simulated result at the outlet in this case is simply the sum of generated runoffs (or the runoff components) from every grid cell. It means that the runoff from different sources (grids) experiences the same travelling time, which is not true in reality. The time delay significantly affects the total flow in the channel network or at the outlet location and it physically depends on the travel distance of the runoff to the calculated point, the land use surface resistance, the soil characteristics, etc. Therefore, the magnitude of the time delay varies from grid cell to grid cell over the catchment and can be estimated by the quotient of the length of flow path and the flow velocity. Nevertheless, it is difficult to build up and calibrate a map indicating the single value of time delay for every grid cell in the catchment. However, it can be replaced by applying the hydrological response unit (HRU), which is described in the following paragraph.

8	1	1	7
1	5	7	1
23	5	1	7
1	1	1	1
1	1	1	6
1	7	1	1
1	1	1	0

(a)

0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	93

(b)

Figure 19 – Maps of distributed cell runoff (a) and simulated output (b)

Hydrological response units (HRUs)

Hydrological response units (HRUs) can be defined as areas within the catchment that respond in a hydrologically similar way to given inputs. A catchment can be divided into a number of HRUs of homogeneous land cover, management and soil characteristics. By doing so, similar soil and land use areas are grouped into a single unit, which is virtually located in the catchment. It means the travelling distance from each HRU to the outlet has to be approximately calculated. HRUs can be also considered as a mean to represent the spatial heterogeneity of a watershed. The number of HRUs of a given catchment is determined by the modellers and normally depends on the complexity of the land use and soil types in the study area (Arnold et al., 1993; Marechal and Holman, 2005).

Applying the source-to-sink approach, the runoff simulated from each HRU is routed directly to the outlet of the catchment ignoring the effect of the travelling distance. There are no hydrological interactions among HRUs regardless of their extents, either (Figure 20). However, since number of HRUs in a catchment is limited, the estimation and calibration of the time delays for different HRUs due to catchment characteristics can be carried out quickly. It is done by establishing a response function that performs the interactions between the sources (HRUs) and the sink. This response function, which describes the shape of the hydrograph at the sink to a given instantaneous input at the source, includes a measure of travelling time.

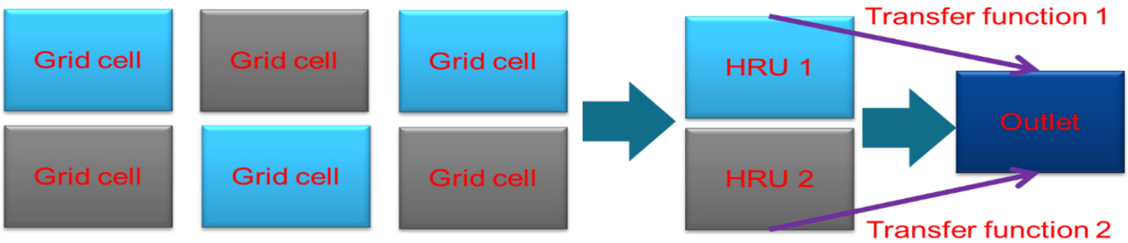


Figure 20 – Schematic representation of the source-to-sink concept, after applying HRUs

In some cases, when no spatial soil type map of the catchment is available, a landscape unit instead of HRU can be alternatively selected. This landscape unit is defined purely by using the available land use map and is a virtual and lumped unit for areas having similar characteristics of surface cover.

3.3.2 Grid-to-grid approach (G2G)

The grid-to-grid approach consists of determining the amount of water that flows from a grid cell to its neighbor downstream cell(s) across a predefined area that would generally not correspond to a specific catchment or river basin. For this reason, grid-to-grid models are as well described as area-wide models (Moore et al., 2007). This type of models requires the predefined flow paths from grid to grid (or a local drainage direction - LDD map) which can be delineated with reference to a digital elevation model (DEM) or a digital terrain model (DTM). The routing effect within each grid cell is normally skipped. Unlike the source-to-sink approach, the flows routing between grid cells are represented explicitly.

The LDD map with flow directions from each cell to its steepest downslope neighbor can be created using the 8 point pour (eight-direction) algorithm. Water from each cell is assumed to drain to one of its eight neighboring cells. Flow directions are estimated from elevation differences between the given grid cell and its eight neighboring cells. If two or more neighboring cells having the steepest drainage slope can be found, one of them will be randomly selected to receive water from the source cell. An example of construction of a local drainage direction map is illustrated in Figure 21 below.

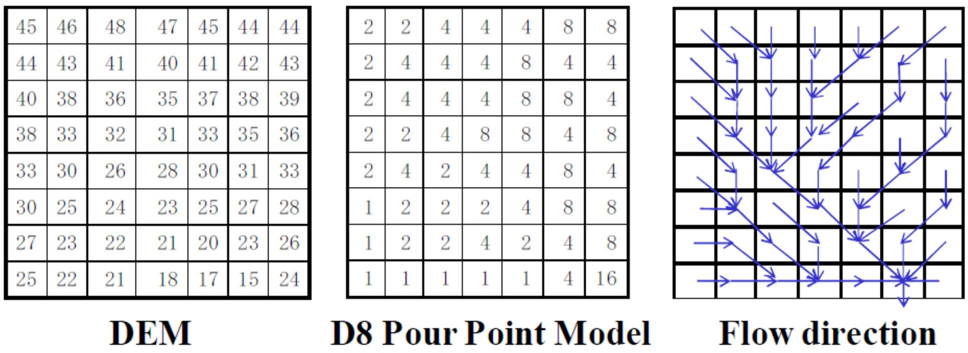


Figure 21 – Example of construction of a local drainage direction map

Spatial runoff accumulation

A similar idea as illustrated in section 3.3.1 is examined for the grid-to-grid approach where spatial information is additionally taken into account. Based on the LDD map, the accumulated amount of runoff flux that flows from a cell to its downstream cell is calculated. The runoff amount at the downstream cell is the sum of the runoff produced by the cell itself and that received from the upstream cells. This process is consequently applied for all grid cells in the catchment, starting from the most upstream parts to the most downstream cells (or the river cells). Finally, a map that describes the total runoff at every grid cell at a certain time of simulation is created. This is a simple way to route the total catchment runoff to the river. Figure 22 below illustrates this methodology.

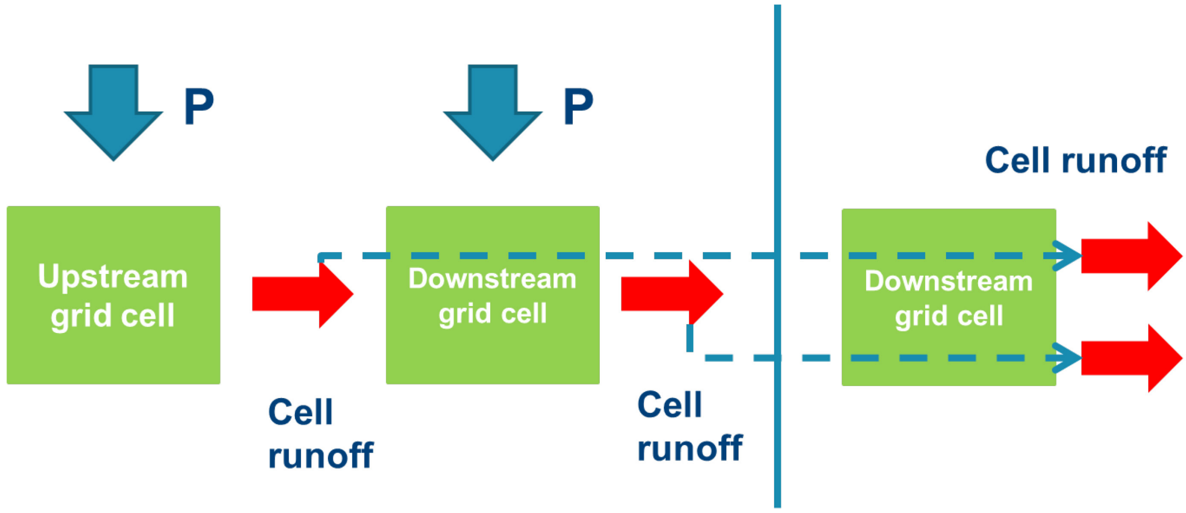


Figure 22 – Routing scheme using the simple runoff accumulation approach

Depending on the runoff production scheme and the soil characteristics, several options can be made in order to adjust the flow routing close to the catchment nature. For example, a transport capacity of the drainage network or a transport threshold, which depends on the flow velocity and the channel network itself, can be introduced. By doing so, one can control the amount of water transporting out of the cell and the remaining amount, which is stored in the cell.

Kinematic and dynamic wave equations

The dynamic wave and kinematic wave equations (Chow et al., 1988) are normally employed to calculate the flows through the channel network. It means the main application of both equations is to route the water from a river cell to another river cell. They are rarely seen to be used to route the flow between neighboring catchment grid cells. The equations are commonly solved in an explicit way and in a finite forward-difference scheme.

Some examples of the Grid-To-Grid models

Some examples are given below of spatially distributed models, with details on how the explicit spatial linking is implemented, related to the model structure selected per grid cell.

The Grid Model

The grid model (Bell and Moore, 1998a) involves an isochrone-based kinematic routing scheme to route the direct runoff and drainage generated from every grid storage to the catchment outlet along a parallel system of fast and slow response pathways, respectively (Figure 23). Firstly, a runoff production scheme yields water that is stored in a grid cell. Apart from evapotranspiration, the water can be taken out from the grid storage and contributed to the fast catchment response and slow catchment response. They are then transported to the catchment outlet throughout a number of isochrone pathways, which connect the points of equal travelling time to the basin outlet. The catchment is then sub-divided into reaches, which are corresponding to isochrone bands by these isochrones.

The set of isochrones forms a cascade of routing reaches from the headwaters to the catchment outlet. Each reach is modelled by a discrete kinematic wave equation. The number of isochrone bands together with a wave speed parameter controls the lag and attenuation of water movement through the reaches. In this case, water is transferred in an implicit way.

Further discussion on the grid model and its routing procedure can be found in the reports of Bell and Moore (1998a, 1998b).

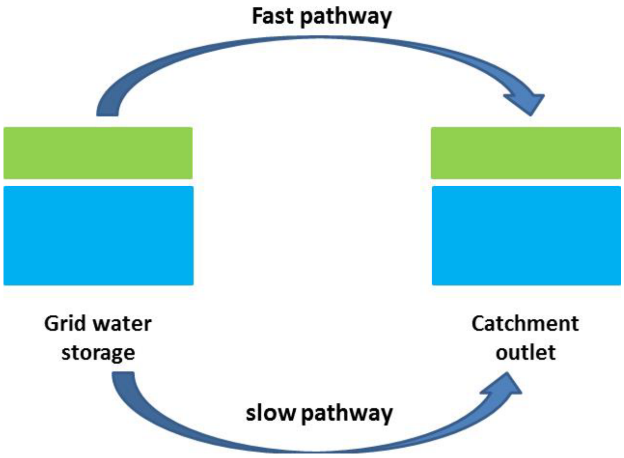


Figure 23 – The schematic structure of the routing scheme of the grid model

The 2-D grid-to-grid model

The simple kinematic wave scheme, applied to the grid model (see section 3.3.2) has been used by Bell et al. (2007) to develop a 2D grid-to-grid formulation for routing both land and river flows. The same runoff production is employed to calculate the water stored in the grid cell and to contribute the generated water to surface and subsurface runoff. The kinematic routing scheme is applied separately to each runoff component and as well enables to calculate differently for the overland and river pathways (Figure 24). A "return flow" term is introduced in the 2D approach in order to allow water transfers between surface and subsurface pathways, which represent the interactions between sub-flows. The return flow is normally positive but it might also take negative values depending on the slope of the topography. This approach, which is different from the 1-D scheme, explicitly transfers water from one grid cell to another based on topographic control.

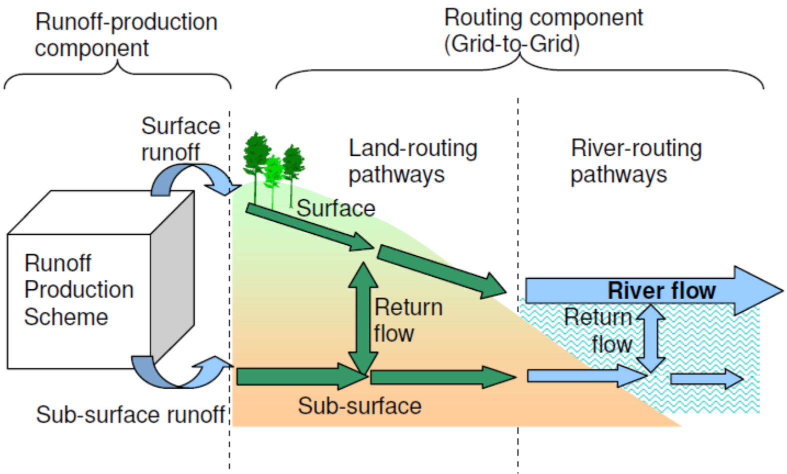


Figure 24 – The schematic structure of the 2-D grid-to-grid approach

The HydroFlow runoff routing model

As another example of a spatially distributed model, the HydroFlow runoff routing model was developed by Liston and Mernild (2012). The model assumes that there are two transport mechanisms within each individual grid cell: fast-response and slow-response systems. These two systems are described by linear reservoir type equations, where the inflow in the fast-response reservoir is the runoff flow from the different adjacent grid cells. These equations above are solved firstly for the grid cells at the head of the watershed where there are no inflows. Then, the equations are continuously solved for any grid cell that is fed with calculated cells. Finally, a matrix of solutions for the entire catchment is carried out. Figure 25shows the calculation scheme of this approach.

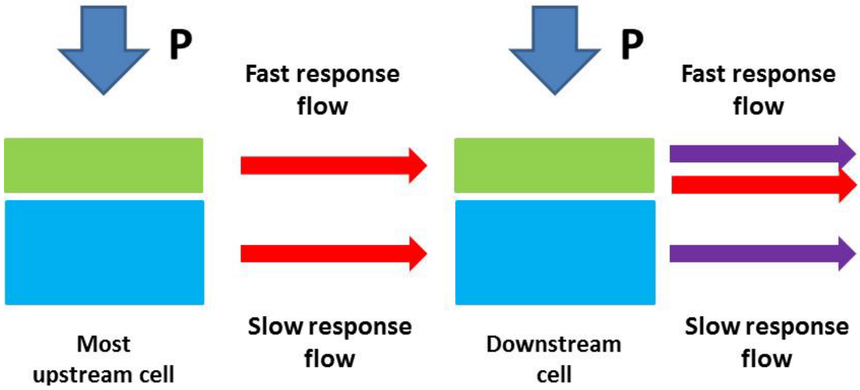


Figure 25 – Routing scheme applied in the HydroFlow runoff model

Simple distributed routing technique

A simple distributed routing technique was applied by Li et al. (2013) based on a distributed version of the HBV model. Firstly, a runoff production is performed in the most upslope cells. The generated runoff is added to the soil moisture storage and subsequently to the groundwater storage in the downslope landscape cell. The runoff from the downslope cell is then determined by the runoff from the upslope cells and the local net rainfall. The routine keeps computing from the most upstream cells to the river cells. The basic equations of the routing technique are as follows:

$$SM_j = NetP_j + \sum_{i=1}^{n} Ri$$

$$R = RU + RL$$

where SM is soil moisture storage; $NetP_j$ is the net precipitation of the j^{th} grid cell; R_i is the generated grid total runoff of the i^{th} upstream cell; and n is the number of the upslope cells of the j^{th} grid cell. RU and RL are the local grid runoff from the upper zone and lower zone, respectively.

3.3.3 Concluding remark

The spatial linking is an important module for any hydrological structures to describe how water moves inside the catchment or to the outlet. Both S2S and G2G approaches, which are used to represent the spatial linking, have major advantages and disadvantages. For the S2S approach, the hydrological connectivity is implicitly calculated so that the spatial information is lost but the computational time is quite small. For G2G approach, the explicit representation of the hydrological connectivity can produce results in spatial details but the time consuming for calculation is much larger. Users can select the spatial linking approach based on the applications or on the spatial level of the available data. Since the proposed concept allows flexibility in spatial resolution, both of the approaches are needed to be studied and implemented.

4 Proposed framework

The proposed framework for flexible hydrological modelling consists of several aspects. They are hereafter addressed in a step-wise way:

- Flexibility in spatial resolution
- Data based approach
- Flexibility in model components and equations
- Spatial implementation
- Model calibration approach
- Modelling platform
- Flexibility to future extension

4.1 Flexibility in spatial resolution

Based on the discussion in chapter 2 and 3, it is clear that many hydrological impact applications require a high spatial resolution. However, spatially detailed hydrological models have a high computational time demand and suffer from over-parameterization. Hence, the model is not appropriate to cope with applications that require a fast calculation time or a large number of computing iterations such as real-time prediction, real-time control, and different types of optimization, uncertainty analysis, etc. Furthermore, due to the large number of parameters, it is impossible to identify and calibrate these parameters based on the available data (“equifinality” (Beven, 2001)). Therefore, in many cases, spatially distributed models are not the best choices but lumped conceptual models (i.e. PDM, NAM, VHM…) might be.

To meet these needs and overcome these limitations, an approach for flexible hydrological modelling is proposed that provides flexibility in the spatial resolution, i.e. the spatial resolution can be adjusted based on applications. This is illustrated in Figure 26, with examples of differences in spatial resolution for a catchment depending on the application.

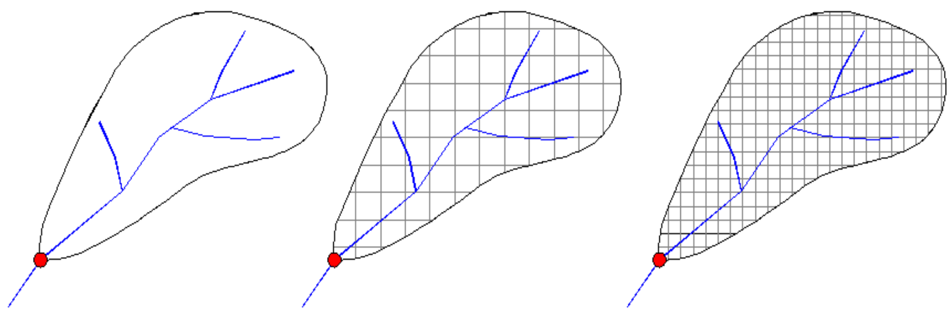


Figure 26 – Different spatial modelling scales

Thus, the proposed modelling tool replaces existing types of models by allowing a choice of the applied spatial detail. Additionally, for a specific catchment, the user can change the spatial resolution depending on the needs and/or the evaluation of the accuracy of the model results, or use different spatial resolutions in parallel for different applications. However, one of the concerns in this case is to obtain consistent results at any spatial detail. In particular, there should not be strong and sudden change in model parameters and corresponding simulation results, when one moves from one level of spatial detail to another. Moreover, to ensure that the lumped models can produce results as accurate as more distributed models regardless of their number of parameters and described physical processes, the structure of the lumped models might need to be adjusted. The tool therefore must have the flexibility to implement additional conceptual processes or to adjust the spatial processes.

The requirement of consistency between spatial resolutions is an extra constraint, which helps to reduce the over-parameterization problem. Additional model performance statistics based on comparison of model results with observations, e.g. flow at internal flow gauging stations, groundwater well levels, soil moisture products, etc. would also be very useful in order to further decrease the equifinality.

4.2 Data based approach

The VHM approach is based on the concept of identifying the model components (or equations) and related model parameters that are identified from analyzing the available data. Therefore, the amount of extracted information from the available measurements is maximized and the number of parameters will be limited, which prevents the over-parameterization problem (Willems, 2000; 2010; Willems et al., 2002). The model components only will be considered or detailed if there is an evidence that this leads to higher model accuracy without leading to equifinality / overparameterization. This also means that the approach provides flexibility in the model structure (which components are incorporated) and flexibility in the model components (equation(s) to be used).

The calibration of rainfall-runoff models is normally done by using the river discharge measurements inside or downstream the catchment. These measurements are affected by hydraulic influences along the river, and are not covered by the rainfall-runoff model. Therefore, the first step of the VHM approach (Step 1a in Figure 27) is to assess the runoff discharges averaged for the catchment area upstream of the river flow gauging station from the river discharge observations. For the unbiased calibration of the low flows in the hydrological model, for instance, it is important to assess the external flow from industrial activities and/or domestic wastewater or outflow from WWTPs. These external flows may indeed strongly influence the low river flows during dry periods.

The second step (Step 1b in Figure 27) is to separate the total runoff into sub-flows. This procedure is based on a numerical filtering technique to split the total runoff discharge into two or three components depending on the study. A recession constant will be determined for each of the components and consequently, it can be used to estimate the parameters of the routing models in the conceptual rainfall-runoff model in the next step. If the linear reservoir method is applied to route the sub-flows, these recession constants are immediately taken as the parameter for the reservoir models. Subsequently, the third step (Step 1c in Figure 27) aims to divide the time series into nearly independent slow and quick events and to extract from these events the high and the low flow extremes. Both these steps can be done by applying the WETSPRO tool (Willems, 2009).

In the next steps (Step 2, 3 and 4 in Figure 27), hydrological responses are identified. According to the events separation and the precipitation volumes per event, the primary hydrological processes can be easily identified. For each event, the precipitation is distributed over the sub-flows in the hydrological model. This splitting can be obtained from the ratios of the runoff volumes in the different sub-flows (per event; slow flow events for the slow runoff processes, quick flow events for the quick runoff processes). To close the water balance, the remaining water is contained in the soil and then possibly evaporated out of the catchment. To identify the hydrological responses, relationships are derived between the precipitation fractions contributing to each sub flow per event and other explanatory variables. Soil moisture is typically the main explanatory variable (saturation excess process). Therefore, the precipitation fractions contributing to each sub-flow and to soil moisture for all events are plotted versus the accumulated soil moisture content in order to derive sub-model equations and parameters. After identification of the most dominant process, other processes or explanatory variables can be identified, e.g. infiltration excesses, interflow, surface disposal, extra soil layer, etc. To keep the model parsimonious (avoid overparameterization and equifinality) this will only be done if these additional relationships can be derived from the data and if their addition increases the accuracy of the model simulation results.

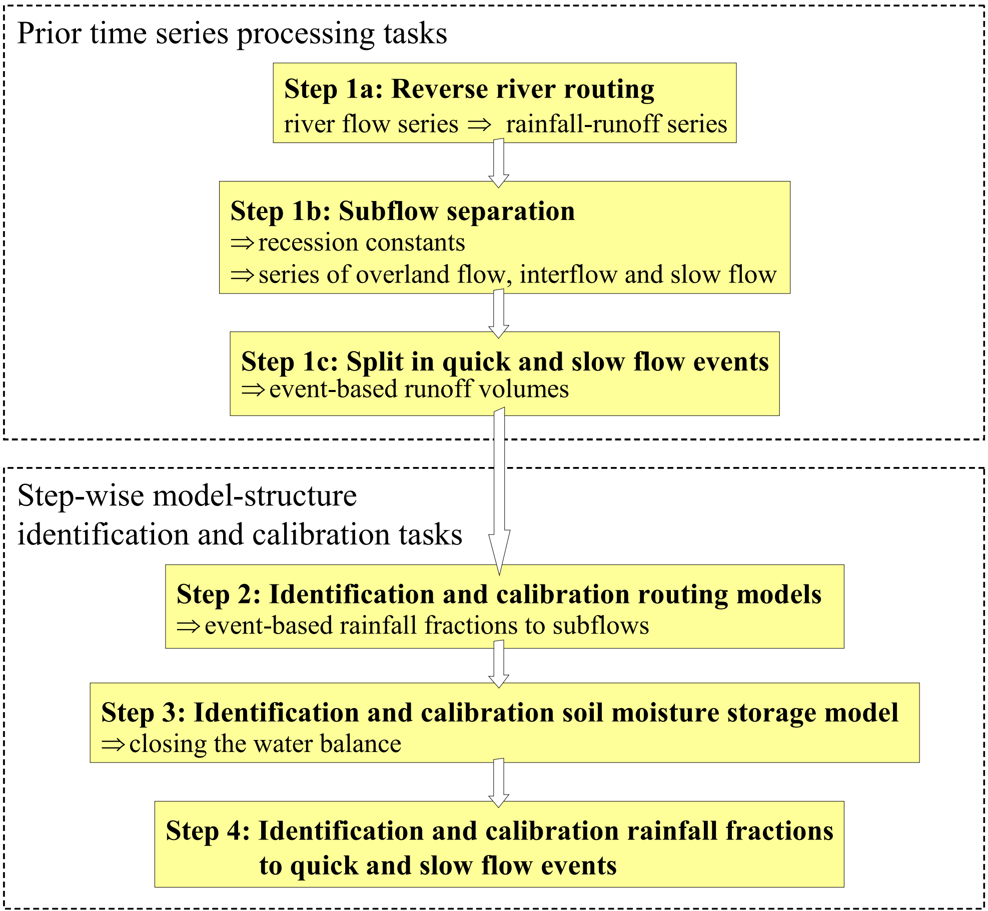


Figure 27 –VHM systematic stepwise method to construct and calibrate the lumped conceptual rainfall-runoff model structure

The VHM approach, however, has been developed for lumped conceptual models. Hence, it cannot take into account the spatial information of catchments. Hence, in the proposed approach, a spatial functionality needs to be included with the flexible spatial resolution, which can be adjusted based on applications. This will be discussed next.

4.3 Flexibility in model components and equations

Next to the identification of the model structure according to the VHM approach and the use of the corresponding VHM model components and equations, it would be useful to allow also other model structures, e.g. models that are currently used for catchment hydrological modelling. In this way, the ensemble modelling approach can be applied (as recommended in chapter 3) for investigating the effect of the selected model structure and underlying process assumptions on impact results (e.g. impact of climate change, but also impact of land use change, and other types of impact investigations for which the models will be used).

Therefore, a generalized hydrological model structure which can integrate or couple different sub-models from various existing modelling approaches is needed for the proposed framework. The equations for all model components can be taken the same to those of a given model, or only for one or few specific components. This means that in general for every model component (surface storage, infiltration, percolation or recharge, soil storage, quick flow routing, slow flow routing, etc.) several options of equation can be selected. The generalized structure will be intensively researched in the next phase of the project.

4.4 Spatial implementation

In spatially distributed models, catchments are needed to be discretized into grid cells (or pixels) where the calculations are executed. The size of the grids is chosen based on available spatial data and on the spatial resolution required for the results in the specific application.

The storage components of the model (see example in Figure 28) are simulated at the sale of each grid cell (or pixel) and the output from each grid cell will be routed explicitly to the neighboring ones.

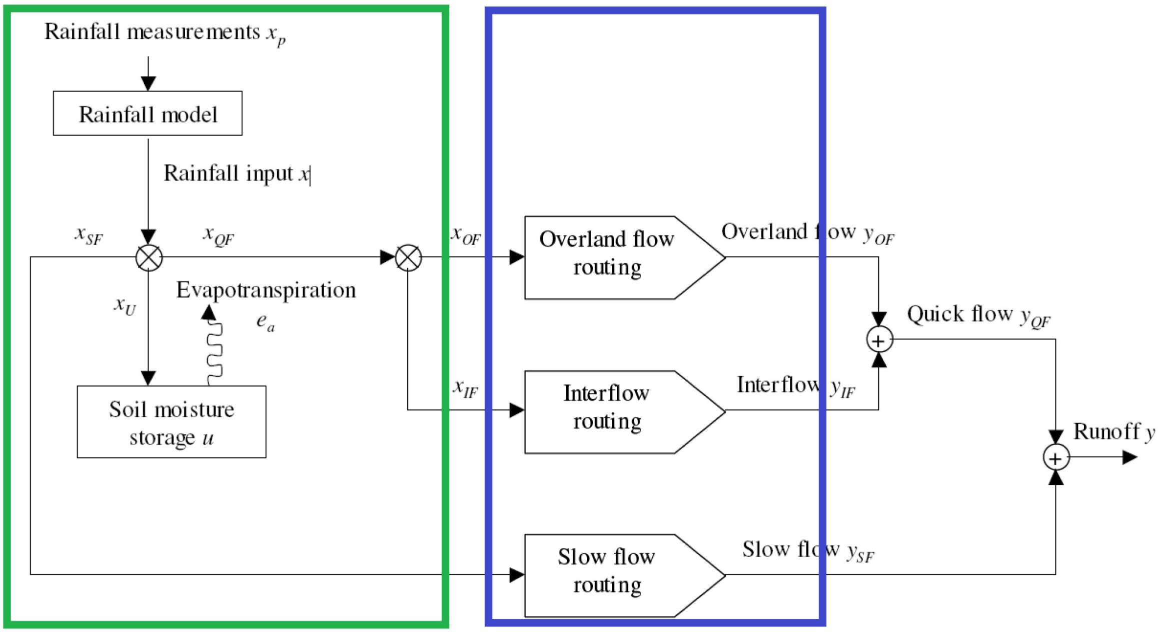


Figure 28 – Storage (green) and routing (blue) parts of the VHM model structure

The spatial coupling of the sub-flows and their direction of movements are determined by the local runoff direction (flow pathways), which is derived from the Digital Elevation Model (DEM) (see section 3.3.2). The model time step can be changed depending on the characteristic time scales of the different sub-flows. For example, the quick runoff sub-flow requires short time intervals (e.g. 15 minutes or 60 minutes) while the slow flow sub-model or soil moisture storage model can be simulated for longer time steps.

4.5 Model calibration approach

For the lumped conceptual model, the step-wise, transparent VHM based calibration approach presented in section 4.2 is proposed. For fixed model structures, such as NAM and PDM, the basic principles of the approach can still be applied, as explained in Willems et al. (2002). This was done by Vansteenkiste et al. (2012a). This approach limits the equifinality problem.

Question is how to extend this approach to the spatial model versions. Considering the flexibility in spatial resolution (see section 4.1), another question is how to ensure that the model calibrations at the different scales and the corresponding model simulation results are consistent? In order to reach such consistency, it would be useful if the calibrated parameters for the model at one spatial resolution can be used for the models at other spatial resolutions.

Taking these principles and needs into account, the approach that is proposed here, starts from the lumped scale. At that scale, by applying the data-based principles, only hydrological processes are incorporated that can be identified from the data, to avoid overparameterization. These calibrated parameters at lumped scale then will be disaggregated to distributed parameters. This can be done in two steps. Firstly, a first disaggregation is conducted based on spatial calibration data such as the flow at internal flow gauging stations and the groundwater heads at wells. If later remote sensing provide reliable soil moisture data, these can be considered as well. In a second disaggregation step, the available spatial catchment characteristics such as land use, soil type and geology will be used. The disaggregation approach for model parameters from average values in lumped model to spatially distributed values using the spatial information of the catchment will be investigate carefully in the next phase of the project.

Thanks to the disaggregation, one can make sure that the simulation results for all spatial resolutions remain consistent. Or, at each spatial resolution, model calibration can be done by optimization, conditioned on the model calibration and simulation results at the coarser spatial resolutions already conducted. It is clear that the second disaggregation step will involve assumptions. Because many different assumptions can be made, at least a sensitivity study needs to be done to investigate the impact of these assumptions to the uncertainty in the model calibration and simulation results. Several plausible assumptions will exist, such that the second disaggregation step leads to equifinality. If the uncertainty in this “unknown” spatial disaggregation induced by the second disaggregation step can be assessed, this would allow the additional uncertainty in the spatially variable model simulation results due to the spatial disaggregation uncertainty to be quantified. For the model simulation results of the total runoff discharges, it is expected that these simulation results have the highest accuracy at the flow gauging stations. At other locations along the river, the uncertainty will be higher, and higher for locations at larger distance from the gauging stations. It would be useful to quantify this spatial variation in the runoff discharges.

During the model calibration, the model performance needs to be evaluated by comparing model simulation results with observations for:

- Peak values
- Low values
- Cumulative values
- Extreme frequency distributions
- Change versus rainfall change
- Sub-responses that can be identified from the available data (e.g. quick and slow runoff coefficient variations)

This will be conducted as successfully done by Vansteenkiste et al. (2012a, 2012b, 2012c) for the Grote Nete catchment based on evaluation plots and related statistics, for (at all stations or grid cells for soil moisture):

- Flows at river flow gauging stations
- Groundwater heads at wells
- Soil moisture levels

When statistically evaluating the model results, one has to account for the:

- Model error heteroscedascticity
- Serial dependency

The latter is done by applying a Box-Cox transformation to the simulated and observed values, and by separating the time series in nearly independent events (and selecting maximum values, minimum values, mean or cumulative values). This will be done as proposed in Willems (2009) and also applied by Vansteenkiste et al. (2012a, 2012b, 2012c).

4.6 Modelling platform

The proposed modelling approach can be implemented in several modelling platforms. Because of the focus on flexibility, only platforms are considered that are open source and have direct GIS support. PCRaster (with an extension in the programming language Python) and OpenStreams are two promising candidates due to their flexibility in modifying model structures and their abundant supported tools. However, thanks to the great functionality for taking into account the spatial information, PCRaster is selected to develop the proposed model.

The PCRaster environment allows implementing different model structures, model components and model equations for each component. It also allows flexibility in the selected grid size, to derive models that range from the very lumped and conceptual models (such as NAM, PDM, VHM) to very detailed, distributed ones (i.e. MIKE SHE). Obviously, not the entire original models but only the major equations which describe the hydrological processes are re-coded in the system. Moreover, it is possible to switch on and/or off different components corresponding to different processes. Consequently, a number of various combinations can be carried out.

4.7 Flexibility to future extension

The proposed framework has the additional advantage that it enables extending the spatially distributed models with extra modules to deal with other issues such as leaching of nutrient, pesticides and other substances in the soil using the spatial information in land use. Similarly, it might be useful to model sediments (erosion, transport). Moreover, other modelling approaches can be as well coupled in the proposed framework for an ensemble evaluation on hydrological structures.

5 Testing the usefulness of PCRaster as platform for implementation of the proposed framework

5.1 Implementation of lumped models

Three lumped models NAM, PDM and VHM were implemented in the PCRaster environment. The case study of the Grote Nete was used to evaluate the performance of these models using the same inputs and model parameters as in the report of Vansteenkiste et al., (2012a). The results generated by the model scripts coded in PCRaster were compared to those from the existing Matlab scripts as applied by Vansteenkiste and his colleagues.

The three lumped hydrological models require only meteorological input data, i.e. catchment precipitation and potential evapotranspiration input series. River flow observations as well as the runoff results from the Matlab scripts were taken as references to evaluate the PCRaster scripts results.

For the dynamic temporal modelling in the PCRaster framework, a predefined class, named as DynamicModel, was called. This class helps in running time series by simple iteration module and as well to define inputs and outputs of a model. There are two methods that are used when constructing the model: the initial and the dynamic methods. In the initial method, the initial state of the different variables and the values of the different model parameters are indicated. This method has to run only one time at the beginning of the simulation. After that, the dynamic method computes the different model variables in the sequence of the equations provided. It updates the variables to their new values and iterates the calculation sequence up to the number of time-steps indicated. Moreover, if necessary, other calculations can be added outside these two methods for additional components or other applications.

For the PCRaster calculation, a clone grid map is needed. It is a Boolean type map and was used as a base map, where precipitation and evapotranspiration are distributed on. The size of the clone map as well as its attributes are user defined in the case of lumped models. However, since the implemented PCRaster scripts calculate all variables for every cell in the base map, the number of grid cells of the generated map was minimized in order to reduce the computational time. In this study, for the lumped models, a map of 1x1 grid cell is used (Figure 29). The single grid cell hence represents the entire catchment in a lumped form.

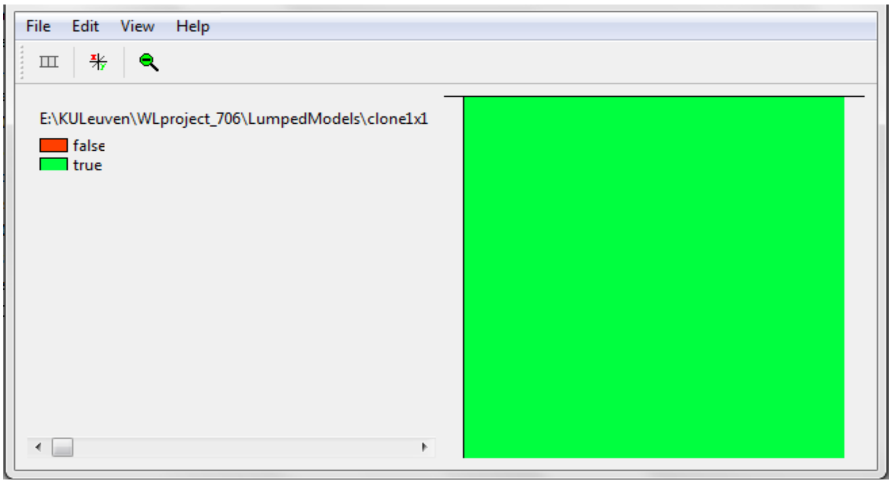


Figure 29 – Generated clone map for the lumped model

Depending on how the observation stations are distributed over the catchment, one can choose whether the precipitation and potential evapotranspiration inputs are distributed either uniformly over the whole catchment (over all gird cells, applying catchment averaged rainfall and potential evapotranspiration) or in a spatially variable way. In this study, the following script was used to uniformly distribute the areal inputs:

```
self.Prec =     timeinputscalar('precip.tss',1)
self.Evap =     timeinputscalar('evapo.tss',1)
```

where: self.Prec and self.Evap are representative for the precipitation and potential evapotranspiration and the precip.tss and evapo.tss are the input files in timeseries format.

By distributing the inputs over the catchment, the PCRaster scripts convert the inputs and variables into maps. Hence, the equations are solved by map computation. For example, the comparison between two variables cannot simply be done in a straightforward way but will involve the generation of a Boolean "control" map.

Since the models tested in this case are lumped, the simulation results can be reported at any location in the catchment. However, as aforementioned, the catchment was represented by a one-cell-clone map so there is only one available location to obtain the results. Instead of writing the output in text file format, which may consume more time, it was reported in timeseries format (*.tss). This file format can be opened by Microsoft Windows Notepad or by Aguila. Aguila is a specific executable program, which allows graphical (and animated) presentation of the simulation results from PCRaster scripts, such as stack of maps or timeseries.

Figure 30, Figure 31 and Figure 32 below were plotted using Aguila and present the results simulated by the NAM, PDM and VHM models implemented in the PCRaster environment. They are based on the Grote Nete models calibrated by Vansteenkiste et al. (2012a) after simulation of the first 26000 time steps (hours) of the period from Aug 2002 to Aug 2005.

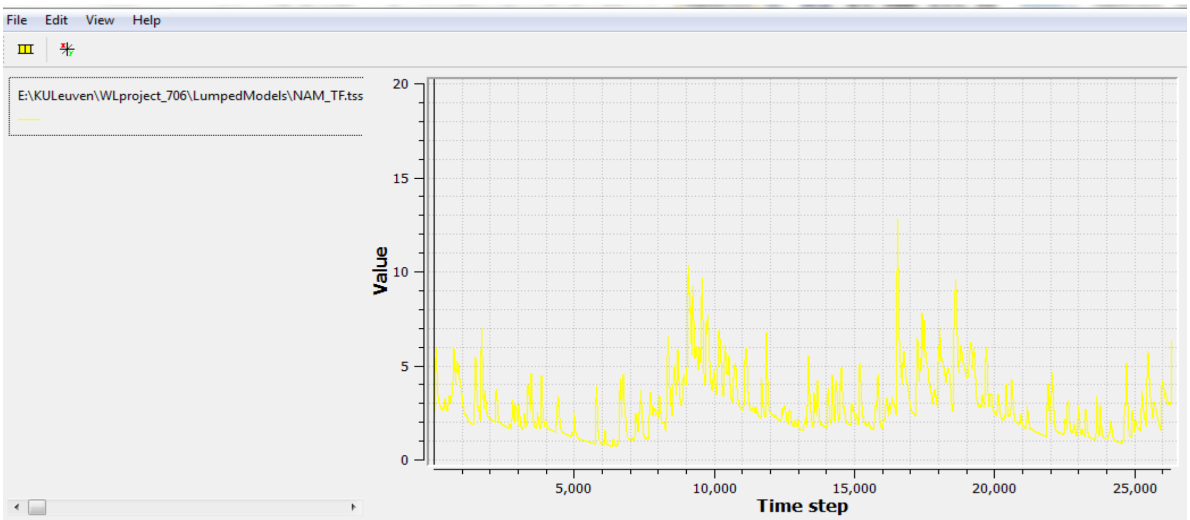


Figure 30 – The total runoff produced by NAM in PCRaster

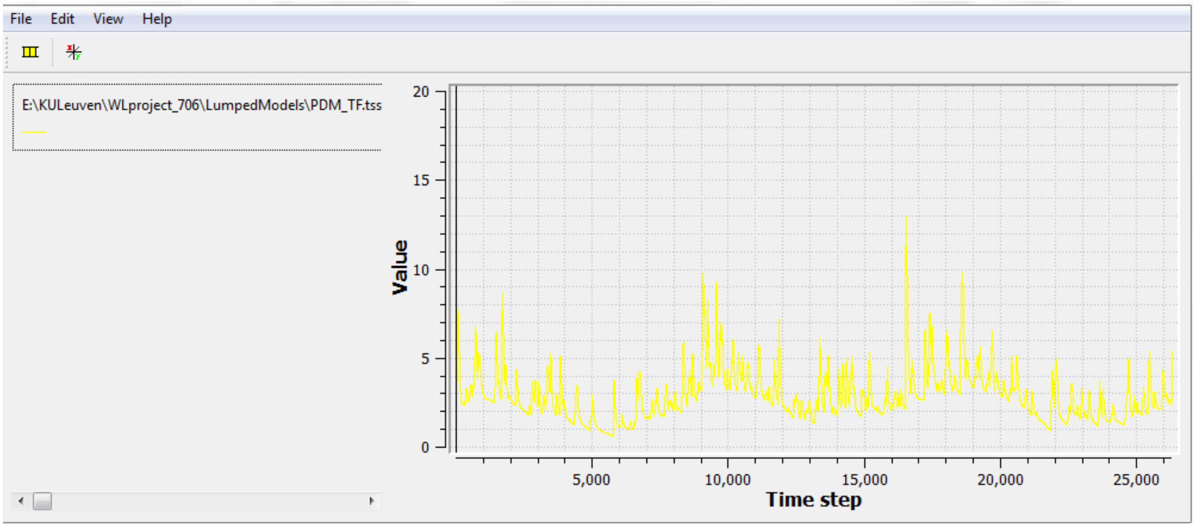


Figure 31 – The total runoff produced by PDM in PCRaster

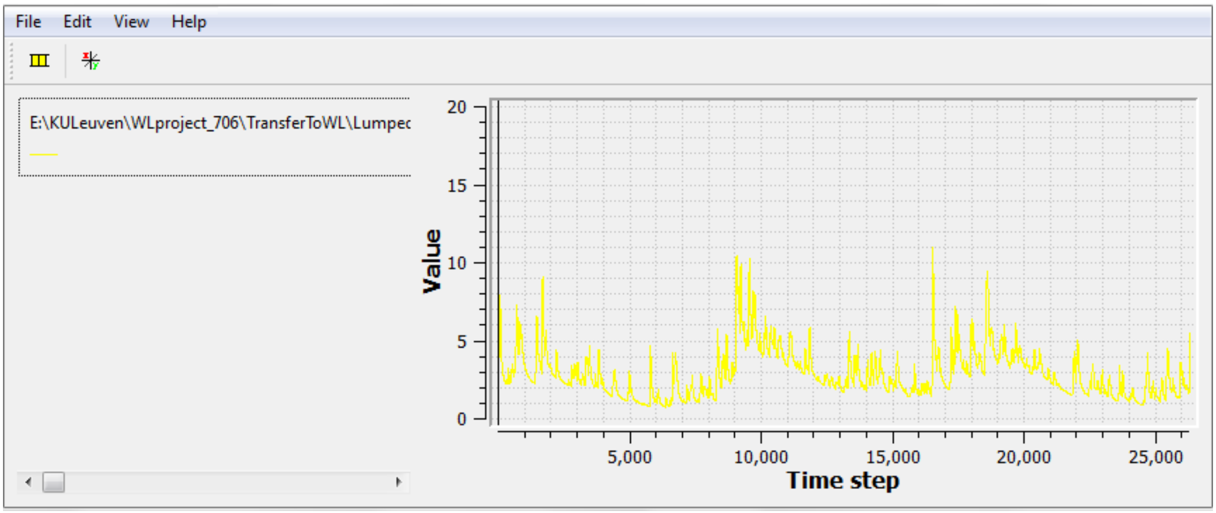


Figure 32 – The total runoff produced by VHM in PCRaster

Model calibration or model uncertainty analysis were not the main focus of the test reported in this section (actually the calibration and uncertainty analysis were extensively discussed before by Vansteenkiste et al., 2012a). Hence, it is more reasonable to inter-compare the simulated hydrographs by the PCRaster scripts to those by the Matlab scripts rather than to compare to the observed discharge. By doing so, the differences in simulation results due to the differences between two languages are recognized. Three following figures (Figure 33, Figure 34 and Figure 35) show these comparisons.

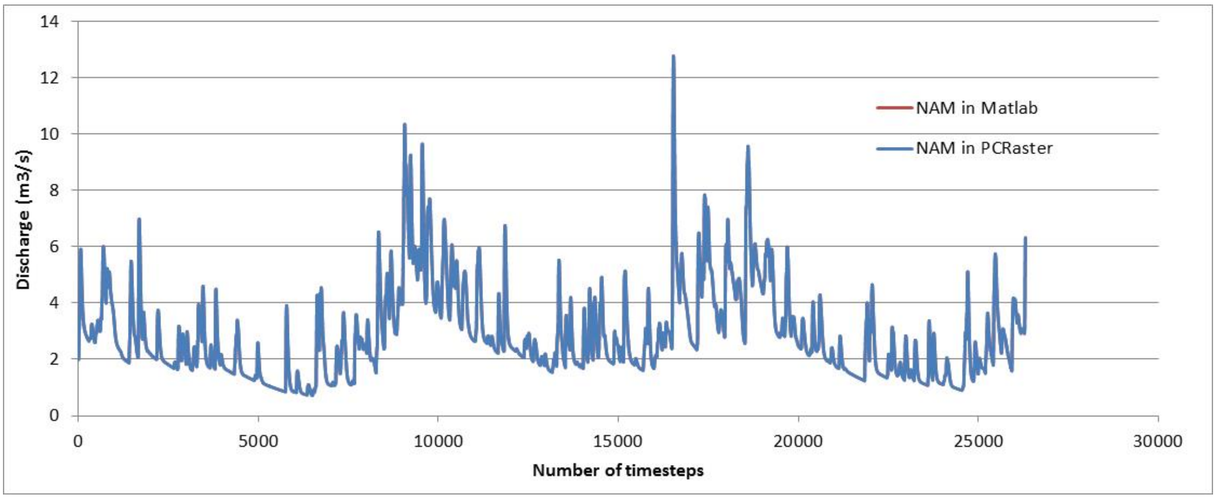


Figure 33 – Comparison between simulated hydrographs produced by the NAM models implemented in PCRaster and Matlab

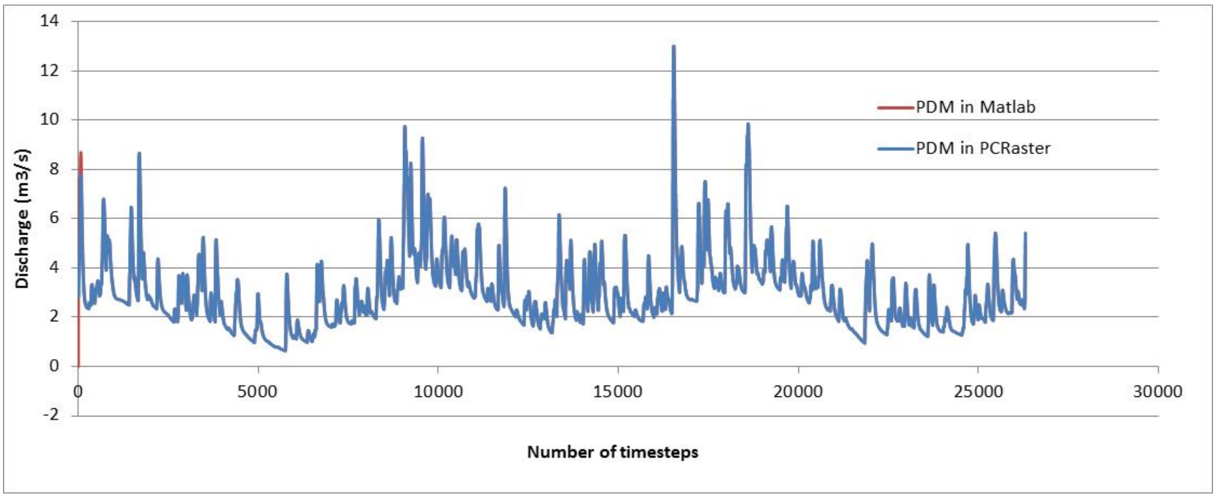


Figure 34 – Comparison between simulated hydrographs produced by the PDM models implemented in PCRaster and Matlab

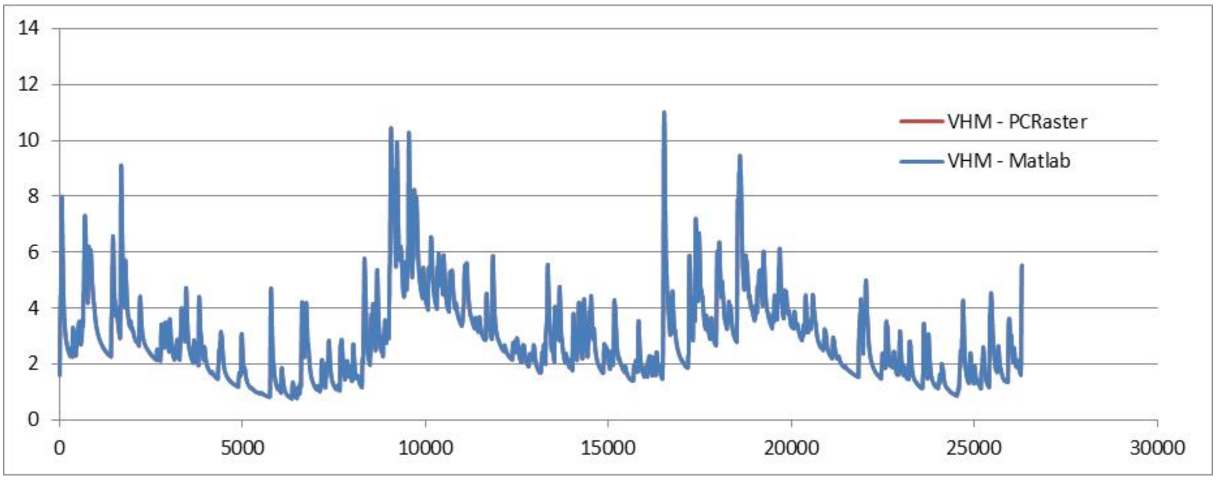


Figure 35 – Comparison between simulated hydrographs produced by the VHM models implemented in PCRaster and Matlab

As can be seen from the figures, the total runoff series simulated using PCRaster and Matlab languages are identical for all three rainfall-runoff models. Only a small difference is noted for the PDM model in the beginning of time series, due to differences in the initial values. Therefore, it is concluded that the three lumped rainfall-runoff models (NAM, PDM and VHM) were well-translated into Python in the PCRaster framework. Furthermore, the PCRaster scripts took only a few seconds more than the Matlab scripts for simulation, which is acceptable.

5.2 Implementation of a distributed approach

After the lumped models were successfully re-coded in the PCRaster framework using Python, a distributed version based on the lumped rainfall-runoff model NAM was implemented.

Similarly to the lumped model construction, the DynamicModel class was used in order to construct a distributed model in a dynamic modelling framework. A Boolean clone map is also required as a base map, on which the equations are solved. However, since the model is constructed using a distributed approach, the clone map must have the same attributes as the available raster spatial maps, instead of containing only one grid cell as for the lumped models. The created clone map is shown in Figure 36:

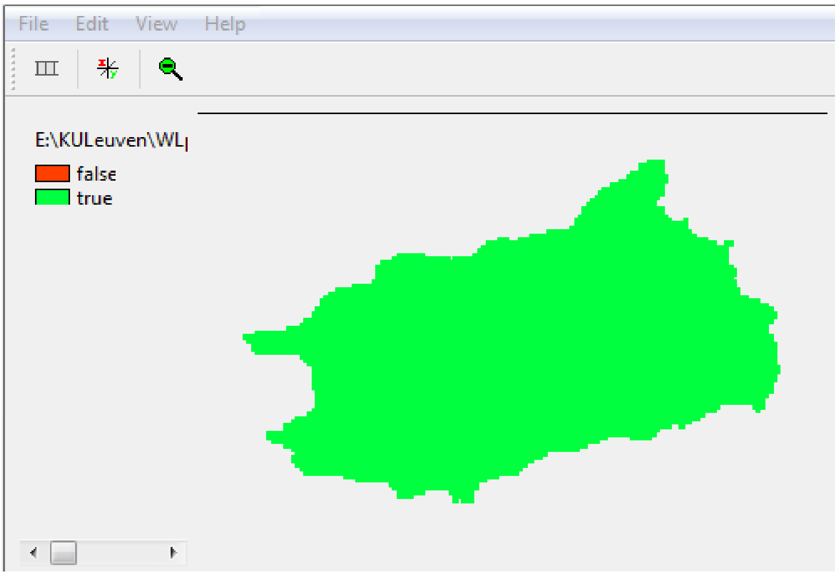


Figure 36 – Generated clone map for distributed hydrodynamic model

Meteorological inputs were uniformly distributed over the catchment based on the created clone map since the time series was lumped but it is possible to switch into spatially distributed input if needed. The same functions were used for importing the input data as mentioned above for the lumped models. It means every cell of the map was assigned the same amount of precipitation and the same rate of potential evapotranspiration.

A set of parameters which varies from cell to cell depending on the catchment characteristics was used for every single grid cell. However, for this first attempt, these parameters were taken uniform in order to make it easier to calibrate the model. The parameters, which describe the vertical characteristics of the catchment (i.e. max. water content in the surface storage, max. water content in root zone, etc…) or the soil characteristics were maintained the same, given that they might not be affected by the spatial information. Other parameters were slightly calibrated to examine if the model was able to run properly. Further calibration will be carried out carefully in the next phase of the implementation.

There are various results that can be produced from the distributed model, such as the soil moisture state, the total runoff, the sub-flows, etc… at different locations in the catchment. The runoff flux, composed by sub-fluxes was generated as shown inFigure 37. As can be seen, the total flux was illustrated as a stack of maps, which can be displayed animatedly by Aguila. Each grid cell of the total map contains a value of the flux for every time-step. Using the “Cursor and Values” function, one can specify the total flux at a specific location for the desired time-step. Since the parameters were selected the same for every single cell, the total flux values were as well equal for all the grid cells at a particular time step.

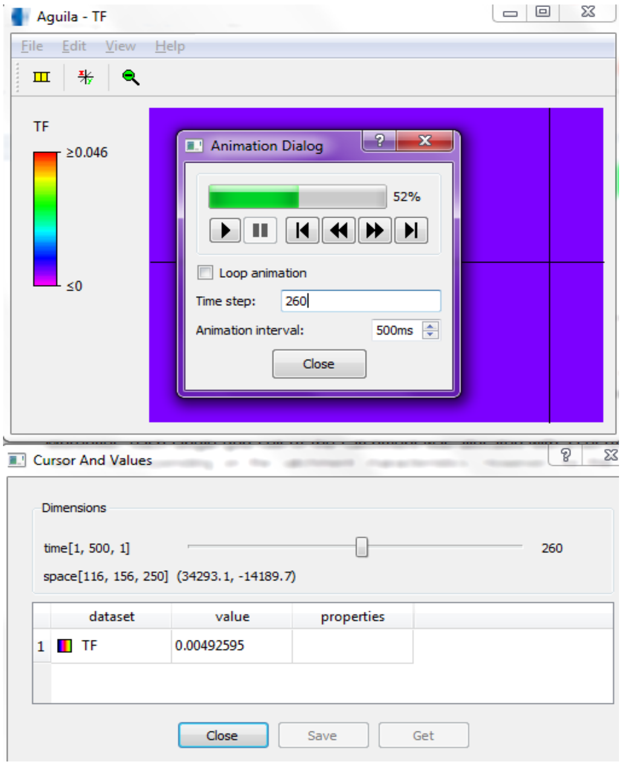
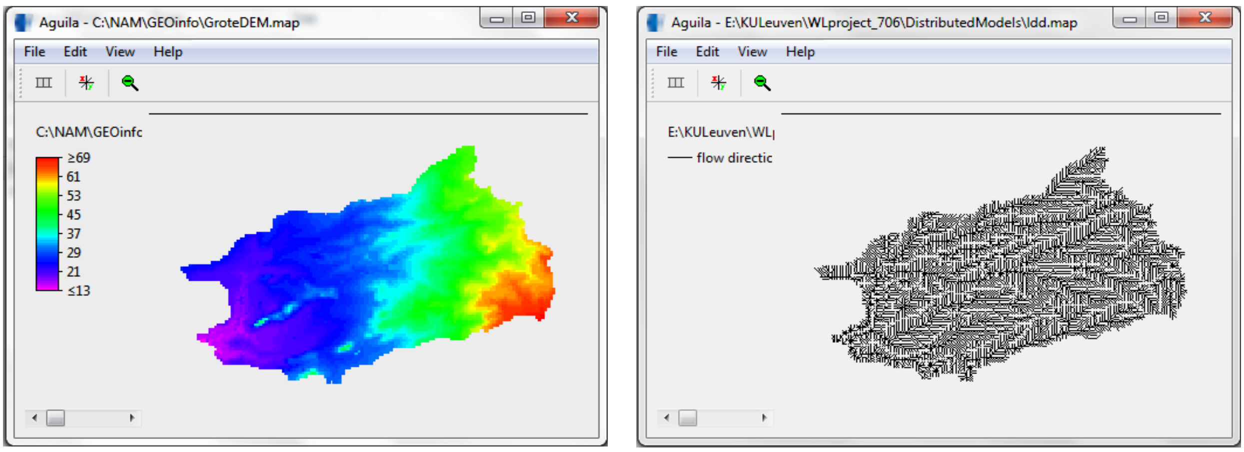


Figure 37 – Total runoff flux simulated by the constructed distributed NAM model

However, to calculate the runoffs from the catchment to the river, a local drainage direction (LDD) map was applied to take into account the spatial information of the catchment. This map (Figure 38b), created using the DEM map, defines the flow directions from each cell to its steepest downslope neighbor.



(a) (b)

Figure 38 – The DEM map (a) and LDD map (b) of the study region of the Grote Nete catchment

Based on the LDD map, the accumulated amount of runoff flux that flows out of the cell into its neighboring downstream cell was calculated. This amount is the sum of the flux in the cell itself and that in the upstream cells. The total fluxes of all grid cells in the catchment were summed and were routed to the cell of the total runoff map, which is the final result map of the simulation (Figure 39). This is, however, the very simple way of routing (i.e. the G2G runoff accumulation – see section 3.3.2) the catchment runoff to the river.

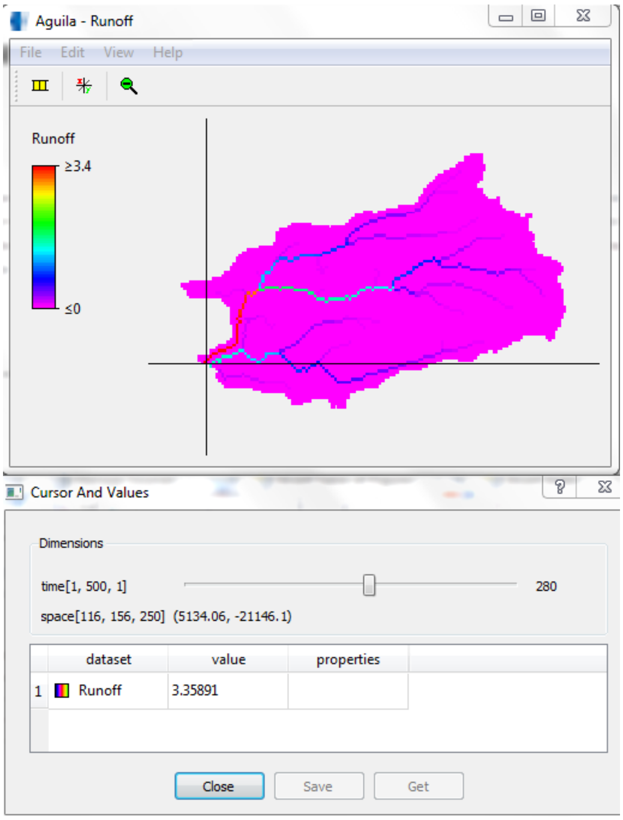


Figure 39 – The total runoff generated by the distributed model at any location along the catchment and at a specific downstream location

For a particular time step, the total runoff can be obtained at any location in the catchment. However, since no spatial model calibration or parameter disaggregation was applied yet (this is planned for the next phase), evaluation of the goodness-of-fit of the spatial model did not make sense. The main objective so far was to test the possibility of creating a distributed model using the NAM (or PDM or VHM) approach in PCRaster. The results of this test are positive. There is a good potential for a successful implementation of the models in the spatial dimension and to continue with the implementation phase where other aspects, including the spatial calibration or disaggregation procedure, the more physical explicit spatial linking between gird cells, etc… are carried out. An outline of the proposed implementation phase is discussed in the next section.

6 Implementation plan

Based on the review presented in chapters 2 and 3, the proposed flexible modelling framework in section 4 and the successful feasibility testing in section 5.1, a continuation plan is proposed here to implement the proposed framework in the PCRaster platform. This will consist of the following steps:

- **Construct a generalized hydrological model structure** of the framework where any model structure can be implemented in principle. In this structure, more or less model components (more or less detail) can be considered, and where flexibility is provided to the model equations selected per component. Other hydrological modelling approaches (i.e. NAM, PDM and VHM) will be reformed into this generalized structure. They will be tested to produce the similar results as the Matlab scripts did. However, when the flexible structure provides hydrological processes to be modeled as separate components / modules, which allows users to choose the suitable equations for specific processes, the classical methodology of coding becomes insufficient (or limited). Another approach of coding has to be applied, based on Object Oriented Programming (OOP). This enables to replace a module with another appropriate one without changing the systematic structure of the modelling system. It demands to divide (and arrange) the original scripts into similar processes or groups. A generalized hydrological model structure has to be developed in order to define the main groups of processes such as: (i) rainfall and evapotranspiration components to generate the net rainfall and actual evapotranspiration; (ii) storage components for soil moisture (root zone or unsaturated zone), surface storage (to transform into direct runoff), and groundwater storage (to produce the baseflow); (iii) splitting components which distribute the net rainfall to the available storages; and (iv) routing components to transform the water from the different storages into the sub-flows and rout them to the outlet. Furthermore, there is a major issue in the model calibration phase when a large number of parameters from different models are involved. This problem might be solved by translating and re-arranging the various parameters into generalized values.

- **Implementation and testing of different approaches for spatial linking**: With spatial explicit modelling the outflows (for the different subflows) from one grid cell are routed to the neighboring grid cells explicitly. The linking direction is based on the flow pathways derived from the DEM. An implicit approach, which may be interesting to include in the propose framework is to simulate the runoff from the different grid cells independently and cumulate the results. This accumulation can be done per type of spatial unit (following the concept of "hydrological response units" or "landscape units") and from up-to downstream in the catchment following the flow pathways such that runoff flow can be generated at any location in the catchment.

- **Implementation of the proposed model calibration approach**: Starting from the data-based lumped approach and spatially disaggregating the calibrated model parameters, consistency in model calibration and simulation results for the different spatial resolutions is required. Different spatial disaggregation methods will be tested and the simulation results compared at different locations along the river network. In this way, it can be tested whether the uncertainty in the model results increases at locations further away from the flow gauging stations.

- **Implementation and evaluating impact results for a Belgian catchment**: Three implementation steps above will be tested first for a pilot catchment (e.g. same as used in the feasibility analysis of chapter 5, and before by Vansteenkiste et al., 2012a, 2012b and 2013: the catchment of the Grote Nete – Grote Laak). Afterwards, they will be applied to other selected catchments in Flanders (in agreement with Flanders Hydraulics Research). The impact of climate change and land use change will be simulated in the implemented models (for NAM, PDM and VHM), at different spatial resolutions. In this way, the sensitivity of the impact results on the selected model structure and spatial resolution will be investigated. Moreover, the results will be used to present the impact results based on an ensemble approach not only for the climate and land use scenarios themselves but also for the hydrological model.

The timing of this implementation plan goes as in Table 2:

Table 2 – Timing of the proposed implementation plan

Task	**Year 2013**			**Year 2014**								
	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Construct and implement the generalized model structure in PCRaster Re-arrange NAM, PDM and VHM models into the generalized structure												
Implementation and evaluation of different spatial linking approach for the distributed models of NAM, PDM and VHM												
Implementation of the proposed model calibration method for the distributed models of NAM, PDM and VHM												
Implementation and testing the proposed framework for the catchment of the Grote Nete – Grote Laak												
Investigation of climate change impact on hydrological extremes for the Grote Nete – Grote Laak catchment using three distributed models within the framework Investigation of different resolutions of remote sensing data on the performance of the models												

Bibliography

Abbott, M., Bathurst, J., Cunge, J., Oconnell, P. and Rasmussen, J. "An introduction to the European Hydrological System - Systeme Hydrologique Europeen, SHE .1. History and Philosophy of A Physically-Based, Distributed Modelling System", *Journal of Hydrology* (87 (1-2)), 1986a, pp. 45-59.

Abbott, M., Bathurst, J., Cunge, J., Oconnell, P. and Rasmussen, J. "An introduction to the European Hydrological System - Systeme Hydrologique Europeen, SHE. 2. Structure of a physically-based, distributed modelling system", *Journal of Hydrology* (87 (1-2)), 1986b, pp. 61-77.

Abbott, M. and Refsgaard, J. *Distributed Hydrological Modelling*, Kluwer Academic Publishers, Dordrecht, 1996.

Arnold, J., Allen, P. and Bemhardt, G. "A comprehensive surface-groundwater flow model", *Journal of Hydrology* (142), 1993, pp. 47-69.

Baguis, P., Boukhris, O., Ntegeka, V., Roulin, E., Willems, P. and Demarée, G. "Climate change impact on hydrological extremes along rivers and urban drainage systems. I. Literature review, Belgian Science Policy – SSD Research Programme", Technical report, Technical report CCI HYDR project by KULeuven -Hydraulics Section Royal Meteorological Institute of Belgium, 2008.

Baguis, P., Roulin, E., Willems, P. and Ntegeka, V. "Climate change scenarios for precipitation and potential evapotranspiration over central Belgium", 2009.

Bell, V.A., Moore, R.J., 1998a. A grid-based distributed flood forecasting model for use with weather radar data: Part 1. Formulation. Hydrology and Earth System Sciences, 2, 265–281.

Bell, V.A., Moore, R.J., 1998b. A grid-based distributed flood forecasting model for use with weather radar data: Part 2. Case studies. Hydrology and Earth System Sciences, 2, 283-298.

Bell, V.A., Kay, A.L., Jones, R.G., Moore, R.J., 2007. Use of a grid-based hydrological model and regional climate model outputs to assess changing flood risk. International Journal of Climatology, 27, 1657-1671.

Bergström, S. "The HBV model - its structure and applications - SMHI Reports RH No. 4", Technical report, Swedish Meteorological and Hydrological Institute, 1992.

Bergström, S. "Development and application of a conceptual runoff model for Scandinavian catchments - SMHI Reports RHO No. 7", Technical report, Swedish Meteorological and Hydrological Institute, 1976.

Beven, K. *Rainfall-Runoff Modelling: The Primer*, Wiley, Chichester, UK, 2001.

Beven, K. "Changing ideas in hydrology – the case of physically-based models", *Journal of Hydrology* (105), 1989, pp. 157-172.

Boukhris, O., Willems, P., Vanneuville, W. and Van Eerdenbrugh, K. "Climate change impact on hydrological extremes in Flanders Regional differences", Technical report, Waterbouwkundig Laboratorium, 2008.

Bultot, F., Dupriez, G. L. and Gellens, D. "Estimated regime of energy-balance components, evapotranspiration and soil moisture for a drainage basin in the case of a CO2 doubling", *Climatic Change* (12), 1988, pp. 39-56.

Chow, V.T.and Maidment, D. and Mays, L. , McGraw-Hill, S., (eds.) *Applied Hydrology*, Chow, V.T., Maidment, D.R., Mays, L.W., 1988. Applied Hydrology, 1988.

Cools, J., Vlieghe, P., Huygens, M. and Bauwens, W. "Modelleren van het effect van maatregelen voor stikstofreductie ter ondersteuning van bekkenbeheerplannen”, *Tijdschrift water (in Dutch)* (27 (14)), 2007.

Crooks, S. and Naden, P. "CLASSIC A semi-distributed rainfall-runoff model”, *Hydrology and Earth System Sciences* (11 (1)), 2007, pp. 516-531.

van Deursen, W. "Geographical Information Systems and Dynamic Models- development and application of a prototype spatial modelling language", 1995.

DHI "MIKE11 - Reference Manual", 2007.

EUROTAS "European River Flood Occurrence & Total Risk Assessment System. Task T3 - Thames catchment study", 2000.

Gellens, D. and Roulin, E. "Streamflow response of Belgian catchments to IPCC climate change scenarios”, *Journal of Hydrology* (210), 1998, pp. 242-258.

Gellens, D. and Schädler, B. "Comparison of the water balance responses of Belgian and Swiss catchments to a climate change”, *Revue des Sciences de l'Eau* (10), 1998, pp. 395-414.

Grayson, R. B., Moore, I. D. and Mcmahon, T. A. "Physically based hydrologic modelling. Is the concept realistic”, *Water Resources Research* (28), 1992, pp. 2659 - 2666.

Griensven, A. V. and Bauwens, W. "Application and evaluation of ESWAT on the Dender basin and the Wister lake basin”, *Hydrological Processes* (19), 2005, pp. 827 - 838.

Hörmann, G., Zhang, X. and Fohrer, N. "Comparison of a simple and a spatially distributed hydrologic model for the simulation of a lowland catchment in Northern Germany”, *Ecological Modelling* (209), 2007, pp. 21-28.

Harbaugh, A. W. "MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model—the Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods 6-A16", 2005.

Jeong, J., Kannan, N., Arnold, J., Glick, R., Gosselink, L. and Srinivasan, R. "Development and Integration of Sub-hourly Rainfall–Runoff Modelling Capability within a Watershed Model”, *Water Resources Manage*, 2010.

Kim, N., Chung, I. M., Won, Y. S. and Arnold, J. G. "Development and application of the integrated SWAT–MODFLOW model”, *Jounal of Hydrology* (356 (1-2)), 2008, pp. 1-16.

Kraft, P. "A hydrological programming language extension for integrated catchment models", 2012.

Kraft, P., Vaché, K. B., Frede, H.-G. and Breuer, L. "CMF - A Hydrological Programming Language Extension For Integrated Catchment Models”, *Environmental Modelling & Software* (26), 2011, pp. 828-830.

Kristensen, K. and Jensen, S. "A model for estimating actual evapotranspiration from potential evapotranspiration”, *Nordic Hydrology* (6), 1975, pp. 70-88.

Leavesley, G., Lichty, R., Troutman, B. and Saindon, L. "Precipitation runoff modelling system – User's manual: Water-Resources Investigations Report 83-4238", 1983.

Leavesley, G., Restrepo, P., Stannard, L. G., Frankoski, L. A. and Sautins, A. *A modelling framework for multidisciplinary research and operational applications, in GIS and Environmental Modelling: Progress and Research Issues*, GIS World Books, 1996.

Li, H., Beldring, S., Xu, C-Y., 2013. Implementation and testing of routing algorithms in the distributed Hydrologiska Byråns Vattenbalansavdelning model for mountainous catchments. Hydrology Research, in press.

Limbrick, K., Whitehead, P., Butterfield, D. and Reynardc, N. "Assessing the potential impacts of various climate change scenarios on the hydrological regime of the River Kennet at Theale, Berkshire, south-central England, UK: an application and evaluation of the new semi-distributed model, INCA", *The Science of the Total Environment* (251/252), 2000, pp. 539-555.

Lindström, G., Johansson, B., Persson, M., Gardelin, M. and Bergström, S. "Development and test of the distributed HBV-96", *Journal of Hydrology* (201 (1-4)), 1997, pp. 272-288.

Liu, Y. and De Smedt, F. "Wet Extension, A GIS-ased Hydrologic Model for Flood Prediction and Watershed Management. Documentation and User Manual", Vrije Universiteit Brussel, 2004.

Marechal, D. and Holman, I. "Development and application of a soil classification-based conceptual catchment-scale hydrological model", *Journal of Hydrology* (312), 2005, pp. 277 - 293.

McDonnell, J. "Where does water go when it rains Moving beyond the variable source area concept of rainfall-runoff response", *Hydrological Processes* (17), 2003, pp. 1869, 1875.

Moore, R. "The PDM rainfall-runoff model", *Hydrology and Earth System Sciences* (11(1)), 2007, pp. 483 - 499.

Moore, R. "The probability-distributed principle and runoff production at point and basin scales", *Hydrological Sciences Journal* (30), 1985, pp. 273-297.

Naden, P. "A routing model for continental scale hydrology", *Macroscale Modelling of the Hydrosphere*, 1993.

Ntegeka, V. and Willems, P. "Trends and multidecadal oscillations in rainfall extremes, based on a more than 100 years time series of 10 minutes rainfall intensities at Uccle, Belgium", *Water Resources Research* (44), 2008.

Ntegeka, V., Willems, P., Baguis, P. and Roulin, E. "Climate change impact on hydrological extremes along rivers and urban drainage systems. Summary report Phase 1: Literature review and development of climate change scenarios", Technical report, KULeuven - Hydraulics Section Royal Meteorological Institute of Belgium, Belgian Science Policy - SSD Research Programme, CCI-HYDR project, 2008.

Ntegeka, V., Willems, P., Roulin, E. and Baguis, P. "Developing tailored climate change scenarios for hydrological impact assessments", *Journal of Hydrology*, 2010.

Ott, B. and Uhlenbrook, S. "An investigation of the effects of model structure on model performance to reduce discharge simulation uncertainty in two catchments", *Hydrology and Earth System Sciences* (8 (1)), 2004, pp. 62-78.

Perkins, S. and Sophocleous, M. "Development of a comprehensive watershed model applied to study stream yield under drought conditions", *Ground Water* (37 (3)), 1999, pp. 418 - 426.

Salvadore, E. "Development of a spatially distributed hydrological model for urban water management analysis: Third year report", Technical report, Vrije Universiteit Brussel, 2012.

Schellekens, J., Becker, B., Donchyts, G., Goorden, N., Hoogewoud, J., Patzke, S. and Schwanenberg, D. "Open Source Components as Building Blocks for Integrated Hydrological Models", Deltares, 2012.

Schmitz, O., Karssenberg, D., van Deursen, W. and Wesseling, C. "Linking external components to a spatio-temporal modelling framework- Coupling MODFLOW and PCRaster", *Environmental Modelling & Software* (24), 2009, pp. 1088-1099.

Sheikh, V., Visser, S. and Stroosnijder, L. "A simple model to predict soil moisture Bridging Event and Continuous Hydrological (BEACH) modelling", *Environmental Modelling & Software* (24), 2009, pp. 542-556.

Shultz, M. "Comparison of distributed versus lumped hydrologic simulation models using stationary and moving storm events applied to small synthetic rectangular basin and an actual watershed basin", 2007.

Singha, R., Subramaniana, K. and Refsgaardb, J. "Hydrological modelling of a small watershed using MIKE SHE for irrigation planning", *Agricultural Water Management* (41), 1999, pp. 149-166.

Thornthwaite, C. and Mather, J. *The water balance*, Vol. 8, Climatology, 1955.

Vandenberghe, V., Bauwens, W. and Vanrolleghem, P. "Evaluation of uncertainty propagation into river water quality predictions to guide future monitoring campaigns", *Environmental Modelling & Software* (22), 2007, pp. 725-732.

Vandenberghe, V., Goethals, P., Van Griensven, A., Meirlaen., J., De Pauw, N., Vanrolleghem, P. and Bauwens, W. "Application of automated measurement stations for continuous water quality monitoring of the Dender river in Flanders, Belgium", *Environmental Monitoring and Assessment* (108), 2005, pp. 85-98.

Vandenberghe, V., Van Griensven, A., Bauwens, W. and Vanrolleghem, P. "Effect of different river water quality model concepts used for river basin management decisions", *Water Science & Technology* (53 (10)), 2006, pp. 277-284.

Vansteenkiste, T., Pereira, F., Willems, P. and Mostaert, F. "Effect of climate change on the hydrological regime of navigable water courses in Belgium: Subreport 5 - Comparison of lumped and distributed models in the climate change impact assessment", Technical report, Waterbouwkundig Laboratorium and KU Leuven, 2012c.

Vansteenkiste, T., Pereira, F., Willems, P. and Mostaert, F. "Effect of climate change on the hydrological regime of navigable water courses in Belgium: Subreport 3 - Climate change impact analysis by distributed models", Technical report, Waterbouwkundig Laboratorium KU Leuven, 2012b.

Vansteenkiste, T., Pereira, F., Willems, P. and Mostaert, F. "Effect of climate change on the hydrological regime of navigable water courses in Belgium: Subreport 2 - Climate change impact analysis by conceptual models", Technical report, Waterbouwkundig Laboratorium KU Leuven, 2012a.

Vansteenkiste, T., Pereira, F., Willems, P. and Mostaert, F. "Effect of climate change on the hydrological regime of navigable water courses in Belgium: Subreport 1 - Literature review on climate research", Technical report, Waterbouwkundig Laboratorium and KU Leuven, 2011.

Van Hoey, S., Vansteenkiste, T., Pereira, F., Nopens, I., Seuntjens, P., Willems, P. and Mostaert, F. "Effect of climate change on the hydrological regime of navigable water courses in Belgium: Subreport 4 - Flexible model structures and ensemble evaluation", Technical report, Waterbouwkundig Laboratorium and KU Leuven, 2012

van der Velde, Y., de Rooij, G. H. and Torfs, P. J. J. F. "Catchment-scale non-linear groundwater-surface water interactions in densely drained lowland catchments", *Hydrology and Earth System Sciences* (13), 2009, pp. 1867 - 1885.

Wade, A., Durand, P., Beaujouan, V., Wessel, W., Raat, K., Whitehead, P., Butterfield, D., Rankinen, K. and Lepisto, A. "A nitrogen model for European catchments INCA, new model structure and equations", *Hydrology and Earth System Sciences* (6 (3)), 2002, pp. 559-582.

Wanders, N., Hendriks, D. and van der Velde, Y. "Combined groundwater – surface. LGSI model report for Drentsche Aa", Technical report, Deltares, 2011.

Willems, P. "Waterloopmodellering", ACCO Leuven, 2013.

Willems, P. "Parsimonious rainfall-runoff model construction supported by time series processing and validation of hydrological extremes", 'EGU General Assembly, 2010.

Willems, P. "A time series tool to support the multi-criteria performance evaluation of rainfall-runoff models", *Environmental Modelling & Software* (24), 2009, pp. 311 - 321.

Willems, P., et al. "Methodologie ter hydrologische modellering van Vlaamse hydrografische (sub)bekkens en de afleiding van maatgevende hydrogrammen", Technical report, KU Leuven Afdeling Hydraulica i.s.m. IMDC, 2002.

Willems, P. "Probabilistic immission modelling of receiving surface waters", Doctoral dissertation, KU Leuven Faculty of Engineering, 2000.

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