Master thesis

COMPARISON OF THE EFFECTS OF NATURE-BASED SOLUTIONS ON URBAN RUNOFF IN KIGALI USING DIFFERENT PARAMETRISATIONS

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Summary

Many cities in the world face rapid and unsustainable urban developments, increasing the prevalence of paved surfaces. The combined effect of urbanisation and climate change cause the rainwater peak discharges and thus the number of flooding events to increase over time. Therefore, there is a need for applying Nature-Based Solutions (NBSs) which complement the more traditional grey flood reduction measures - because of their ability to adapt to changing environmental conditions. The capital city of Rwanda, Kigali, is a city facing unsustainable urban developments. As a results, numerous urban flood events have occurred over the past few decades. The World Bank is actively investigating the implementation of NBSs in the city. Previously, the hydrological wflow Simple Bucket Model (SBM) has been used to estimate the effects of NBSs on the urban runoff in Kigali. This approach is referred to as the old implementation in this study. The effects computed by the old approach are uncertain, because of the lack of quantitative data and challenges to parametrise NBSs.

Hence, the aim of this research is to compare the effects of NBSs on urban runoff simulated with the old NBS implementation into wflow-SBM and a more physically based NBS implementation, such that it also benefits NBS studies in other catchments where different hydrological models are used. Almost thirty NBSs are included in this study.

First, interviews are conducted to discover the strengths and possible improvements of the old implementation. The expected effects of NBSs on hydrological processes are described, to cluster all NBSs into groups that can be implemented using the same model parameters. Next, sensitivity analyses of the model parameters and fluxes are used to derive a suitable implementation for each NBS-cluster. All individual NBSs are then parametrised by translating hydrological changes to model parameter value changes.

Some limitations of the old implementation, that are improved, include the use of unrealistic Manning values, the omission of infiltration, and the parametrisation of surface runoff storage (e.g., ponds and retention areas) and small-scale NBSs. The sensitivity analyses of the model parameters and fluxes show that infiltration is a hydrological process that is relevant for the peak runoff and should be included when determining the effects of NBSs. The parametrisation of surface runoff storage NBSs is improved by using the function for paddy areas instead of increasing the branch trunk storage (Swood). After the implementation of NBSs, the individual and combined effects are obtained in terms of the delay of the peak runoff, and reductions of the maximum runoff and peak runoff volume.

The unit effects of NBSs in Kigali are updated and the possibilities of the wflow-SBM concept for implementing NBSs are assessed. In addition, more insight is gained in the effectiveness of NBSs in different types of urban catchments. The most important conclusion is the old implementation is likely to underestimate the effects of NBSs. This is suggested because infiltration is included in the new implementation and the parametrisation of surface runoff storage NBSs is improved. In addition, it is shown that the location of a NBS mainly determines its effects. Individual NBSs can increase or decrease the maximum runoff depending on where they are implemented in both approaches. NBSs are especially effective in preventing flood hazards in Mpazi, which is a sub-catchment consisting of steep slopes and paved areas. In this sub-catchment, combining all NBSs could lead to a 90% reduction of the maximum runoff in the new approach.

To improve the accuracy of the obtained NBS effects, it is recommended to obtain local measurements of the runoff effects of NBSs in Kigali and to do further research to the negative effects of individual NBSs. Since the results are not validated and location specific, the results of this study should not be used as generalised effects of NBSs. However, the methodology can be used to assess NBSs in other catchments using different physically based hydrological models.

Keywords: Nature Based Solutions, hydrological modelling, wflow-SBM, parametrisation, runoff reduction, urban flood management, Kigali, hydrological processes, climate change, urbanisation

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List of abbreviations

Abbreviation	Details
AST	Adaptation Support Toolbox
CN	Curve Number
DEM	Digital Elevation Model
GAML	Green-Ampt Mein_Larson
GCM	General Circulation Models
ISRIC	Internation Soil Reference and Information Centre
ITCZ	Intertropical Convergence Zone
LAI	Leaf Area Index
LDD	Local Drainage Direction
LULC	Land Use Land Cover
NBS	Nature-Based Solution
NOAA	National Oceanic and Atmposheric Administration
RMA	Rwanda Meteorological Agency
RWB	Rwanda Water Resources Board
SBM	Simple Bucket Model
SCS-CN	Soil Conservation Service Curve-Number
Sl	Specific leaf storage
SRES	Spectral Report of Emission Scenarios
Swood	Tree trunk storage
SWOT	Strengths-Weaknesses-Opportunities-Threats
WGS1984	World Geodetic System 1984
WRB-IUSS	World Reference Base-International Union of Soil Sciences

1. Introduction

1.1. Research motive

Many cities in the world face a rapid and unsustainable urban development, resulting in the prevalence of paved surfaces (World Bank, 2021). Paved surfaces prevent rainwater from infiltrating into the soil and have a low surface roughness. This causes a rapid rainfall-runoff response, which could lead to urban flooding (Lee et al., 2018). The rainwater peak discharges and thus the number of flooding events are expected to increase over time, because of urbanisation and climate change (Lee et al., 2018). Therefore, there is a need for sustainable and effective flood management (World Bank, 2021). Applying Nature-Based Solutions (NBSs) complements the more traditional grey flood reduction measures (curb-gutter-pipe network) because of their ability to adapt to changing environmental conditions, while also improving the urban quality and strengthening the livelihoods in urban neighbourhoods (IUCN, 2021; Seddon et al., 2020).

Studying the application of NBSs in African cities is relevant as studies show that the urbanisation rate is significantly higher in Africa than in other places across the globe during the last decades (Acheampong & Ibrahim, 2016). In this research, Kigali, the capital city of Rwanda, is studied. Near Kigali, numerous urban flood events have occurred over the past few decades (World Bank, 2021). The World Bank is actively investigating the implementation of NBSs near the city. Urban development plans for Kigali predict the city to have grown significantly by 2050 (World Bank, 2021). The originally forested hill slopes are being transformed into built-up areas, which results in an increased and high velocity rainwater runoff towards the low lying wetlands (World Bank, 2021). Traditional grey flood mitigation measures are no longer achieving desirable results as they are unable to adapt to the changing environment (Seddon et al., 2020; Vojinovic et al., 2021). Literature suggests that the effectiveness of NBS is usually limited to smaller rainfall events (Vojinovic et al., 2021). For extreme events, a combination of traditional grey measures and NBSs are required (Vojinovic et al., 2021).

The effects of NBSs in Kigali are investigated in this study using a distributed hydrological model. The use of a distributed hydrological model allows NBSs to be implemented at relevant spatial scales and suitable locations. The distributed wflow Simple Bucket Model (SBM) is used in this study because a fully calibrated model is available for the city of Kigali (Gebremedin et al., 2020) and therefore allows the focus of the research to be on the implementation of NBSs.

1.2. State-of-the-art

NBSs are defined as "actions that protect, sustainably manage and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity" (IUCN, 2021). The hydrological performance of NBSs is often evaluated in terms of the reductions of maximum runoff and runoff volume at the urban catchment scale (Qiu et al., 2021; Zahmatkesh et al., 2015). Most studies investigating locations of NBSs do not use hydrological models. Instead, the implementation of NBSs to improve storm water management is mostly based on general estimated effects of NBSs by expert judgement and landscape characteristics (Asare, 2021; Guerrero & Haase, 2018; Turconi et al., 2020). In a study by Asare (2021), these landscape characteristics include the land cover, closeness to rivers, soil texture, elevation, and slope. This method tends to work quite well for small-scale NBSs (i.e. buildings, streets or roofs), but is less reliable for catchment scale NBSs, as those need to be connected to the hydrological system to assess their effectiveness (Ruangpan et al., 2020). Therefore, there is a need for using hydrological models to quantify the effects of large scale NBSs.

However, even the most complex distributed models can only approximate the response of a real catchment (Shaw et al., 2011). The model outputs should always be expected to be associated with some error. Modelling studies have been conducted for individual NBSs at a local scale (scale at which a single measure is investigated under site-specific conditions (Haghighatafshar et al., 2018; Kumar et al., 2021)). Assessing the effectiveness of NBSs on a catchment scale using generalised models has proven to be inconclusive and impractical (Blanc et al., 2012; Metcalfe et al., 2017). Major issues are the uniqueness of each catchment, scaling of small-scale NBSs and the money and time required to set up a catchment's model (Blanc et al., 2012). However, several NBS-studies using hydrological models have been conducted. These studies use different hydrological models, such as TOPMODEL, Multi-Hydro and the SWAT-model (Her et al., 2017; Metcalfe et al., 2017; Qiu et al., 2021). Each study uses a different NBS parametrisation. Research shows that model configuration strongly influences the hydrological performance of NBSs in the model (Her et al., 2017).

The SBM concept is a modified version of the TOPOG-SBM concept, which was originally developed for steep slopes and thin soil layers (Hagen et al., 2020; Vertessy & Elsenbeer, 1999). The model considers the response of different processes and fluxes to precipitation including interception, evapotranspiration, infiltration, percolation, horizontal groundwater flow, capillary rise and surface runoff (Hagen et al., 2020). The model uses the kinematic wave approach for runoff routing, which assumes that the topography mostly controls the water flow. This assumption is valid for a steep terrain, but should be questioned for a flat terrain (Schellekens, 2019). Since Kigali is located in a relatively hilly area, this assumption is assumed to be valid. Wflow-SBM is suitable for simulating river flows of large catchments. However, due to its relatively low spatial resolution (90x90m for the Kigali model), the Kigali model is less accurate for small sub-catchments and interventions (Ramirez Morales et al., 2015). As part of the NBS analysis project of the World Bank in Kigali, HKV has implemented NBSs in wflow-SBM by classifying them into three types (World Bank, 2021):

1) measures that store water;
2) measures that increase the roughness on the surface;
3) measures that increase the roughness in the drains.

Each type is then represented by one wflow-SBM parameter. HKV's study has shown that the potential combined effect on the peak discharge reduction is between 15 and 30% depending on the characteristics of the sub-catchment (World Bank, 2021**).** The effectiveness of different types of NBSs depend on the location where they are implemented (World Bank, 2021). NBSs are most effective when implemented in originally paved areas. Storage measures are most effective in upstream areas, while NBSs in the drains are most effective in downstream sections (World Bank, 2021). It was found that storage measures tend to become less effective with more rainfall (World Bank, 2021)**.**

1.3. Knowledge gap

The main knowledge gap in this field of research is regarding the parametrisation of NBSs in catchment scale hydrological models. In HKV's study, the model parameters and resolution proved impractical for the implementation of NBSs (World Bank, 2021)**.** Their implementation of NBSs is simplified as it only uses three parameters (World Bank, 2021) and therefore, its accuracy should be questioned. Literature shows that there is no generalised methodology for parameterising NBSs since all hydrological models use different parameters (Blanc et al., 2012; Metcalfe et al., 2017). In addition, the quantitative effects of NBSs are highly uncertain (Asare, 2021). Therefore, the use of hydrological models is often avoided in NBS-related studies (Metcalfe et al., 2017). Using hydrological models for catchment-scale NBS-studies can help to quantify the effects on urban runoff. A hydrological model can be used to substantiate why NBSs should be applied in certain areas, which is relevant for convincing relevant stakeholders (Ruangpan et al., 2020). This research builds on HKV's findings. It attempts to find a more physically based parametrisation, such that it also benefits NBS-studies using different hydrological models.

1.4. Aim and research questions

The main objective of this research is to compare the effects of NBSs on urban runoff simulated with the current NBS implementation and an innovative physically based implementation into wflow-SBM.

This study should not only benefit the implementation of NBSs in Kigali using wflow-SBM, but also other (urban) catchments represented by different hydrological models. Since many hydrological models use similar hydrological concepts, a physically based NBS implementation potentially aids NBS-analyses in other catchments using different physically based hydrological models.

The main objective of the research is split up into five smaller research questions, which are listed below. The approach for implementing NBSs developed in this report is referred to as the new approach and the approach previously used by HKV is the old approach

1. What are the limitations of the old implementation and the opportunities for a new implementation of NBSs into wflow-SBM affecting the simulated urban runoff?
2. To what extent can NBSs be clustered using common effects on hydrological processes such that each cluster can be represented by the same model parameters?
3. What is a more physically based implementation for the clustered NBSs?
4. What are the individual and combined effects of NBSs on urban runoff using the new implementation devised in Q3?
5. What are the differences in individual and combined effects of NBSs on urban runoff between the old and the new implementation for different sub-catchments and rainfall forcings?

An overview of all major steps in the research process is shown in the flowchart in Figure 1. This figure also includes the main result of each research question, which are used as input for the next research question.

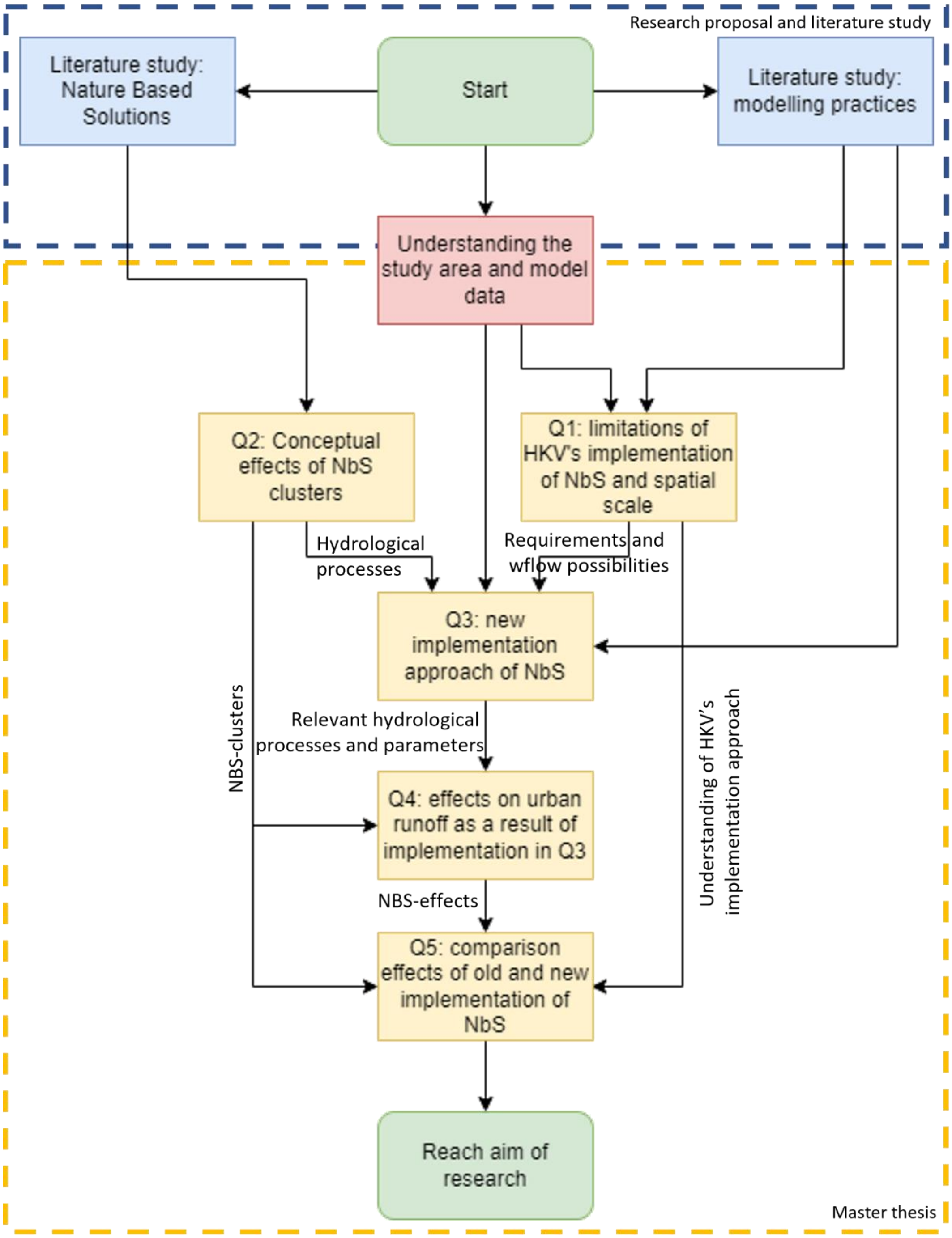

Figure 1 - flowchart of research questions

1.5. Thesis structure

The study is presented in six chapters. Chapter 2 focusses on the study area and modelling approach. Chapter 3 specifies the research methods and chapter 4 presents the results. In chapter 5, these results are interpreted and discussed. The study's conclusion and recommendations are presented in the final chapter.

2. Study area and modelling approach

In this chapter the characteristics of the study area are described. Also, the hydrological processes included in the wflow-SBM concept are explained. In addition, the required data for running the model are provided.

2.1. Study area

Rwanda is among the least developed countries in the world (World Bank, 2021). Its capital city, Kigali, stretches across several hills and wetlands. The wetlands are used for agriculture or industry. Some of them are currently being restored (World Bank, 2021). Within the city boundaries, there are multiple mountains, of which Mount Kigali is the highest. Kigali is located within the Nyabugogo catchment. The catchment is named after the Nyabugogo river, which flows through Kigali from the north to the west and is the main mechanism for draining storm water from the city (Nhapi, 2011). A satellite image of Kigali is shown in Appendix I.

2.1.1. Spatial planning

The combined effect of the hilly terrain, soil conditions, rainfall, unsustainable land management, urbanisation and other factors results in extensive erosion, which induces the risk of landslides in parts of the city (World Bank, 2021). Due to this risk of landslides and some environmental and planning restrictions, only half of the city area can be built upon (World Bank, 2021). However, despite these spatial restrictions, Kigali has expanded significantly over the past years and is even considered as one of the fastest growing cities in Africa. Recent studies even predict the current population to have doubled by 2050 (World Bank, 2021).

2.1.2. Rainfall

Rwanda lies in the tropics and is close to the equator. It has two rainy seasons, because its annual rainfall rate is influenced by the Intertropical Convergence Zone (ITCZ) (Byrne et al., 2018). The first season occurs from March to May and is characterised by long storm durations (World Bank, 2021). The second season occurs from September to December, and typically has short storm durations (World Bank, 2021). Urban flooding and extensive soil erosion related to storm water typically occurs during short and intense rainfall events. The rainfall patterns are schematised in Figure 2.

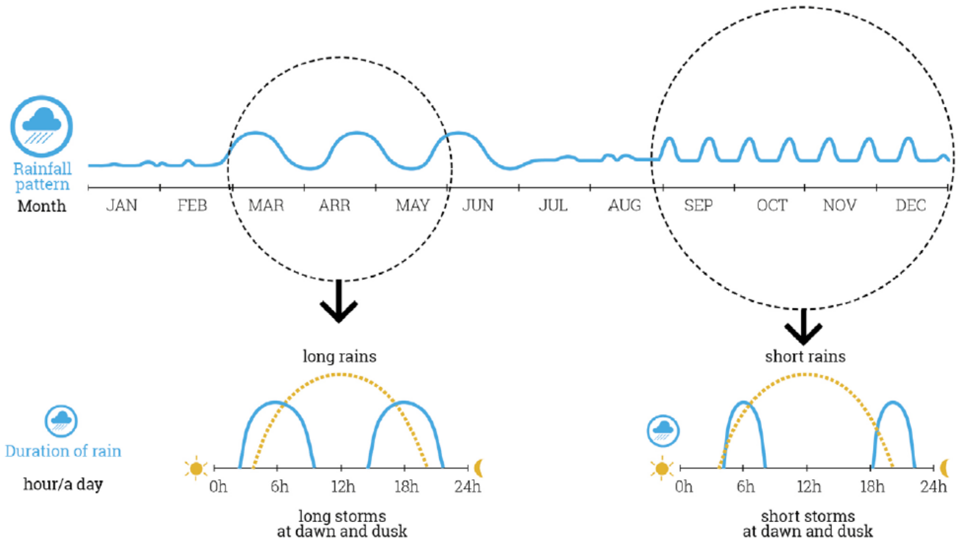

Figure 2 - rainfall patterns and durations during different seasons for Kigali (World Bank, 2021)

Statistical downscaling of a General Circulation Models (GCMs), HadCM3, estimated the total amount of precipitation to remain relatively constant for Kigali as a result of climate change using the predictors A2 and B2 of the Spectral Report of Emission Scenarios (SRES) (Rukundo & Dogan, 2016; WMO & UNEP, 2000). However, it is also suggested that the heavy rainfall events can become more frequent in the city and that urban flooding is more likely to occur (Tsinda et al., 2019). Though this development should be taken into account, studies have shown that land use change impacts (e.g. urbanisation) predominate the climate change impacts at the evaluation of floods in Kigali (Asare, 2021; Rukundo & Dogan, 2016).

2.1.3. Sub-catchments

The Nyabugogo catchment consists of 45 sub-catchments. A few sub-catchments are used to investigate the effects of NBSs in this study. Firstly, because considering the full catchment is not computationally efficient. Secondly, because the local effects of NBSs are expected to be less pronounced in downstream sub-catchments since water has already travelled a long way and may be affected by upstream effects. Therefore, three upstream sub-catchments are selected, which depend on precipitation and not on inflow from other catchments. The selection criteria for these catchments are as follows and shown in Figure 4.

- The sub-catchments have different areal characteristics (land use, elevation difference and soil type).
- The sub-catchments lie entirely within the boundary of the city of Kigali. Only these sub-catchments are representative, because no NBSs are implemented outside of the city boundary.

It is decided to select the Rufigiza, Kavure and Mpazi catchments, corresponding to the catchments numbered 12, 17 and 45 in Figure 3 respectively. These catchments are entirely located within the city boundaries and have different areal characteristics based on Figure 4. The characteristics of these catchments are described in Table 1. Some pictures taken during a field trip in Mpazi are shown in Appendix I. These pictures show the large, paved areas, hillslopes and unplanned settlements.

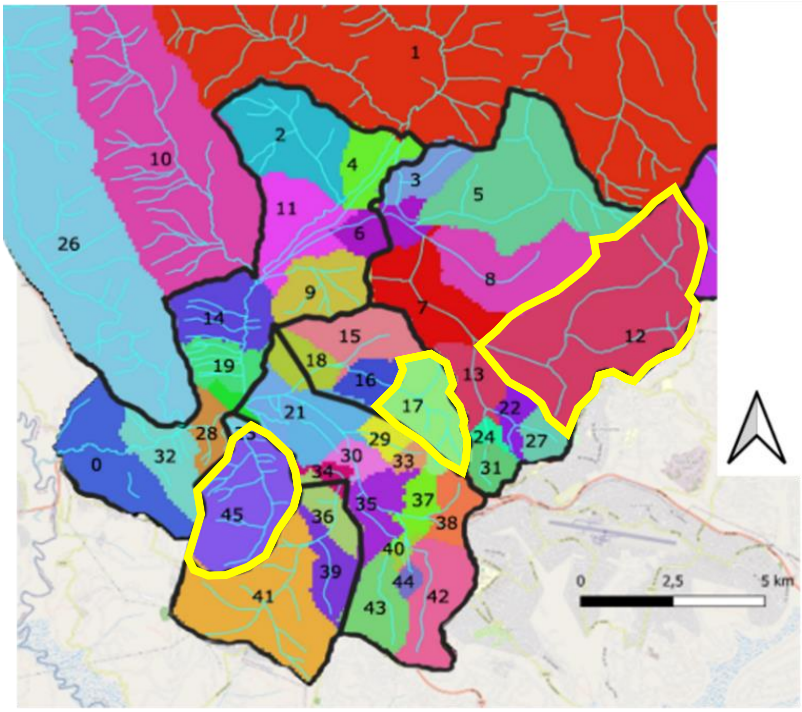

Figure 3 - numbered sub-catchments of the Nyabugogo catchment (selected sub-catchments marked in yellow)

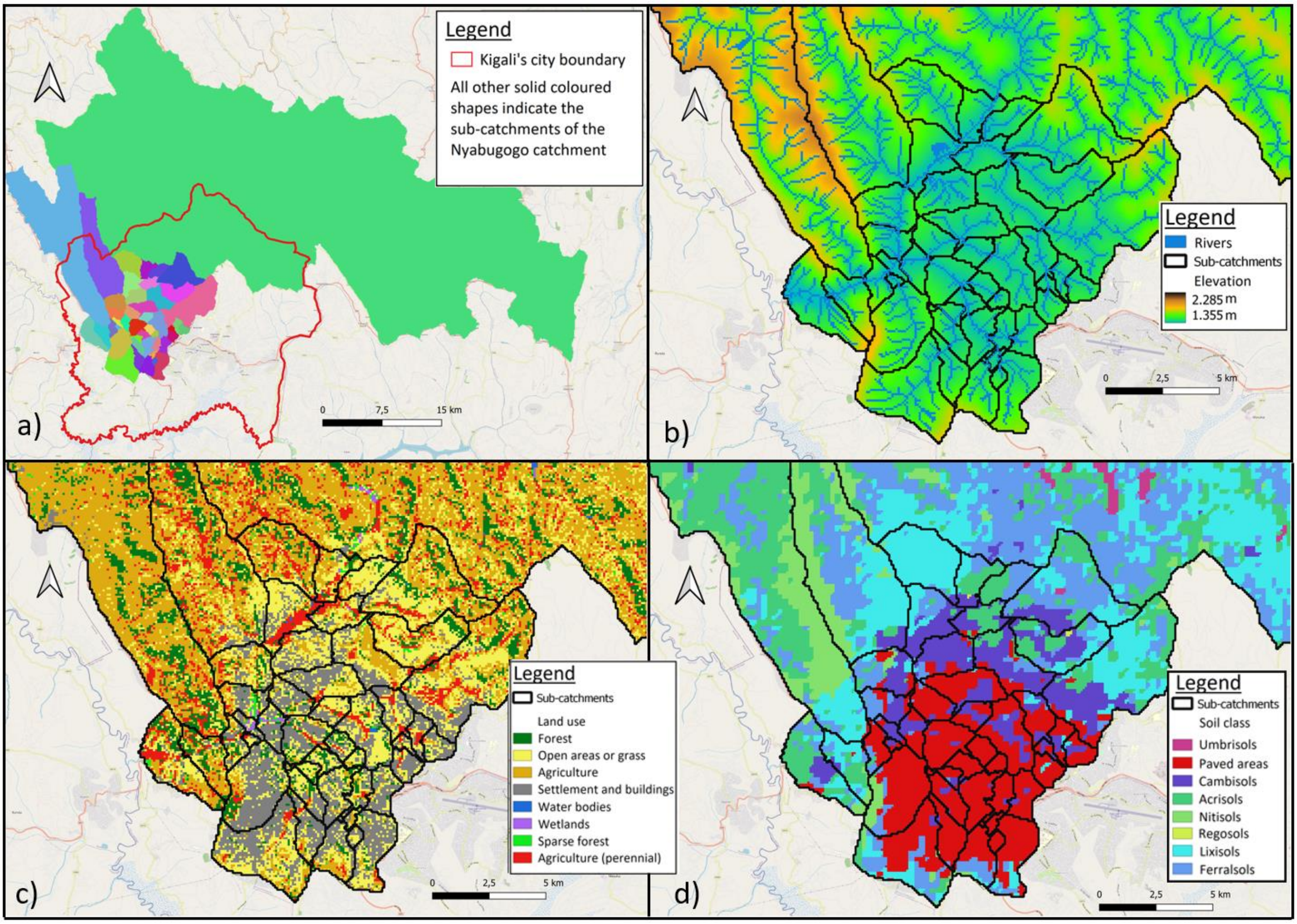

Figure 4 - maps of the different characteristics of the sub-catchments of the Nyabugogo catchment: a) Kigali's city boundary, b) Digital Elevation Map (DEM) and rivers, c) Land use, D) Soil classification (ISRIC, 2021; WRB-IUSS, 2014)

Table 1 - characteristics of three sub-catchments considered in this study

ID	Name	Area [km^2]	Elevation difference [m]	Relative rainfall volume [-]	Land uses	Reference soil group
12	Rufigiza	19.37	446	1.001	Mainly open areas or grass, but also settlement, forest, sparse forest, and agriculture (seasonal and perennial)	Cambisols, lixisols, acrisols, paved
17	Kavure	5.02	109	1	Mainly open areas or grass, but also perennial agriculture, settlement, forest, and a water body	Mainly paved, but also cambisols and ferralsols
45	Mpazi	7.93	460	1.064	Mainly settlement, but also forest, agriculture (seasonal and perennial) and open areas and grass	Mainly paved, but also ferralsols and regosols

2.2. Modelling approach

An overview of the hydrological fluxes incorporated in the wflow-SBM concept is shown in Figure 5. In response to precipitation, water can be intercepted by canopy, infiltrate in the soil or end as surface runoff. Evaporation occurs through transpiration, and soil and open water evaporation. The kinematic wave approach is used to route channel, overland and lateral subsurface flow. The drainage direction for each time step is fixed and is determined by a Local Drainage Direction (LDD) map.

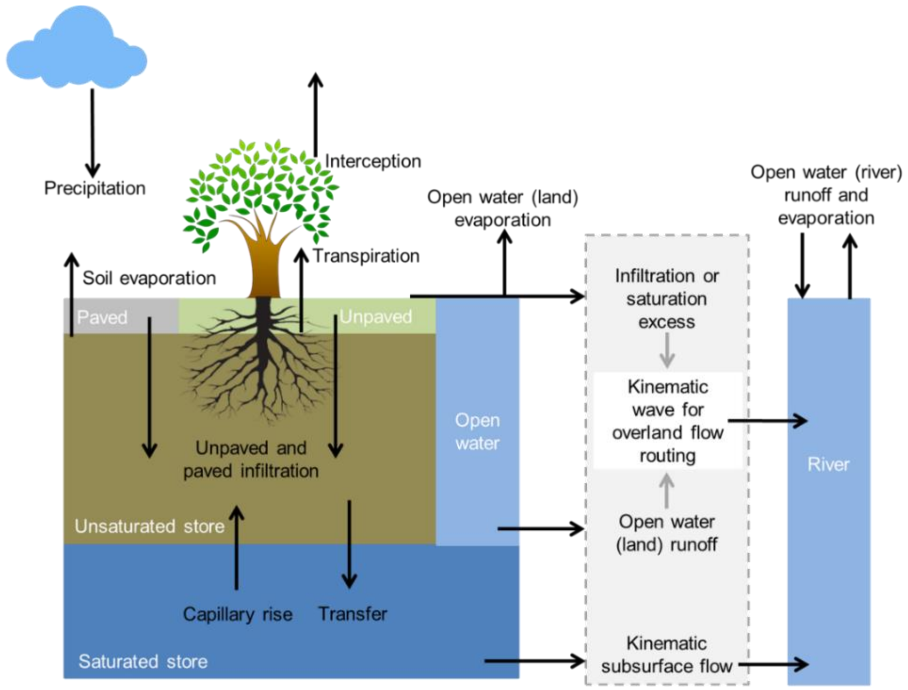

Figure 5 - overview of the wflow-SBM concept (Schellekens, 2019)

2.2.1. Model calibration

The calibrated model of the Nyabugogo catchment is used in this study. The calibration is performed by Deltares but was challenging. Reliable water level data is only available at Nemba, which is a station downstream of Kigali (Gebremedin et al., 2020; Russell, 2021). Therefore, this station provides little insight into how the upstream catchments generate runoff. The Rwanda Water Resources Board (RWB) mentioned that the urban upland areas quickly generate runoff, flooding urban wetland and inundating roads. Temporary lakes can form in the wetland and drain in a matter of hours. Since other data suitable for calibrating the model was unavailable, the model was calibrated such that this response is shown (Gebremedin et al., 2020). This was achieved by reducing the quick subsurface runoff and increasing the leakage to deeper groundwater (Gebremedin et al., 2020). So, a larger fraction of effective rainfall is infiltrating to groundwater and not reappearing in the river channel. Due to calibration, the Manning surface roughness and infiltration capacity are unrealistically high.

Validation at the Nemba station shows that the model is more accurate for low flows than for high flows (Gebremedin et al., 2020). However, since Nemba is just upstream of a narrow bridge, the water level data are assumed to be inaccurate at high flows due to flooding (Russell, 2021). Given these constraints, it was concluded that the hydrological model is performing as good as can be achieved with the available data (Gebremedin et al., 2020).

2.2.2. Temporal scale and model initialisation

The model initialisation uses a 1-day timestep, which matches the input rainfall data. Following best practices, the model is initialised by a run of one year to establish a representative soil moisture and groundwater state (Gebremedin et al., 2020). The model is used to simulate storm events of 10 days (event mode), which have a 10-minute time step and result in water level and discharge outputs for every 10 minutes at 45 outlets of main tributaries (World Bank, 2021). All other model variables can also be saved for all grid cells and timesteps. The storm event is simulated in January. Since Kigali lies in the tropics, the exact timing of the simulation is of minor importance because there is little seasonal variability in the characteristics of the vegetation.

2.2.3. Spatial scale

The wflow-SBM concept is a fully distributed model using orthogonal grids. The Kigali model is set up with a 0.000833 degree grid resolution (corresponding to approximately 90m pixels) in the World Geodetic System 1984 (WGS1984) coordinate system (World Bank, 2021). For the implementation of NBSs smaller than the grid size of the model, it would have been useful to obtain a finer resolution. However, at a higher resolution, the kinematic wave approach and non-linear processes operate differently (Aerts, 2021). This would require re-calibration of the model. Given the lack of data, the grid size is not reduced in this study.

2.2.4. Rainfall data

Modified rainfall data from the original Nyabugugo model is used in this study. Three sub-catchments are extracted, in which theoretical rainfall events are simulated with return periods of two and 100 years. The cumulative rainfall sum during the simulated period for a return period of two years in Figure 6 (left). When comparing this sum to the cumulative rainfall sum for a return period of 100 years in Figure 6 (right), it is shown that there is some spatial variation in the total rainfall in the catchment. However, there is no spatial variability in the precipitation pattern, such that the maximum precipitation is received at the same time in all grid cells. A typical precipitation event for a period of 10 days is shown in Figure 7.

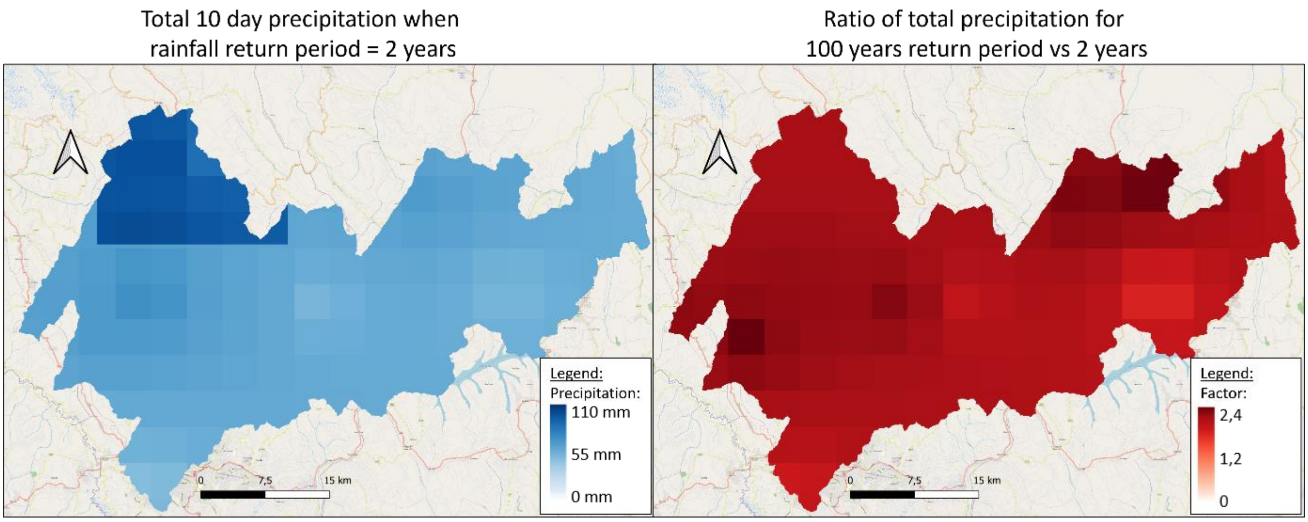

Figure 6 – cumulative precipitation sum in Nyabugogo catchment for a return period of two years (left) and the corresponding ratio of cumulative rainfall when the return period is 100 years to when it is two years

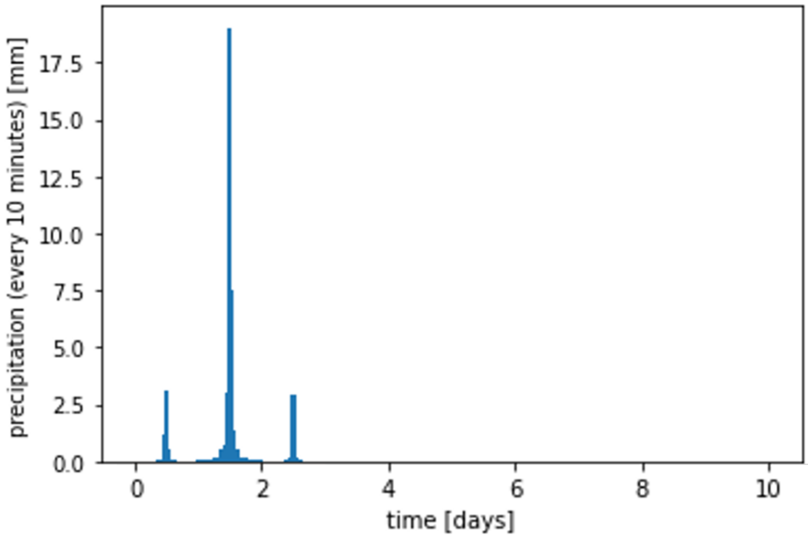

Figure 7 – precipitation data at the city centre of Kigali used by the model

Figure 7 shows that three narrow precipitation peaks are simulated during a period of 10 days. The second precipitation peak has the highest intensity.

2.2.5. Methods for calculating hydrological fluxes

The wflow-SBM concept is physically based, meaning that it is based on scientific principles of energy and water fluxes. The simulated runoff is determined by calculating the relevant hydrological fluxes. The hydrological processes included in the wflow-SBM concept and relevant to this study are shown in Table 2. Schellekens (2019) discusses the methods for calculating all hydrological fluxes and the methods in Table 2 in more detail.

Table 2 - methods used by wflow-SBM for calculating the hydrological fluxes

Hydrological process	**Method**
Infiltration	Vertessy's approach
Interception	Analytical Gash model and Rutter's numerical model
Overland, channel and subsurface flow	Kinematic wave approach

2.2.6. Other input data and model parameters

The other input data to simulate the runoff in the selected catchments are described in Table 3 below:

Table 3 - main input data of the Wflow model of Kigali (Gebremedin et al., 2020)

Type of data	**Provided data**
Meteorological	Potential evapotranspiration, temperature.
Terrain	Land use, Digital Elevation Map (DEM), slope characteristics of rivers, lakes & gauges, LDD, Manning roughness.
Soil	Paved fraction, vertical and lateral saturated conductivity, saturated water content, infiltration capacity of paved and unpaved areas.
Vegetation	Rooting depth, max. tree trunk storage (Swood), Leaf Area Index (LAI), Specific Leaf storage (Sl).

An overview of the considered wflow-SBM parameters driving each hydrological process is given in Table 4 (Schellekens, 2019). These parameter values are obtained either by calibration or by land use characteristics.

Table 4 – wflow-SBM parameters driving each hydrological process of this study and their meanings

Hydrological process	Wflow parameter	Description
Interception	Swood	Amount of water that can be stored in the woody fraction of vegetation.
	Sl	Specific leaf storage, amount of water that can be stored on the leaves of vegetation.
	LAI	Monthly average Leaf Area Index which is a measure of the total green (leaf) area per unit ground area. This parameter is also relevant to the soil evaporation.
Infiltration	InfiltCapSoil	Maximum infiltration rate for non-compacted soil.
	InfiltcapPath	Maximum infiltration rate for compacted soil.
	KsatVer	Saturated hydraulic conductivity of the store at the surface.
	M	Soil parameter which determines the decrease of vertical saturated conductivity with depth.
	PathFrac	Fraction of paved area per grid cell.
Transpiration	RootingDepth	Rooting depth of vegetation.
Runoff by rivers/drains	N_River	Manning value for the kinematic wave function for river flow.
Surface runoff on land	N	Manning value for the kinematic wave function for overland flow.
Open water evaporation	PET (meteorological forcing)	The open water evaporation is equal to the potential evapotranspiration whenever the LandUse is open water.

2.2.7. NBSs implemented into wflow-SBM

Table 5 shows all the NBSs that were implemented into wflow-SBM by HKV and their ID's.

Table 5 - list of NBSs for Kigali and their ID's (World Bank, 2021)

NBS-ID	NBS	NBS-ID	NBS
A1	Forest transition	**D3**	Water retaining public space
A2a*	Contour planting (forest and open space)	D3.1*	Green spaces
		D3.2*	Connecting ditch
A2b	Contour planting (agricultural areas and housing areas)	**D4***	Slope Park (Combine with H2)
A3	Green urban parks	**D5**	Green integrated Drain
A3.1*	Park landscape	D5.1*	Footpath
A3.2*	Vegetated pond	D5.2*	Vegetated swale
A4*	Forest protection/ demarcation	D5.3*	Vegetated slope
B1	Integrated road profile / Green blue spine	**D6**	Gabions
B2	Integrated neighbourhood drain	**E1**	Constructed wetland park and edge
B2.1*	Footpath concrete	**E2***	Demarcation wetland (protection)
B2.2*	Stone pavement vegetated	**E3***	Integrated drain landscape park

B3a	Water storing playground	**E4***	Stepped landscape gradient
B3b	Water storing playground (apply 70%)	**E5***	Gatenga Valley water retention
B4	Street profile regulations /zoning	**E6***	Forest cliff edge
B5*	Water storage tank	**F1**	Bioswales and water buffer
C1a	Water storing pond	**F2a***	Terraced Park
C2a*	Green roofs	**F2b***	Gabions stabilize
C3a*	Green façade	**F3a**	Stepped footpath with planters
(C1-3) b	Water storing pond + green roof + green façade (in urban upgrading area)	**F3b***	Climbing plants with arches
C4	Linear Park	**F4**	Stepped drain
C4.1*	Rain garden	**G1a**	Multifunctional sports field
C4.2*	Water retention area	**G1b**	Multifunctional sports field (apply 30%)
C5	Integrated road profile	**G2a***	Wall with planter boxes (urban upgrading areas)
C5.1*	Green swales	**G2b***	Wall with planter boxes (parks, public facilities, low and medium density residential areas)
C5.2*	Permeable Pavement		
C6	Permeable Parking	**H1**	Contour planting (with trenches)
D1a	Guidelines private water storage	**H2**	Reforestation (Combine with D4)
D1b	Guidelines private water storage (lower density)	**H3**	Water storage ponds along road
D2a*	Water storing walls	**H4***	Rain tank and gutter
D2b*	Water storing walls (lower density)	**H5***	Green blue development standard

* Indicates measures that have been excluded from the analysis by HKV, either because they are assumed to have a negligible effect on the peak runoff or because they are part of a ‘parent’ NBS (indicated by grey text colour).

3. Methods

3.1. Research question 1 – limitations and opportunities

What are the limitations of the old implementation and the opportunities for a new implementation of NBSs into wflow affecting the simulated urban runoff?

Given an understanding of the study area and basic knowledge of the wflow-SBM concept, the limitations of the current implementation of the NBSs are analysed. Since not all the technical details of the NBS implementation have been reported, this is done by interviewing the developers of the model (Deltares), the implementers of NBSs into the model (HKV) and other wflow users.

The aim of these interviews is to gain a thorough understanding of the current implementation of NBSs, such that all steps can be reproduced. The interview protocol, questions and transcripts are included in Appendix B (Jacob & Furgerson, 2015). After doing the interviews, a Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis is performed (Gürel & Tat, 2017). This allows the research question to be answered.

3.2. Research question 2 – hydrological effects of NBS clusters

To what extent can NBSs be clustered using common effects on hydrological processes such that each cluster can be represented by the same model parameters?

Defacto has composed a set of potentially suitable NBSs for Kigali (see Table 5) (World Bank, 2021). All these NBSs influence the hydrological cycle. This research question focuses on providing a qualitative description of the effects of the different NBSs on the hydrological processes that are included in the wflow-SBM concept. Only the hydrological processes influenced by the presence of NBSs are considered. For example, if a NBS increases the infiltration capacity, the groundwater processes will be affected, but only indirectly. Therefore, it has been decided to exclude all processes related to the subsurface, except infiltration, from this analysis (see Figure 5). Note that surface water retention is not included in Figure 5, but that it is included as a relevant process in this analysis. This is because surface water retention is currently not included in the wflow-SBM concept.

The conceptual effects of NBSs on hydrological processes are obtained either by reviewing literature or by using hydrological equations and corresponding look-up tables. When using hydrological equations, not all parameter values in an equation need to be known to conceptually describe the effects of NBSs on a hydrological process.

In the next section, the hydrological processes that are directly related to the implementation of NBSs are explained. The equations and look-up tables used for the relevant hydrological processes are also described. If using literature or equations proves to be infeasible for a NBS, an approximation of the hydrological effect is made using my own understanding and knowledge of the relevant NBSs.

Interception

Interception occurs when precipitation does not reach the ground, because it stopped by vegetation (Van der Ent et al., 2014). The proportion of the precipitation that is intercepted generally increases with vegetation density (NOAA, 2021). Both crops and larger canopy trees can cause interception. The modified Rutter model states that interception is proportional to increasing LAI and Sl (Rutter et al., 1975; Schellekens, 2019). Table A- 1 shows how Sl and the storage capacity of the woody fraction of vegetation ($C_{max,wood}$) are related to land cover. In addition, the Curve Number (CN) is also an indication of the potential interception, as they are inversely proportional (United States Department of Agriculture, 1986). Relevant values for CN for different cover types, hydrological soil groups and hydrological conditions can be obtained from Table A- 5. Table A- 6 describes the characteristics of the different hydrological soil groups.

Infiltration

Infiltration is the process of water entering the soil (NOAA, 2021). Typically, the infiltration rate depends on many factors, including texture and structure of the soil, the initial soil moisture content, the porosity and the permeability of the soil (NOAA, 2021). The Green-Ampt Mein-Larson (GAML) equation is often used in literature to calculate the infiltration rate (Her et al., 2017). This equation states that the infiltration rate increases with increasing hydraulic conductivity. Values for the hydraulic conductivities of different soil textures can be found in Table A- 4.

Transpiration

Transpiration is the delayed biological flux, which occurs mostly during daytime (Van der Ent et al., 2014). It occurs when water inside of plants is transferred to the atmosphere as water vapour through the stomata of leaves (NOAA, 2021). Transpiration is greatly affected by the species of plants and amount of sunlight to which the plants are exposed (NOAA, 2021). Temperature, humidity, wind and soil moisture also play an important role (NOAA, 2021).

Soil evaporation

Soil evaporation occurs when infiltrated water in the soil returns to the atmosphere by evaporation (Schellekens, 2019). Vegetation generally limits the soil evaporation, as it offers shade to the soil (NOAA, 2021). In addition, soil evaporation increases with increasing soil moisture content (Schellekens, 2019).

Runoff by rivers and on land

The runoff rate in rivers and over land is mostly influenced by the slope and roughness (Schellekens, 2019). The Soil Conservation Service Curve-Number (SCS-CN) method and Manning equation can be used to quantify the runoff. The SCS-CN method suggests that runoff is proportional to CN (United States Department of Agriculture, 1986). Table A- 5 and Table A- 6 are used to obtain representative CN values.

The Manning equation is often referred to in this report. It is as follows (Manning, 1891):

$$Q = \frac{1}{n} A R^{\frac{2}{3}} \sqrt{S} \tag{1}$$

Where:

- Q is the discharge (surface or drain runoff) in m^3/s.
- n is the Manning roughness coefficient in $s/m^{1/3}$.
- A is the cross-sectional area of the channel or surface in m^2.
- R is the hydraulic radius in m.
- S is the slope in m/m.

Manning values for channels are shown in Table A- 2. Table A- 3 contains the values for overland flow.

Open water evaporation

Open water evaporation occurs when water evaporates from open water bodies, such as lakes, retention areas and ponds.

Surface water retention

Surface water retention occurs when runoff is temporarily stored, before being released or used for other purposes. Examples of surface water retention are rainwater tanks, ponds, and water squares. Note that surface water retention does not always occur in combination with open water evaporation (e.g., rainwater tanks).

Synthesis:

The final product of this research question is a table in which the conceptual effects of all NBSs on hydrological processes are provided. The common hydrological effects allow the NBSs to be clustered into groups as they can be implemented using the same model parameters. Since this table describes the effects of NBSs in terms of hydrological processes, it may also be used in other hydrological modelling studies of NBSs for a different city or modelling concept. An overview of the method described in this paragraph is shown in the flowchart in Figure 8 below:

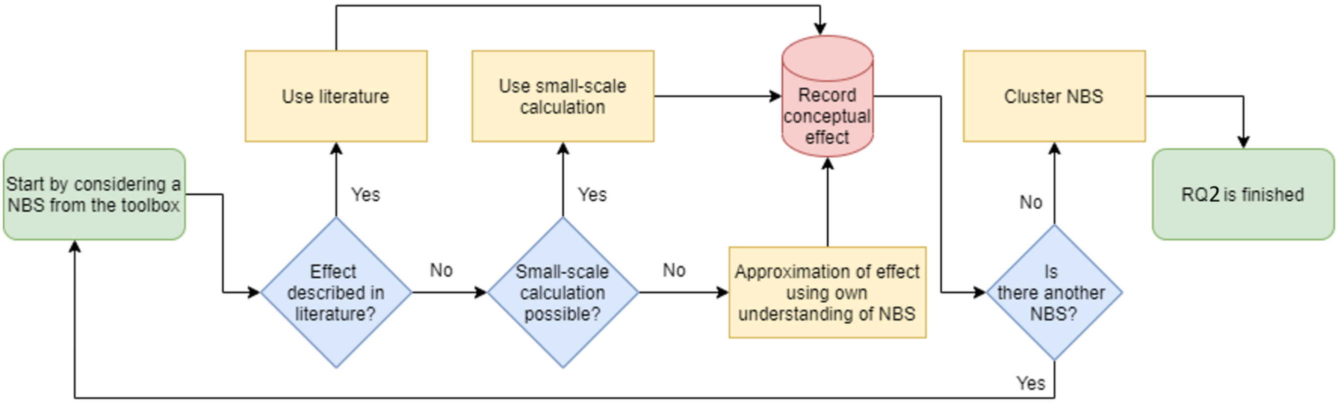

Figure 8 - flowchart of method of research question 1

3.3. Research question 3 – more physically based parametrisation

What is a more physically based implementation for the clustered NBSs?

Using the SWOT analysis and the NBS clusters, a new physically based implementation for different clusters of NBSs is derived. This is achieved by linking the hydrological processes to model parameters (see Table 4) and testing the sensitivity of the peak runoff to changes in these parameter values. Also, an additional storage layer is added to the wflow-SBM concept to aid the implementation of surface runoff storage NBSs. To identify relevant hydrological processes and corresponding parameters, several sensitivity analyses are done for the maximum runoff, runoff volume and runoff timing. Based on the results of this research question, suitable parameters to implement each NBS-cluster are proposed.

3.3.1. Sensitivity of peak flows to model parameter values

A univariate sensitivity analysis is carried out to assess the sensitivity of the modelled maximum runoff and peak runoff volume to changes in the model parameters. This is done for the different return periods of two and 100 years and the three catchments. Eight different model parameters are considered. For each parameter, all values in the model domain are decreased and increased by 10%, 25% or 100%, while keeping all other parameter values unchanged. These percentages are used so that the changes in the hydrological processes driven by these parameters are still realistic. In the case of some parameters, it was impossible to set a parameter to 0 (decrease by 100%), because this would result in a division by zero and thus in infinite values. Therefore, for these parameters, all values were only decreased by 99%. In total, 98 model simulations are done for this sensitivity analysis.

The model calculates the outflow at the downstream boundary for a time interval of 10 minutes. These runoff values are used to determine the maximum runoff, peak runoff volume and the peak timing (see Figure 9). The peak timing is the time between the start of the main rainfall event and the maximum runoff in hours. The main rainfall event is the second peak in Figure 7. The peak runoff volume is obtained by estimating the baseflow in each catchment and subtracting it. The baseflow is usually defined as the discharge without any rainfall event (Booij, 2020). In this case, it is approximated by taking the maximum runoff of all simulations, performed to assess the sensitivity to model parameters, of a sub-catchment at the timestep at which the rainfall event starts (see Table 6 below). The beginning of the runoff peak is then defined as the first runoff measurement above the baseflow. Subsequently, the flood wave ends when the runoff becomes less than the baseflow. Note that the constant discharge method is applied for the sake of simplicity, but that the baseflow is normally not constant over time (Sima, 2018). The integral of the peak runoff over time is then equal to the runoff volume.

Table 6 - baseflows for different catchments

Sub-catchment	Rufigiza	Kavure	Mpazi
Baseflow [m^3/s]	3.22	1.26	2.26

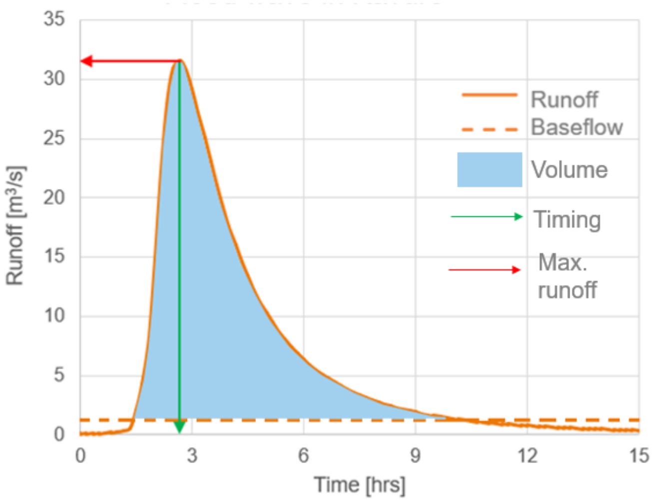

Figure 9 - illustration of baseflow, maximum runoff, peak runoff volume and timing for a flood wave in Kavure

3.3.2. Hydrological processes affecting the peak runoff

The results of Paragraphs 3.3.1 will show that some model parameters are more important than others to the simulated peak runoff. This could be used to estimate which hydrological processes are relevant to the peak runoff and which have a negligible effect. However, this could also be misleading, since not all model parameters allow values in the same range. Therefore, the average fluxes for the hydrological processes of infiltration, interception, soil evaporation and transpiration are compared to the total amount of peak rainfall. This is done for a return period of two years as well as for 100 years. Overland flow is not included in this analysis, because HKV has already proven its relevance to the peak runoff (World Bank, 2021).

3.3.3. Implementation of surface runoff storage NBSs

An interviewee suggested to implement surface runoff storage measures using a bucket on top of the unsaturated store, by adding a threshold value for surface runoff before it is allowed to flow to the next grid cell. This threshold value will act as an additional storage bucket. Infiltration and open water evaporation occur when water is in this additional storage bucket. When this bucket is full, water will overflow to the next grid cell according to the Kinematic Wave approach. The threshold values are determined for all grid cells, by approximating the increase in total storage capacity due to the surface runoff storage NBSs. The Paddy areas function of wflow-SBM is used to implement the additional storage bucket. More information about the implementation of this additional storage bucket is provided in Appendix D. The runoff in terms of its maximum, volume and timing are compared for changes in Swood and wflow_hp values. The latter is the total capacity of surface runoff storage NBSs per grid cell when the Paddy area function is applied.

3.3.4. Synthesis

Based on the results of the sensitivity analyses, the parameters, that are to be used to implement the different NBS-clusters, are listed. Using only the relevant hydrological processes for calculating the simulated peak runoff in the catchment, some clusters can be merged. For each hydrological process, the relevant parameters to implement NBSs, are listed. This list is used to construct a table in which all relevant model parameters for each cluster are listed. This is the final product of this research question and is used as a basis for Research Questions 4 and 5.

3.4. Research question 4 – effects of new implementation of NBSs

What are the individual and combined effects of NBSs on urban runoff using the new implementation devised in Q3?

Following the SWOT analysis resulting from Paragraph 3.1, the old implementation of NBSs is improved. In the previous research question, it is determined which model parameter values should be changed to implement different NBS-clusters. Each NBS within a cluster has a unique effect on the involved hydrological processes, which should be quantified. Next, these estimated changes in the hydrological processes are translated to model parameters for each NBS. The effects of NBSs on urban runoff are then simulated for different scenarios and sub-catchments.

3.4.1. Quantification of hydrological processes involved

Literature, look-up tables, small-scale calculations and substantiated assumptions are used to quantify the changes in hydrological processes due to the implementation of NBSs. In this study, only NBSs which are expected to have a significant effect on the urban runoff are considered. Detailed considerations are shown in Appendix G. For NBSs that are larger than the size of a grid cell and only consist of a single intervention, the following methods are used to quantify changes in the relevant hydrological processes:

- Infiltration – representative infiltration capacities of land uses and covers are used to quantify the infiltration capacities of NBSs. The infiltration capacity is defined as the maximum infiltration rate (Holden, 2005). Some NBSs such as permeable pavement, cannot directly be linked to land use or cover changes. The infiltration capacities of these NBSs are obtained from literature.
- Surface runoff on land – the Manning surface roughness is obtained by linking it to a land cover change (see Table A- 3). For NBSs where this is not feasible, literature or the surface slope reduction are used. In the latter case, the Manning equation is used to describe the slope change in terms of the Manning roughness coefficient (as demonstrated in Appendix C.1.)
- Runoff by rivers/drains – this depends on the Manning roughness coefficient for channel flow. Both Table A- 2 and Appendix C.1. are used to estimate the channel roughness of the NBSs.
- Surface water retention – this is based on findings in literature and substantiated assumptions. By estimating the dimensions of the storage measure, the total storage capacity is expressed as the depth per grid cell.

A couple of exceptions to this method of quantification are described below.

NBSs consisting of multiple interventions

A NBS such as a green urban park, consists of multiple interventions: a vegetated pond, urban forestry, and a green swale. For these NBSs, the estimated size of each intervention relative to the size of a grid cell is determined. Then, the hydrological effect of each intervention is quantified, both by using the methods described above and the Adaptation Support Toolbox (AST) (van de Ven et al., 2016). Representative roughness values and infiltration capacities of these NBSs are obtained by taking the weighted averages based on the relative size of each intervention. The total storage capacity is calculated as the sum of the storage capacities of all individual interventions.

Small-scale NBSs

When a NBS is smaller than the size of a grid cell, it is considered a small-scale NBS. Like NBSs consisting of multiple interventions, the estimated size and hydrological effect of the small-scale NBSs is determined. The hydrological effects in the remaining area should also be estimated. Since the NBSs are applied in an urban context, the land use of the remaining part of the grid cell is assumed to be 'Settlements and Buildings.' In the model of Kigali, the maximum paved fraction for Settlements and Buildings is 0.45 m^2/m^2, meaning that 45% of a grid cell consists of paved areas. These paved areas are assumed to be impervious. The land use of the remaining 55% is assumed to be Open areas or grass. Based on these assumptions, the infiltration capacity and roughness of the remaining area are the weighted averages of the paved and unpaved area. These remaining areas have no storage capacity.

Representative roughness values and infiltration capacities are obtained by taking the weighted averages based on the size of the small-scale NBSs. The storage capacity in millimetres per grid cell is equal to the total storage capacity of the NBSs.

NBSs in rivers and drains

Some NBSs increase the roughness in drains, channels, or rivers. For channel flow in the wflow-SBM concept, the kinematic wave approach uses the river width to determine the runoff. This can be smaller than the grid size and therefore, the roughness of these NBSs does not need to be scaled according to its size relative to the grid size. However, the infiltration and retention capacities still require weighted averaging.

3.4.2. Translating NBS effects to model parameters

Next, the hydrological changes are translated to model parameters. Additional storage capacity is implemented by adding the storage capacity per grid in millimetres to the Swood or wflow_hp parameters (initially only contains 0 values). When open water evaporation and infiltration occur, wflow_hp is used, and otherwise Swood is altered. The implementation of new infiltration capacities and Manning values is less straightforward and is described below.

Infiltration capacity

The changes in infiltration capacity are represented by the parameters InfiltCapPath and PathFrac, which describe the infiltration capacity of paved areas and the paved fraction respectively. InfiltCapPath is used instead of InfiltCapSoil (infiltration capacity of unpaved areas), because NBSs generally add more green to a city (Raymond et al., 2017). If InfiltCapSoil would be used, the total amount of infiltration may decrease in a grid cell when a NBS replaces an unpaved area with a higher infiltration capacity.

Whether InfiltCapPath or PathFrac is used, depends on the size of the NBS relative to the grid size. For small scale NBSs, PathFrac is multiplied by a factor for each grid cell in the applied area. This factor depends on the relative sizes of NBSs compared to the grid size. For example, green roofs are assumed to be applied to 40% of a grid cell. Therefore, the paved fraction reduces by 40% and the PathFrac is multiplied by a factor 0.6 m^2/m^2. For large scale NBSs, InfiltCapPath is used to implement NBSs. Large scale NBSs cover an entire grid cell. Therefore, it is assumed that all paved areas in the grid cell are replaced by the large scale NBS, and that the infiltration capacity increases accordingly.

The obtained infiltration capacities for NBSs following from Paragraph 3.4.1 generally appeared to be significantly higher than the current maximum unpaved infiltration capacity in the Kigali model (600 mm/day). However, as shown in Figure 15, the infiltrated amount of rainfall without NBSs is already large. So, the decision is made not to increase the maximum unpaved infiltration capacity. Also, it is odd when NBSs are allowed to have a higher infiltration capacity than regular green unpaved areas (Bean et al., 2004; Litt et al., 2020). Therefore, the quantified infiltration capacities of NBSs are scaled using the modelled unpaved infiltration capacity of 600 mm/day. When the highest infiltration capacity obtained from literature is implemented (113 mm/hr for forests), InfiltCapPath increases to 600 mm/day. However, when the infiltration capacity of a NBS is only 80 mm/hr, InfiltCapPath is linearly scaled: $\frac{600\ mm/day}{113\ mm/hr} * 80\ mm/hr = 425\ mm/day.$

Manning values

When implementing NBSs which increase the surface roughness, the modelled Manning roughness values should not be multiplied by a factor. Firstly, because multiplication causes the NBS effect to be largest when NBSs are implemented in initially rough areas. This would not make sense, because NBSs are mainly supposed to benefit urban areas with large, paved areas (World Bank, 2021). Also, the calibrated Manning surface roughness values are unrealistically high, resulting in unrealistic NBS effects when multiplication is applied (Aerts, 2021; Horn, 2021). Instead of multiplication, the following approach is used:

1. Based on the modelled land use of a grid cell, a physically representative Manning value is obtained from the look-up Table A- 3;
2. A physically representative value for each NBS is acquired from the hydrological quantification of the NBS in Paragraph 4.4.1;
3. When the Manning value of the NBS is larger than the physically representative value of a grid cell, the difference between the two Manning values is added to the modelled roughness value to implement the NBS.

For channel flow, the procedure is similar. The difference is that physically representative Manning values are not obtained using land use data, but that all model values are divided by two. This is because the minimum N_River value in the model is 0.06 $s/m^{1/3}$ and the physically representative Manning value for a clean straight channel from Table A- 2 is 0.03 $s/m^{1/3}$.

3.4.3. Individual and combined effects of NBSs

Both the individual and combined effects of NBSs are computed using the wflow model of Kigali. Using all parameter value changes following from Paragraph 3.4.2, the NBSs are implemented at the same locations as in HKV's old approach. These locations depend on the urban typology of an area, as composed by Defacto (see Table E- 1).

For the individual effects, each NBS is implemented separately. For the combined effect, all NBSs, which are included both in the new and the old approach, are implemented. When combining multiple NBSs within a grid cell, the following rules are applied:

- N and N_River: the increases in roughness due to each measure are summed and added to the original roughness values in the model. For N, the maximum value is 0.76 $s/m^{1/3}$, which is the sum of the maximum N value in the Kigali model and the realistic maximum increase in roughness obtained from Table A- 3. For the same reason but using Table A- 2, the maximum N_River value is 0.19 $s/m^{1/3}$.

- PathFrac: the paved fraction has a minimum of 0. Each time a NBS is implemented using PathFrac, the parameter value is multiplied by the factor corresponding to the NBS. There are no additional restrictions, since it is assumed that many small-scale measures can be combined within a grid cell.
- InfiltCapPath: since InfiltCapPath is used for large scale measures covering an entire grid cell, the infiltration capacity of paved areas is set to the average of all NBSs using InfiltCapPath.
- Swood and wflow_hp: there is no maximum value to the retention capacity of a grid cell.

The effects of NBSs are then computed by comparing runoff due to the implementation of NBSs to the original runoff for all three sub-catchments. The individual and combined effects of NBSs are expressed using the same variables as described in Paragraph 3.3.1.

Some NBS clusters are implemented on a large area, while others are only implemented locally. To homogenize the results, the individual effects are divided by the total applied area of each NBS. These effects per squared kilometer are the unit effects. The total applied area of each NBS is determined by counting the number of grid cells where parameter changes are applied for each NBS and multiplying this by the total area of one grid cell. It is important to note that these individual unit effects cannot be upscaled to the catchment scale, because the NBS-effect strongly depends on its location. For the combined effect, there is no need to calculate the unit combined effect, because the NBSs are implemented on a fixed area. Instead, the combined effect is also expressed as a percentage reduction relative to the original runoff.

3.4.4. Sensitivity of peak runoff to rainfall duration

Kigali has two rainy seasons, which are characterised by long and short storm durations (see Paragraph 2.1.2). To investigate the sensitivity of the NBS-effects to differences in rainfall intensity, a synthetic long rainfall event is developed. The total duration of the main rainfall event currently used in the model is approximately 6 hours and is considered the short rainfall event.

For the grid cell which receives the lowest amount of rainfall, a synthetic long rainfall event is developed. This is done by dividing the cumulative rainfall sum over 24 hours, such that the rainfall volume is equal to that of the short rainfall event. The rising and falling limb are equally steep. The magnitude of the long rainfall event is scaled for each grid cell using the ratio of the cumulative rainfall sum of the specified grid cell to the minimum cumulative rainfall sum. The representative rainfall events for the driest grid cell in the Nyabugogo catchment are shown in Figure 10 for a return period of two years.

The effects are computed for one NBS of each cluster. This is sufficient to assess the sensitivity of the NBS-effects to differences in rainfall intensity. Only the relative maximum runoff reduction and runoff delay are compared, since the uncertainty in the baseflow increases significantly for a long rainfall event.

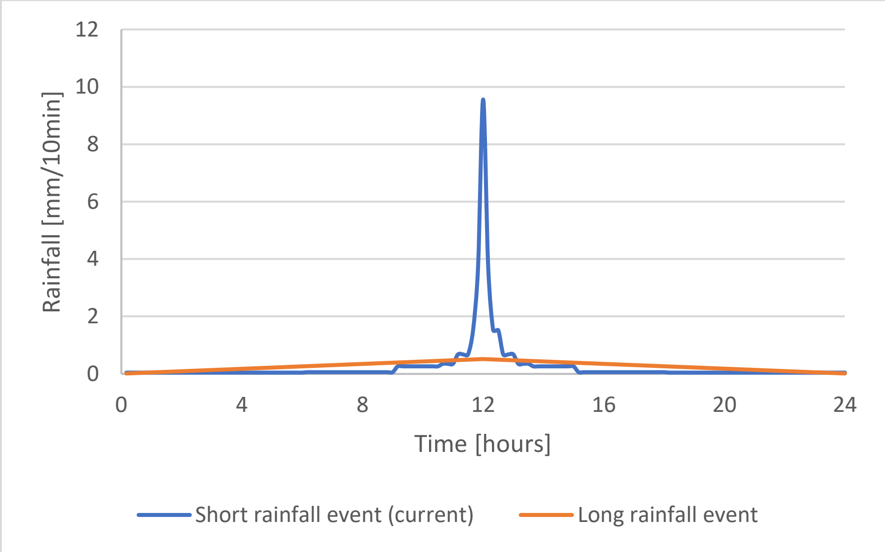

Figure 10 - plotted time series of long and short rainfall events which volume has a return period of two years

3.5. Research question 5- comparison of effects of NBSs

What are the differences in individual and combined effects of NBSs on urban runoff between the old and the new implementation for different sub-catchments and rainfall forcings?

This research question focusses on comparing the effects of the old and the new approach on the urban runoff. The following results are compared:

- Individual effects – to gather reliable individual effects using the old approach, each NBS is implemented separately using the parameter values of the old approach. To compare the effects of both approaches, the relative reduction in maximum runoff and runoff volume are calculated and compared for both approaches. NBSs that are not implemented in either one of the approaches are excluded.
- Combined effects – to obtain combined effects using the old approach, all common NBSs of both approaches are implemented according to the methodology and parameter values of the old approach. Thus, N and N_River can increase to a maximum value of 1. The absolute effects as well as the relative decrease in maximum runoff and runoff volume are then compared.
- Effects for short and long rainfall events – a similar methodology as described in Paragraph 3.4.4 is applied to obtain the effects of the old approach, which are then compared to the effects of the new approach.

4. Results

4.1. Research question 1 – limitations and opportunities

As a result of the interviews, a summary of the strengths and weaknesses of the old implementation and opportunities and threats of the wflow-SBM concept for the new implementation are shown in Figure 11 below. Subsequently, Paragraphs 4.1.1-4.1.4 expand upon these strengths, weaknesses, opportunities, and threats.

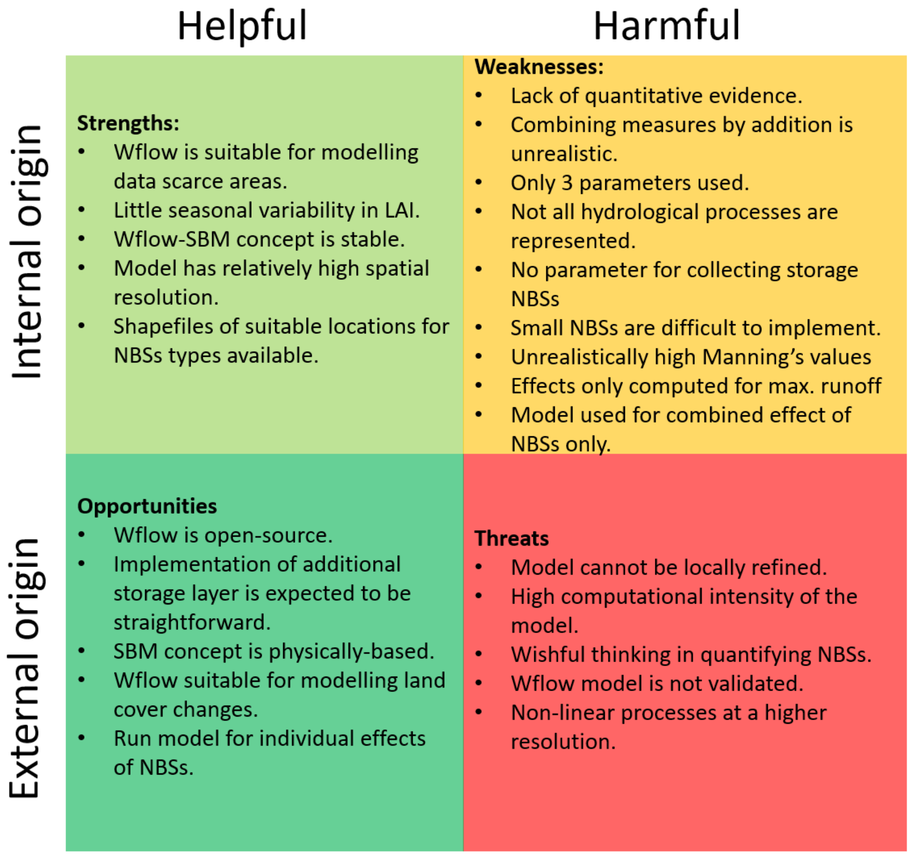

Figure 11 - SWOT analysis of current approach for implementing the effects of NBSs into wflow-SBM resulting from the interviews

4.1.1. Strengths

First of all, wflow is suitable for hydrological modelling studies in data scarce areas (Hegnauer, 2021; Russell, 2021). As mentioned in Chapter 2 of this report, the available data of the Nyabugogo catchment is limited. The wflow-SBM model concept was deliberately designed to cope with a lack of data. For example, it extracts soil data for soil parameters from the global SoilGrid database from the ISRIC. For that reason, the wflow-SBM concept is expected to be a relatively accurate representation of reality in the case of Kigali in comparison to other hydrological models.

In addition, the lack of seasonal variability in the LAI of the Nyabugogo catchment makes it suitable for assessing the effectiveness of NBSs (Hegnauer, 2021). The Nyabugogo catchment lies in the tropics and therefore, it is valid to assume that the effects of NBSs are constant throughout the year. Simulating the 10 days rainfall event, for instance in January, is expected to give approximately the same results as in July.

Another strength of the wflow-SBM concept is that it is stable, as no major errors have been found in the past two years (Russell, 2021). So, the model is reliable, and the focus can be on the implementation of NBSs.

Furthermore, the relatively high model resolution is convenient for the implementation of NBSs (Aerts, 2021). At a 90 m x 90 m spatial resolution, most NBSs can be implemented at the grid size scale.

Lastly, HKV has already performed a detailed assessment of the suitable locations for different types of NBSs based on their potential suitability and areal characteristics of the Nyabugogo catchment (see Appendix E) (Horn, 2021). Shapefiles have been generated indicating the location of each NBS. Using wflow-SBM allows these shapefiles to be re-used in this study.

4.1.2. Weaknesses

The main weakness of the current implementation of NBSs into wflow is that insufficient quantitative evidence is available to prove the accuracy of the NBS implementation and the resulting peak runoff reductions (Horn, 2021; Russell, 2021). All parameter value changes due to NBSs are rough estimates based on expert judgement by Defacto and HKV (Horn, 2021). Especially the measures which increase the roughness in the drains and on the surface may be inaccurate. For example, all the measures in the drains are assumed to increase the roughness by 50%.

Another limitation of the current implementation is that when multiple NBSs are implemented in the same grid cell, their effects are stacked (Horn, 2021). This is done because it may be possible that multiple NBSs occur within the same grid cell of 90m x 90 m. For storage measures, storage capacity is added, while for delaying measures, the surface roughness is either replaced by a new surface roughness or multiplied by a factor depending on the NBS type (Horn, 2021). However, when multiple NBSs are implemented in the same grid cell, the storage capacity and the surface roughness can become unrealistically high.

Furthermore, to implement NBSs, currently only three parameters are used and so, not all hydrological processes are taken into account (Hegnauer, 2021; Horn, 2021; Russell, 2021). Storage measures use the Swood parameter, measures in rivers and drains use N_River and measures on the surface utilise N. An example of a hydrological process that is currently neglected is infiltration. Though it can be argued that infiltration is indeed negligible for extreme rainfall events in sloping areas (Hegnauer, 2021; Horn, 2021), it could affect the simulated runoff.

Surface runoff storage measures, such as ponds and retention areas are not accurately represented by the Swood parameter (Horn, 2021). Swood prevents rainfall from entering the system and stores rainfall within the grid cell it falls on, whereas rainwater ending up in a retention area may have been flowing over land before being stored in the grid cell where the retention area is located (Horn, 2021). In reality, during a high intensity rainfall event, surface runoff storage measures will fill up much quicker than simulated by the model, because water from multiple upstream grid cells enters them.

In addition, it was found that NBSs smaller than the grid size are difficult to implement into the wflow-SBM concept (Aerts, 2021; Horn, 2021; Russell, 2021). Currently, when NBSs are smaller than the grid size, their effects are scaled using their size relative to the grid size. For example, if a NBS increases the roughness from 0.07 $s/m^{1/3}$ to 0.1 $s/m^{1/3}$, but is only applied on 10% of the grid cell, the roughness for the grid cell is set to $0.07 + 0.1*(0.1-0.07) = 0.073$ $s/m^{1/3}$. The implications of applying this simplification should be questioned.

Another limitation of the current approach is that the Manning roughness values, used in the NBS-implementation, are unrealistically high, because they are used as calibration parameters (Aerts, 2021;

Horn, 2021). High Manning values are used to compensate for a model constituent which causes water to be discharged faster than it should be (Aerts, 2021; Horn, 2021). In the current approach, the Manning values are multiplied by certain factors to implement NBSs which cause the roughness in the drains and on the surface to increase. However, by doing so, the absolute increase in roughness due to a NBS can be much larger than intended. For example, when a NBS increases the roughness by 10%, the absolute increase in roughness is larger when a high calibrated Manning value is multiplied by a factor of 1.1 than when this factor is applied to a lower and physically representative Manning value. Therefore, multiplying these Manning values by factors to represent NBSs may overestimate the effects of NBSs on the urban runoff.

Furthermore, the effects of NBSs are currently only assessed using peak discharges at locations where the water leaves a sub-catchment (Horn, 2021). It can be questioned whether this is sufficient to give an accurate indication of the effect of NBSs. Though the peak runoff is most relevant for flooding events (World Bank, 2021), the total runoff volume is also relevant for downstream areas when flooding occurs.

Lastly, the model is only used to compute the combined effects of all NBSs (Horn, 2021). Based on a sensitivity analysis for the three types of NBSs and the total area of implementation, the unit effects on the maximum runoff of the NBSs are computed (Horn, 2021). However, only the combined effects are determined using wflow-SBM. Using this effect to calculate individual effects of NBSs introduces additional uncertainty, because the effect of a NBS does not only depend on its size and type, but also on the location where it is implemented.

4.1.3. Opportunities

The first opportunity is that wflow is open-source software, allowing the code to be viewed and edited to satisfy the requirements of this study (Hegnauer, 2021; Russell, 2021). This has contributed to improved parametrisation of surface runoff storage NBSs as explained in Paragraph 3.3.3.

In addition, the wflow-SBM concept is physically-based and includes all hydrological processes relevant in Kigali (Russell, 2021). Therefore, the SBM concept offers an opportunity for improving the parametrisation of NBSs using the hydrological processes that are involved.

Another opportunity is that the individual effects of NBSs can be more accurately quantified when each NBS is simulated separately (Horn, 2021). When the entire Nyabugogo catchment is considered, these simulations would take a long time. However, since only three sub-catchments are considered in this study, many simulations can be performed within a relatively short period of time and the uncertainty in the unit effects will be reduced.

4.1.4. Threats

First of all, wflow has no functionality to locally refine the model to benefit the implementation of NBSs (Aerts, 2021; Hegnauer, 2021). Also, manually refining the entire model is challenging and time consuming (Aerts, 2021). The spatial resolution of the model may pose as a threat when implementing small-scale measures.

In addition, the wflow model of Kigali, used in this study, is computationally intensive because it runs on PCRaster (Hegnauer, 2021). At the start of this research, the decision was made to use the PCRaster Python version instead of the new Julia version of wflow. The main reasons were that scripts from HKV could be re-used and that programming in Python was expected to be more straightforward than in Julia. However, the Julia version runs significantly quicker than the PCRaster version of wflow (Hegnauer, 2021; Russell, 2021). When performing many simulations to determine the individual effects of NBSs, the computational intensity can pose as a threat.

Furthermore, a potential threat of modelling NBSs is overestimating their effects based on idealised experiments (Huthoff, 2021). These experiments are often carried out for optimum conditions and therefore, the effects of NBSs found in literature can be significantly larger than they are in reality. This should be considered when using the wflow parameters to implement NBSs into the model.

Additionally, the wflow model is not validated and so, it should only be used to compute the relative effects of NBSs (Russell, 2021). For this reason, and because of a lack of quantitative data on the effects of NBSs, the computed NBS effects should be used to evaluate the sensitivity of the simulated runoff to changes in parameters corresponding to relevant hydrological processes (Russell, 2021). Absolute effects on the urban runoff should not form the basis for comparing the two approaches.

Lastly, when estimating the effects of NBSs on hydrological processes, it must be taken into account that non-linear hydrological processes may be involved at a higher resolution, which cannot be represented by wflow parameters (Aerts, 2021). All hydrological equations and concepts have been developed for specific purposes. For example, the Richards equation was derived at a small spatial scale and a much debated question is whether it can be applied for large scale catchment modelling studies (Aerts, 2021; Or et al., 2015). Also, at low resolutions, it may be correct to neglect some hydrological processes, while these processes should be accounted for at higher resolutions. Therefore, when using hydrological concepts to quantify the effects of NBSs, the spatial scale at which these concepts are derived must be considered.

4.2. Research question 2 – hydrological effects of NBS clusters

For each of the NBSs in Table 5 in Paragraph 2.2.7, the hydrological processes that are affected are identified using the following symbology:

++ Strongly positive feedback – the hydrological process affected by the NBS strongly reduces the peak runoff.

\+ Positive feedback – the hydrological process affected by the NBS reduces the peak runoff.

0 Neutral feedback – the hydrological process is not affected when implementing the NBS.

\- Negative feedback - the hydrological process affected by the NBS increases the peak runoff.

-- Strongly negative feedback – the hydrological process affected by the NBS strongly increases the peak runoff.

For instance, when a NBS increases the roughness of the surface, the runoff velocity and thus the peak runoff decrease. Therefore, the surface runoff over land of this NBS has positive feedback on the peak runoff reduction. An overview of the conceptual effects on hydrological processes of the list of NBSs is shown in Table 7. This table is then summarised in Table 8, where the hydrological processes involved for all the cluster numbers are listed. Note that when clustering the NBSs, no distinction is made between ++ and +, and -- and -. NBSs which could not be clustered are indicated with N.A. in Table 7 and excluded from Table 8.

To benefit the readability of Table 7, several meanings of NBS-IDs from Table 5 are listed below:

- A1 – Forest transition
- A3 – Green urban park
- C1a – Water storing pond

- C6 – Permeable parking
- F1 – Bioswales and water buffer
- F4 – Stepped drain
- H4 – Rain tank and gutter

Table 7 - hydrological processes involved for the list of NBSs and subsequently their cluster numbers

NBS-ID	Interception	Infiltration	Transpiration	Soil evaporation	Runoff by rivers/drains	Surface runoff on land	Open water evaporation	Surface water retention	Cluster number	Source
A1	++	+	++	--	0	+	0	0	1	(Bonnesoeur et al., 2019), SCS-CN method
A2a	++	+	++	-	0	+	0	0	1	Rutter model., Manning eq., SCS-CN method
A2b	+	++	+	-		++			1	Rutter model., Manning eq., SCS-CN method
A3	+	++	+	0	0	+	+	+	2	(Bai et al., 2018), Manning eq., SCS-CN method
A3.1	+	++	++	0	0	+	0	0	11	(Bai et al., 2018), Manning eq., SCS-CN method
A3.2	+	++	+	0	0	+	++	++	2	(Bai et al., 2018), Manning eq., SCS-CN method
A4	++	+	++	--	0	+	0	0	1	(Bonnesoeur et al., 2019), SCS-CN method
B1	+	+	+	0	0	++	0	0	1	(V. T. Chow, 1959; Coupe et al., 2013), Manning eq.
B2	+	+	+	0	++	0	0	0	4	(V. T. Chow, 1959; Coupe et al., 2013; Hagglund et al., 2020), Manning eq.
B2.1	0	0	0	0	-	0	0	0	6	(V. T. Chow, 1959), Manning eq.
B2.2	+	+	+	0	+	0	0	0	4	(V. T. Chow, 1959; Coupe et al., 2013), Manning eq.
B3a	0	++	0	0	0	0	++	++	3	(Hampshire & Sipes, 2019)
B3b	0	++	0	0	0	0	++	++	3	(Hampshire & Sipes, 2019)
B4	0	+	0	0	0	+	0	0	7	(World Bank, 2021), own understanding
B5	0	0	0	0	0	0	0	++	10	(Burns et al., 2015; World Bank, 2021)
C1a	0	++	0	0	0	0	++	++	3	(Baird et al., 2020)
C2a	++	+	++	0	0	+	0	0	11	(Her et al., 2017; Li & Babcock Jr., 2014; Manso et al., 2021), GAML eq.
C3a	+	0	+	0	0	+	0	0	9	(Manso et al., 2021)
(C1-3) b	+	+	+	0	0	+	+	+	2	(Baird et al., 2020; Her et al., 2017; Li & Babcock Jr., 2014; Manso et al., 2021), GAML eq.
C4	+	++	+	0	0	+	+	+	2	(Bai et al., 2018; Santos et al., 2012), Manning eq.
C4.1	++	++	++	0	0	+	+	+	2	(Her et al., 2017), GAML eq.

C4.2	0	++	0	0	0	0	++	++	3	(Hampshire & Sipes, 2019)
C5	+	+	+	0	0	++	0	0	1	(World Bank, 2021; Xiao et al., 2017)
C5.1	+	+	+	0	+	0	0	0	4	(Xiao et al., 2017), GAML eq., Manning eq.
C5.2	0	++	0	0	0	+	0	0	7	(Alsubih et al., 2017; Her et al., 2017)
C6	0	++	0	0	0	+	0	0	7	(Alsubih et al., 2017; Her et al., 2017)
D1a	+	++	+	0	0	0	+	++	5	(Northen Territory Department of Health, 2019), own understanding
D1b	+	+	+	0	0	0	+	+	5	(Northen Territory Department of Health, 2019), own understanding
D2a	0	0	0	0	0	0	0	+	10	(Manso et al., 2021)
D2b	0	0	0	0	0	0	0	+	10	(Manso et al., 2021)
D3	+	++	+	0	+	+	+	+	2[1]	(Bai et al., 2018), Manning eq.
D3.1	+	++	+	0	0	+	+	+	2	(Bai et al., 2018), SCS-CN method
D3.2	+	+	+	0	+	0	0	0	4	(Xiao et al., 2017), GAML eq., Manning eq.
D4	0	+	0	0	0	++	0	0	7	(V. T. Chow, 1959; World Bank, 2021), Manning eq.
D5	+	+	+	0	0	+	0	0	1	(Xiao et al., 2017), GAML eq., Manning eq.
D5.1	0	0	0	0	-	0	0	0	6	(V. T. Chow, 1959), Manning eq.
D5.2	+	+	+	0	+	0	0	0	4	(Xiao et al., 2017), GAML eq., Manning eq.
D5.3	+	+	+	-	0	+	0	0	1	(V. T. Chow, 1959; World Bank, 2021), Manning eq.
D6	0	+	0	0	++	0	0	0	8	(Fandel, 2016)
E1	0	0	0	0	0	++	+	+	N.A.	(Hagglund et al., 2020; World Bank, 2021)
E2	+	+	+	0	0	0	+	+	5	(Sueltenfuss & Cooper, 2019), own understanding
E3	0	+	0	-	++	0	0	0	8[2]	(V. T. Chow, 1959; World Bank, 2021), Manning eq.
E4	0	+	0	0	0	++	0	0	7	(World Bank, 2021), Manning eq.
E5	+	++	+	0	0	+	+	+	2	(Bai et al., 2018; Santos et al., 2012; World Bank, 2021), Manning eq.
E6	++	+	++	-	0	+	0	0	1	(Bai et al., 2018), Manning eq., SCS-CN method
F1	+	+	+	0	0	+	+	+	2	(World Bank, 2021; Xiao et al., 2017), GAML equation, Manning eq.
F2a	0	+	0	0	0	++	0	0	7	(World Bank, 2021), Manning eq.
F2b	0	+	0	0	++	0	0	0	8	(Fandel, 2016)
F3a	0	++	0	0	0	++	0	0	7	(Alsubih et al., 2017; Her et al., 2017; World Bank, 2021), Manning eq.
F3b	+	0	+	-	0	+	0	0	9[3]	(World Bank, 2021), Rutter model
F4	0	+	0	0	++	0	0	0	8	(World Bank, 2021), Manning eq.
G1a	0	++	0	0	0	0	++	++	3	(Hampshire & Sipes, 2019)
G1b	0	+	0	0	0	0	+	+	3	(Hampshire & Sipes, 2019)

[1] Difference with cluster 2 is that D3 also decreases the runoff velocity in the drains.
[2] Difference with cluster 8 is that E3 also decreases the soil evaporation.
[3] Difference with cluster 9 is that F3b also decreases the soil evaporation.

G2a	+	0	+	0	0	+	0	0	9	(Ahmed & Borst, 2020), Manning eq.
G2b	+	0	+	0	0	+	0	0	9	(Ahmed & Borst, 2020), Manning eq.
H1	++	+	++	-	0	+	0	0	1	Rutter model, Manning eq., SCS-CN method
H2	++	+	++	--	0	+	0	0	1	(Bonnesoeur et al., 2019), SCS-CN method
H3	0	++	0	0	0	0	++	++	3	(Baird et al., 2020)
H4	0	0	0	0	0	0	0	++	10	(Burns et al., 2015; World Bank, 2021)
H5	+	+	+	0	0	0	++	++	5	(World Bank, 2021), SCS-CN method

Table 8 - overview of hydrological processes involved for all cluster numbers

Cluster number	**Interception**	**Infiltration**	**Transpiration**	**Soil evaporation**	**Runoff by rivers/drains**	**Surface runoff on land**	**Open water evaporation**	**Surface water retention**
1	+	+	+	-	0	+	0	0
2	+	+	+	0	0	+	+	+
3	0	+	0	0	0	0	+	+
4	+	+	+	0	+	0	0	0
5	+	+	+	0	0	0	+	+
6	0	0	0	0	-	0	0	0
7	0	+	0	0	0	+	0	0
8	0	+	0	0	+	0	0	0
9	+	0	+	0	0	+	0	0
10	0	0	0	0	0	0	0	+
11	+	+	+	0	0	+	0	0

4.3. Research question 3 – more physically based parametrisation

In this section, the results used to develop the new parametrisation are presented. It includes the sensitivity of the peak runoff to model parameters driving relevant hydrological processes for the implementation of NBSs.

4.3.1. Sensitivity of peak flows to model parameter values

The results of the univariate sensitivity analysis for return periods of two and 100 years are presented in Figure 12, 13 and 14. The relevant parameters from Table 4 are investigated using the maximum runoff, runoff volume and the timing of the peak runoff.

These figures show that the model is most sensitive to changes in parameters related to infiltration, and the roughness on the surface and in the drains. For the maximum runoff, both roughness and infiltration are important, but for the runoff volume, infiltration is dominant. The roughness in the drains is the most sensitive parameter to the runoff timing. Roughness is dominant over infiltration for the runoff timing.

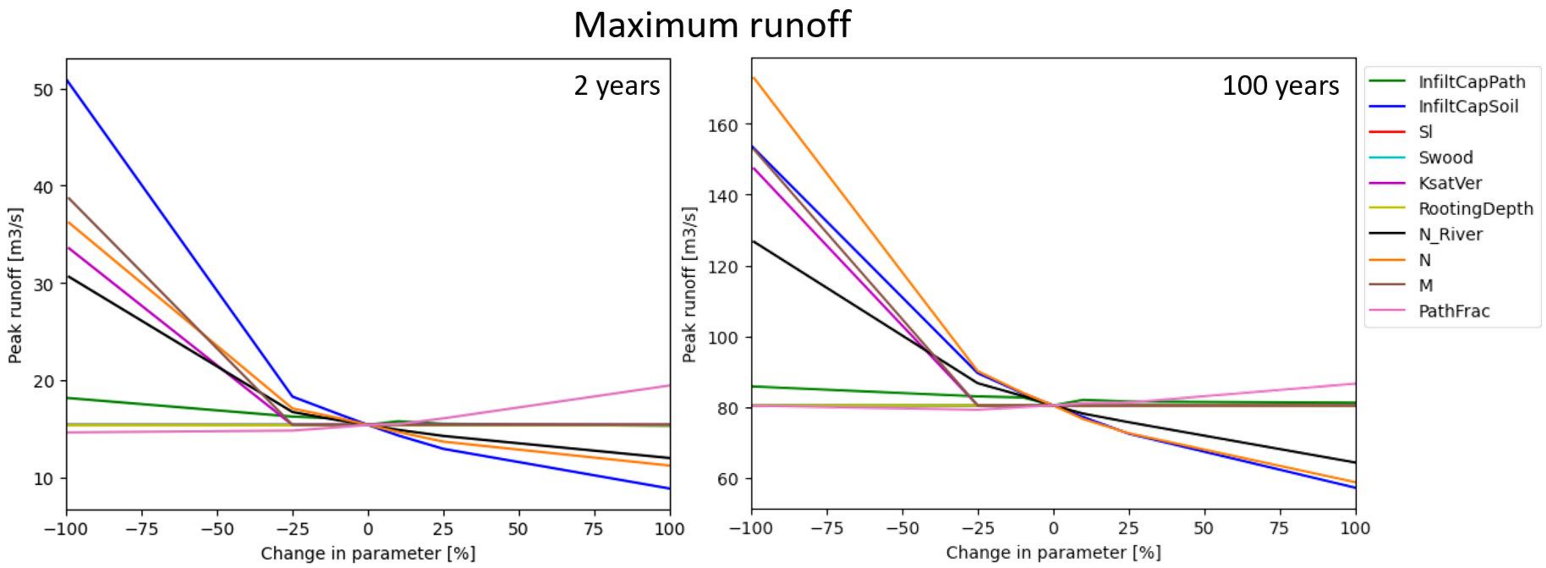

Figure 12 – the average sensitivity of the maximum runoff for different wflow parameters for return periods of rainfall of 2 and 100 years

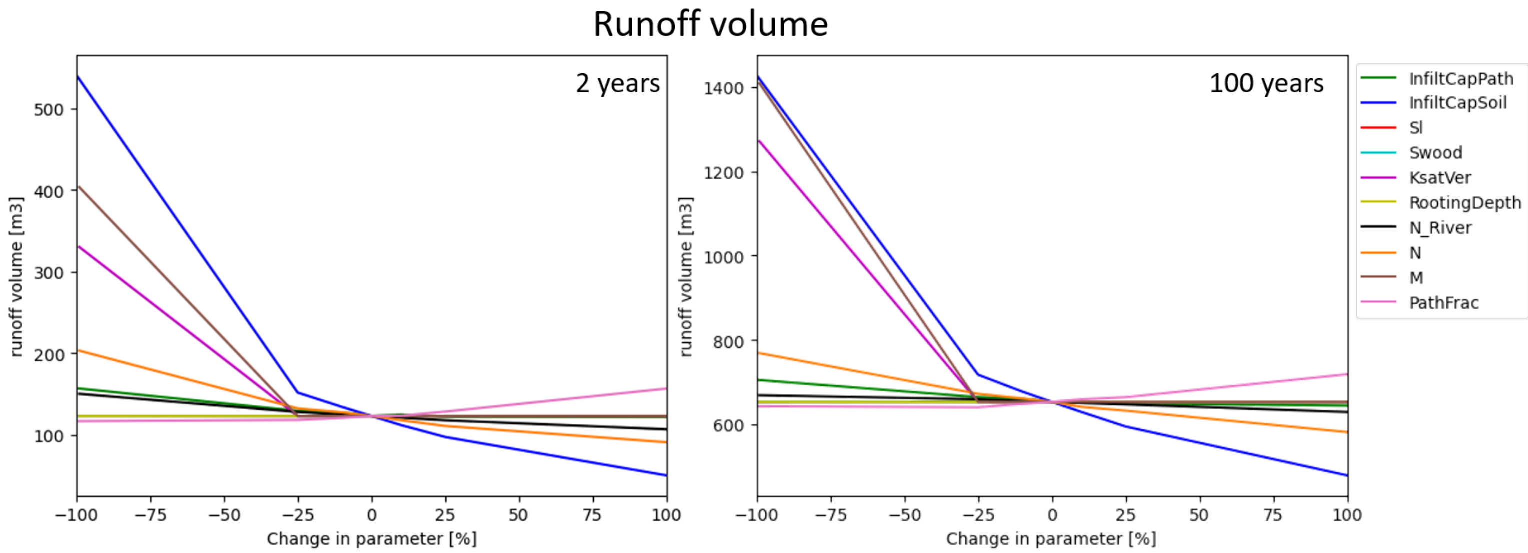

Figure 13 - the average sensitivity of the runoff volume for different wflow parameters for return periods of rainfall of 2 and 100 years

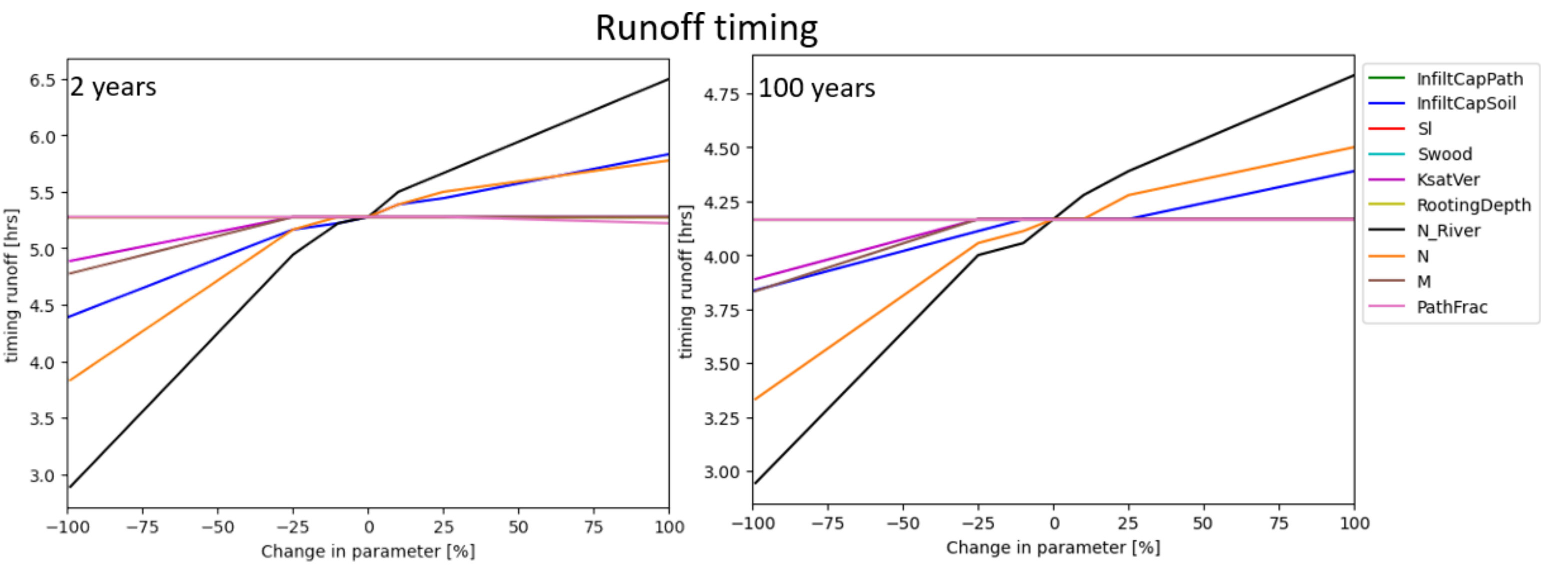

Figure 14 - the average sensitivity of the time between the start of the rainfall event and the maximum runoff for different wflow parameters for return periods of rainfall of 2 and 100 years

Figure 12 and 13 suggest that the model is more sensitive to changes in InfiltCapSoil parameter than in InfiltCapPath parameter. This is probably because the maximum infiltration capacity in unpaved areas is much larger than that in paved areas. Therefore, using the same relative parameter changes, absolute changes in infiltration capacity in unpaved areas are larger than these changes in paved areas. Given the original peak runoff volume and the original maximum runoff, the relative change is larger for shorter return periods.

A higher sensitivity at lower return periods suggests that NBSs increasing the infiltration capacity are likely to be more effective for small amounts of rainfall. Figure 12 and 13 also show that both the modelled runoff volume and maximum runoff are more sensitive to low values of the maximum infiltration capacity than to high values. This indicates that there are factors other than the maximum infiltration capacity affecting the infiltration of rainfall into the ground.

Factors influencing the infiltration of rainfall into the soil include the saturated hydraulic conductivity at the surface (KsatVer), the decrease of KsatVer with depth (M) and the fraction of paved area per grid cell (PathFrac). Like InfiltCapSoil and InfiltCapPath, decreasing the value of KsatVer has a greater effect than increasing it. In this case, it may be because the maximum infiltration capacity is reached, and no more water can infiltrate into the ground despite having a high saturated hydraulic conductivity. For the parameter M, a similar effect is observed. When PathFrac increases, both the peak runoff volume and the maximum runoff increase.

Furthermore, changing the Manning coefficient mainly affects the maximum runoff. The peak runoff volume remains relatively constant. The slight decrease in peak runoff volume can be explained by the fact that more water is allowed to infiltrate into the ground because of lower flow velocities. This effect is expected to be most pronounced in unpaved areas, where the roughness and the infiltration capacity are higher than in paved areas. The maximum runoff is most sensitive to the Manning coefficient when the amount of rainfall is large (return period of 100 years). Like the infiltration parameters, the effect on the maximum runoff decreases with increasing the Manning coefficient. This behaviour is explained by the Manning equation in Equation 1 as it is a rational function (runoff is proportional to 1/n).

A general conclusion from Figure 14 is that the time between the start of the rainfall event and the maximum runoff decreases when increasing the intensity of the rainfall event. It is shown that several parameters have (almost) no effect on the timing of the maximum runoff. These parameters are InfiltCapPath, PathFrac, RootingDepth, Sl and Swood. KsatVer and M only affect the timing when their values are decreased. Parameters that do affect the timing are InfiltCapSoil, N and N_River. For all three parameters, the time to the maximum runoff occurs increases when the parameter values increase. This effect is most pronounced when the return period of the rainfall is two years.

Lastly, the model appears to be insensitive to changes in the RootingDepth, Sl and Swood. When changing the RootingDepth, no runoff changes are observed at all, but for Sl and Swood, only small changes are observed. This is because the initial values of Sl and Swood are small compared to the received rainfall and increasing their values by a factor two is not expected to make much of an impact. Though the interception process becomes unrealistic for large changes in Swood, HKV has shown that high Swood values may significantly affect the peak runoff. The effect is expected to be especially pronounced for small rainfall events. For large rainfall events, the Swood storage bucket is likely to be full prior to the peak rainfall being received. The sensitivity of the model to large changes in Swood to represent surface storage measures is shown in Paragraph 4.3.3.

4.3.2. Hydrological processes affecting the peak runoff

In Figure 15, the average fluxes for infiltration, interception, soil evaporation and transpiration during the peak runoff are compared to the total amount of peak rainfall for different return periods. It is shown that infiltration significantly reduces the peak runoff, while the other hydrological processes have a negligible effect. Infiltration becomes less dominant when the amount of precipitation increases. However, even for an extreme rainfall event with a return period of 100 years, infiltration must be considered.

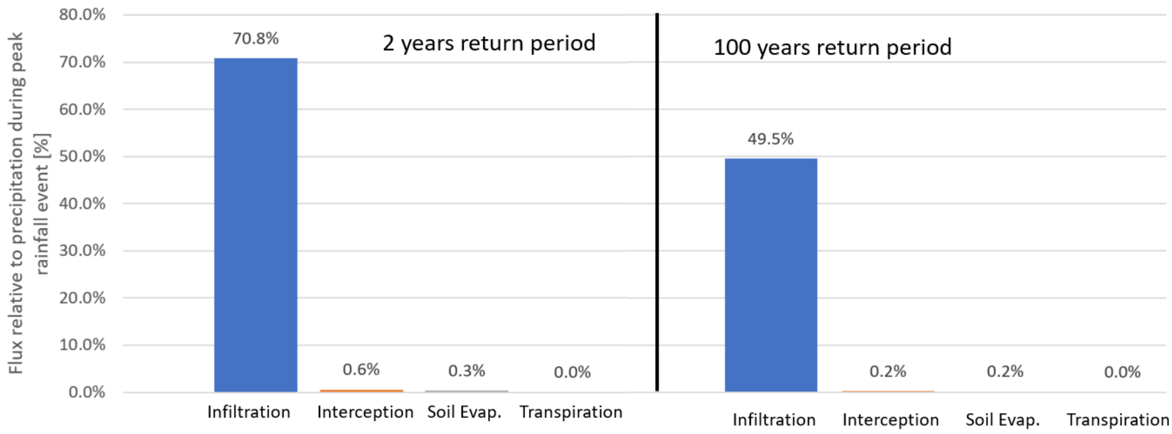

Figure 15 - comparison of average fluxes during the peak rainfall event for different return periods

4.3.3. Implementation of surface runoff storage NBSs

In Figure 16A-F, the sensitivity of the model for the different storage methods (Swood and wflow_hp from the paddy area function) is investigated using the maximum runoff, peak runoff volume and timing for different return periods.

A sudden gradient change in Figure 16A-D indicates that the available storage capacity is not reached during the main rainfall event. Based on the results in these graphs, it is concluded that the peak runoff is significantly more sensitive to wflow_hp than to Swood. When the return period is two years, the runoff reduces significantly (to baseflow only) when using wflow_hp. For a return period of 100 years, the runoff does not reduce to solely baseflow, but the model is also more sensitive to wflow_hp than to Swood. This can be explained by Figure 17, which shows the maximum canopy storage when the value of Swood is increased to 50 millimetres in all grid cells. The maximum storage capacity of 50 millimetres is only reached for high LAI values. When the LAI is 0, no water can be stored on the woody parts of the vegetation and increasing Swood is useless. Therefore, Swood should not be used to implement storage measures, unless the LAI is high (>2 m^2/m^2).

When wflow_hp is used to store water, water is allowed to travel overland before being stored. Therefore, wflow_hp allows rainfall to be stored in areas where less rainfall is stored, when this is no longer possible in the grid cell where the rainfall is received. When Swood is used, rainwater is stored as soon as it is received. In addition, when water is stored using wflow_hp, infiltration and open water evaporation occur. As shown in Figure 15, infiltration is a hydrological process which significantly affects the runoff. When Swood is used, only evaporation occurs. For these reasons, wflow_hp is expected to be more effective than Swood, even when Swood's dependency on the LAI would be removed.

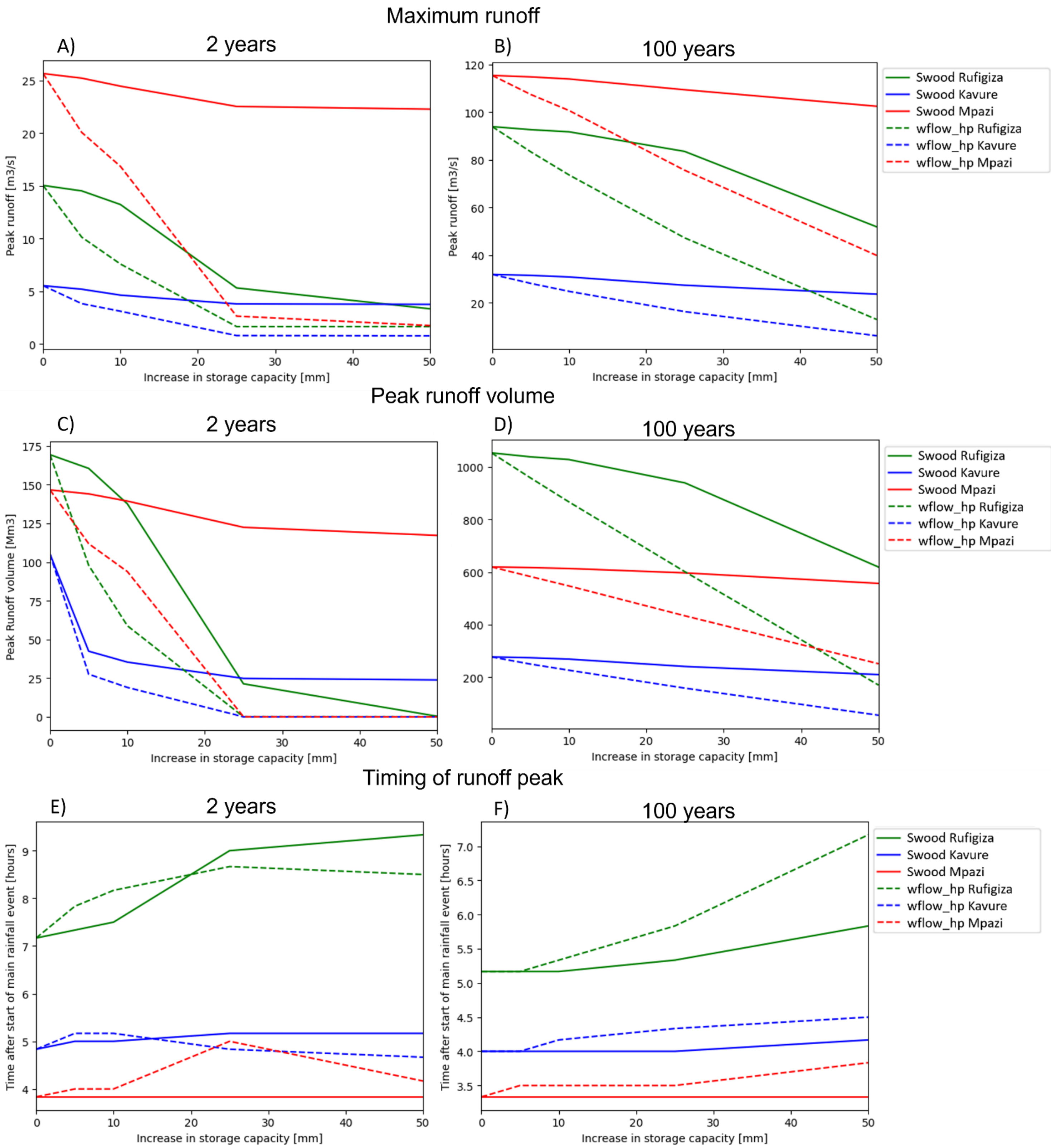

Figure 16 - Sensitivity of the maximum runoff (fig. A & B), runoff volume (fig. C & D) and timing (fig. E & F) when using Swood (tree trunk interception parameter) and wflow_hp (new additional storage layer)

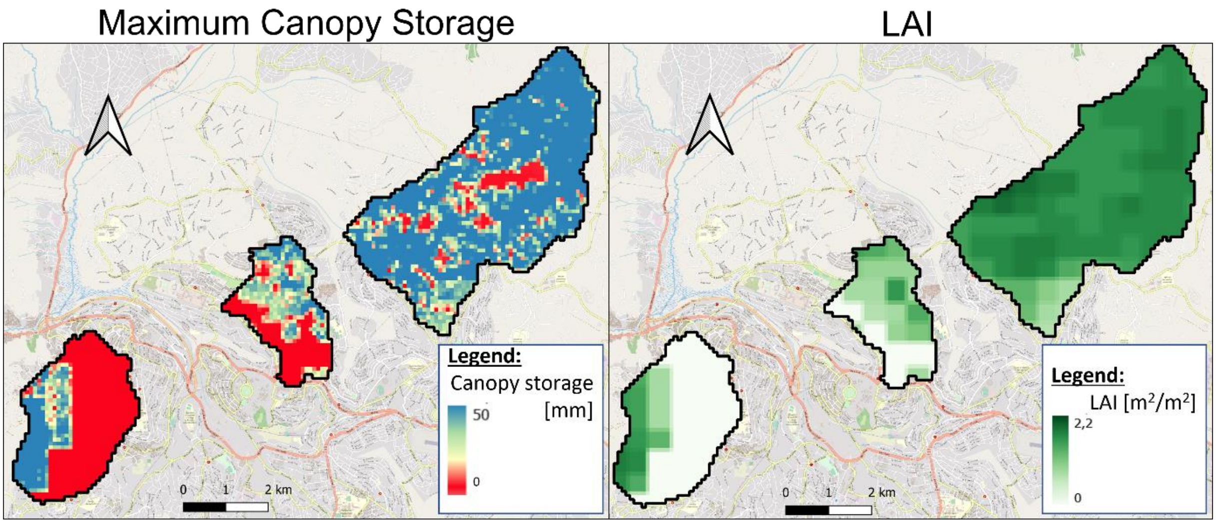

Figure 17 – the maximum storage capacity of Swood (50 mm) is not used when LAI is low

In general, the Kavure catchment appears to be the least affected sub-catchment when the storage increases. This has two reasons. First of all, the effect of storage measures is less pronounced, because of its relatively flat terrain. Secondly, when comparing the rainfall in the Kavure catchment to that in the Mpazi catchment, it can be noticed that more rainfall is received in the Kavure than in the Mpazi catchment (40 and 36 mm respectively during the peak rainfall event with a return period of two years). Thus, storage measures fill up quicker in Kavure and are less effective.

While both the maximum runoff and the runoff volume show a clear correlation with increasing storage capacity, the timing does not. Generally, the time to the peak runoff increases with increasing storage capacity (see Figure 16E-F). Once the maximum storage capacity of wflow_hp is reached in a grid cell, it overflows to the next grid cell. If this occurs before the peak rainfall, storage does not delay the runoff. Also, the effect of surface roughness may decrease. Therefore, the peak runoff may be expedited when storage NBSs are applied.

4.3.4. Synthesis

Paragraph 4.3.2 shows that interception, transpiration, and soil evaporation have a negligible effect on the peak runoff. Therefore, these hydrological processes are not included in the parametrisation of NBSs in this study. This allows some NBS-clusters from Table 8 to be merged, as shown in Table 9 below. The clusters which only consist of negligible NBSs from Appendix G are left out of Table 9. Also, after taking out these negligible NBSs, cluster 10 only consist of one NBS. Therefore, the NBS in this cluster is now considered as an individual NBS rather than a cluster. In addition, Table 9 includes cluster names which are used in the remainder of this report. In these names, the following abbreviations of hydrological processes are used:

- Inf for infiltration
- Riv for runoff by rivers/drains
- Sur for surface runoff on land
- SSt for surface runoff storage

Table 9 - merged cluster numbers and hydrological processes

Cluster number/ individual NBS-ID	Cluster/ NBS name	Infiltration	Runoff by rivers/drains	Surface runoff on land	Open water evaporation	Surface water retention
1+7+11	InfSur	+	0	+	0	0
2	InfSurSSt	+	0	+	+	+
3+5	InfSSt	+	0	0	+	+
4+8	InfRiv	+	+	0	0	0
H4	RainTank	0	0	0	0	+

Using the results from the sensitivity analyses in Paragraph 4.3.1, sensitive parameters are selected to represent changes in the hydrological processes, due to the implementation of NBSs, into the wflow-SBM concept for Kigali. This is shown in Table 10.

Table 10 - hydrological processes and relevant parameters to implement them into wflow-SBM

Hydrological process	Relevant parameter(s)
Infiltration	InfiltCapPath OR PathFrac[4]
Runoff by rivers/drains	N_River
Surface runoff on land	N
Open water evaporation	wflow_hp
Surface water retention	Swood OR wflow_hp

The model parameters that should be used to implement NBS-clusters are listed in Table 11 below. A + symbol indicates that the value of a parameter should be increased and a - symbol indicates that the parameter value should be decreased. In the case of the combined effect of the open water evaporation and surface water retention, wflow_hp is used, whereas when only surface water retention occurs, Swood is used. When wflow_hp is used, the open water evaporation does not need to be quantified, because for surface water, the model assumes that the open water evaporation is equal to the potential evapotranspiration. The parameter changes are quantified for each NBS in the next chapter.

Table 11 – relevant model parameters to the different NBS-clusters

Cluster/NBS name	Model parameters
InfSur	(InfiltCapPath (+) OR PathFrac (-)) AND N (+)
InfSurSSt	(InfiltCapPath (+) OR PathFrac (-)) AND N (+) AND wflow_hp (+)
InfSSt	(InfiltCapPath (+) OR PathFrac (-)) AND wflow_hp (+)
InfRiv	(InfiltCapPath (+) OR PathFrac (-)) AND N_River (+)
RainTank	Swood (+)

4.4. Research question 4 – effects of new implementation of NBSs

4.4.1. Quantification of hydrological processes for individual NBSs

All NBSs of each cluster are quantified in terms of the relevant hydrological processes in Table 12.

[4] InfiltCapSoil cannot be used to implement NBSs. This is explained in Paragraph 3.4.2

Table 12 - quantification of all NBSs for each cluster. I = infiltration capacity, D = new Manning value for channel flow, L = new Manning value for overland flow, R = Surface water retention

NBS-ID	Infiltration capacity [mm/hr]	Manning value for channel flow [$s/m^{1/3}$]	Manning value for overland flow [$s/m^{1/3}$]	Retention capacity [mm]	Source
Cluster InfSur					
A1	113	-	0.18	-	I: (Litt et al., 2020); L: Table A- 3[7]
A2a	80	-	0.15	-	I: (Litt et al., 2020); L: Table A- 3, Appendix G[5], (Farahani et al., 2016)
A2b	80	-	0.15	-	I: (Litt et al., 2020); L: Table A- 3, Appendix G[5], (Farahani et al., 2016)
B1	58	-	0.11	-	I & D: weighted average Table C- 4
B4	52	-	0.09	-	I & L: weighted average Table C- 4
C2a	56	-	0.09	-	I & L: weighted average Table C- 4
C5	58	-	0.11	-	I & D: weighted average Table C- 4
C6	75	-	0.1	-	I: (Bean et al., 2004); L: (Cui et al., 2019)
D5	31	-	0.06	-	I & D: weighted average Table C- 4
F2a	80	-	0.31	-	I: (Litt et al., 2020); L: Table A- 3, Appendix G[6]
F3a	50	-	0.1	-	I & L: weighted average Table C- 4
H1	80	-	0.15	-	I: (Litt et al., 2020); L: Table A- 3, Appendix G[5], (Farahani et al., 2016)
H2	113	-	0.18	-	I: (Litt et al., 2020); L: Table A- 3[7]
Cluster InfSurSSt					
A3	92	-	0.15	233	I & L: weighted average Table C- 1; R: AST (Table C- 1)[8]
(C1-3)b	50	-	0.09	105	I & L: weighted average Table C- 1; R: AST (Table C- 1)[8]
C4	87	-	0.14	251	I & L: weighted average Table C- 1; R: AST (Table C- 1)[8]
D3	87	-	0.14	251	I & L: weighted average Table C- 1; R: AST (Table C- 1)[8]
F1[9]	80	-	0.15	2	I: (Litt et al., 2020); D: Table A- 3; R: AST & (Filterexx, 2020)[10]
Cluster InfSSt					
B3a	75	-	-	218	I: see C6; R: assumed[11]
B3b	75	-	-	153	I: see B3a; R: 70% of B3a
C1a	40	-	-	44	I: (Negev et al., 2020); R: assumed[12]
G1a	75	-	-	218	I and R: see B3a
G1b	75	-	-	65.4	I: see G1a; R: 30% of G1a

[5] Assumptions: initial land use is agriculture or sparse forest (Manning roughness is 0.100)
[6] Assumptions: initial slope is 10%, Manning roughness is 0.100, slope of terraces is 1%.
[7] Assumption: initial land use is open area (Manning roughness is 0.080)
[8] Assumption: depth of retention area/pond is 0.6m.
[9] Assumption: 50% of the surface runoff in a grid cell drains to the bioswale.
[10] AST assumes the depth of a bioswale to be 0.35m and Filterexx mentions that the surface area of the bioswale should be at least 1% of the drainage area to be sufficient (2020). Drainage area is assumed to be 4050 m^2.
[11] Assumption: depth is 1m and surface area is 52x34m (1/4 of football field).
[12] Assumption: depth is 0.4m and surface area is 30x30m

H3	40	-	-	10	I: (Negev et al., 2020); R: (World Bank, 2021)[13]
Cluster InfRiv					
B2	26	0.1	-	-	I & D: weighted average Table C- 3
F4	60	0.033	-	-	I & D: weighted average Table C- 3
RainTank					
H4	-	-	-	20	R: Appendix G

4.4.2. Translating NBS effects to model parameters

Table 13 shows the changes in model parameters due to the implementation of NBSs. Representative and realistic Manning values for overland flow for different land use classes are shown in Table A- 3. These Manning values are indicated by X in Table 13. Y refers to realistic Manning values for channel flow. In Paragraph 4.4.3, the method for changing the Manning roughness is explained in more detail.

Table 13 - changes in model parameters due to implementation of NBSs.'+' indicates addition to the modelled value, '' indicates multiplication of the modelled value and '=' indicates the replacement of the modelled value.*

Cluster	NBS-ID	InfiltCapPath [mm/day]	PathFrac [m^2/m^2]	N [$s/m^{1/3}$]	N_River [$s/m^{1/3}$]	wflow_hp [mm]	Swood [mm]
InfSur	A1	=600		+(0.18-X)			
	A2a	=425		+(0.15-X)			
	A2b	=425		+(0.15-X)			
	B1		*0.74	+(0.11-X)			
	B4		*0.6	+(0.09-X)			
	C2a		*0.6	+(0.09-X)			
	C5		*0.74	+(0.11-X)			
	C6	=398		+(0.1-X)			
	D5		*0.94	+(0.06-X)			
	F2a	=425		+(0.31-X)			
	F3a		*0.89	+(0.1-X)			
	H1	=425		+(0.15-X)			
	H2	=600		+(0.18-X)			
InfSurSSt	A3	=488		+(0.15-X)		=233	
	(C1-3)b		*0.5	+(0.09-X)		=105	
	C4	=462		+(0.14-X)		=251	
	D3	=462		+(0.14-X)		=251	
	F1		*0.5	+(0.15-X)		=2	
InfSSt	B3a	=344				=218	
	B3b	=344				=153	
	C1a	=183				=44	
	G1a	=344				=218	
	G1b	=344				=65	
	H3		*0.95			=10	
InfRiv	B2		*0.99		+(0.1-Y)		
	F4		*0.87		+(0.033-Y)		
Others	H4						+20

4.4.3. Individual and combined effects of NBSs

As a result of implementing NBSs using the new approach, the average individual effects of NBSs are shown in Figure 18. In this chapter, the individual unit effects and the combined effects in Table F- 1 and Table F- 3 can be consulted for quantitative background. The size of each NBS in km^2 per catchment

[13] Assumptions: pond depth is 0.2m and surface area of one pond is 100 m^2 (World Bank, 2021). Four ponds per grid cell.

is also included in Table F- 1. The effects are expressed in terms of peak runoff delay, and reductions of the maximum runoff and peak runoff volume. For each of these variables, the effect is positive when the reduction or delay is greater than zero and negative when less than zero. For instance, a reduction in the maximum runoff is a positive effect.

Individual effects:

Figure 18 shows that the average individual effects of NBSs on the maximum runoff are generally largest in Mpazi. This is the steepest catchment and consists mainly of paved areas. Especially clusters InfSurSSt and InfSSt significantly reduce the maximum runoff. These clusters include the surface runoff storage NBSs. In steep terrains, storage measures are most effective, because the maximum runoff relative to its peak runoff volume is the largest. Storage measures are less effective in Rufigiza and Kavure, as was also shown in Paragraph 4.3.3. The peak runoff volume reduction is the largest in Kavure for all NBS clusters, because this is the smallest sub-catchment.

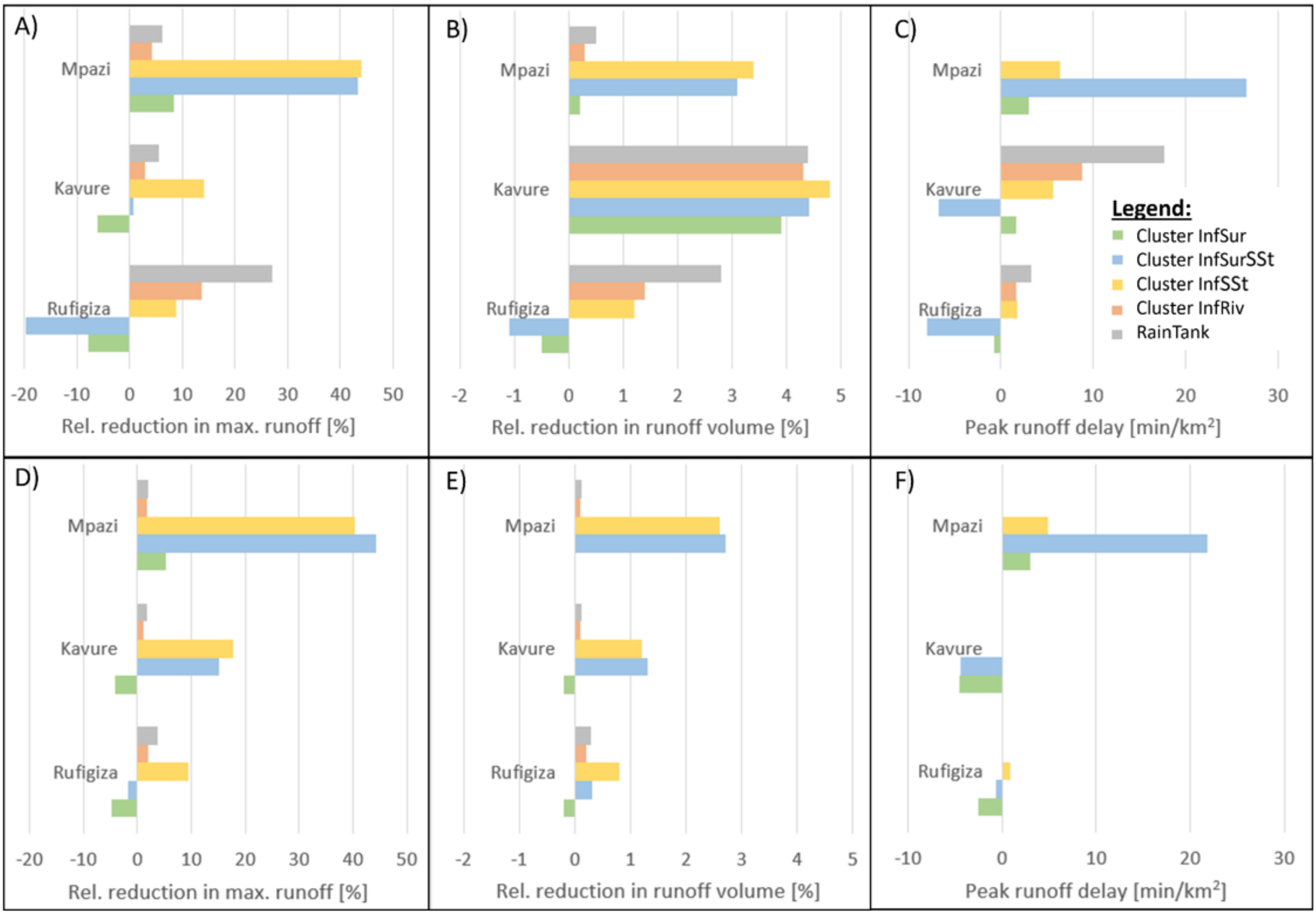

Figure 18 – average individual NBS effects in terms of A, D) relative reduction in maximum runoff, B, E) relative reduction in peak runoff volume, C, F) peak runoff delay. A-C is for a 2-year return period and D-F for a 100-year return period

When the rainfall intensity increase, the NBS effects generally decrease. However, in Mpazi, the effects on the maximum runoff remain relatively constant. The runoff delay decreases when the return period increases, because the depth average bottom friction decreases with increasing flow depth (George et al., 1989).

Anomaly

In Mpazi, all NBSs have a positive effect on the urban runoff. For NBSs in the other two catchments, the reduction in maximum runoff and peak volume, and delay may have a negative value. For example, the average effect of NBSs in cluster InfSurSSt is negative in Rufigiza in terms of maximum runoff, runoff volume and delay. These negative effects are only observed when increasing the surface roughness at the specific locations in these catchments, both in the old and the new approach. This is found by analysing contour planting (NBS A2b) in the Kavure catchment. Figure 19 shows that the runoff increases after increasing the surface roughness by implementing the NBS. The same effect is observed in Rufigiza. Traditionally, it is believed that increasing the surface roughness decreases the runoff, because it decreases the flow velocities (Darboux & Huang, 2005). This is also supported by the results of the sensitivity analysis in Paragraph 4.3.1 when the roughness increase is applied to the entire catchment.

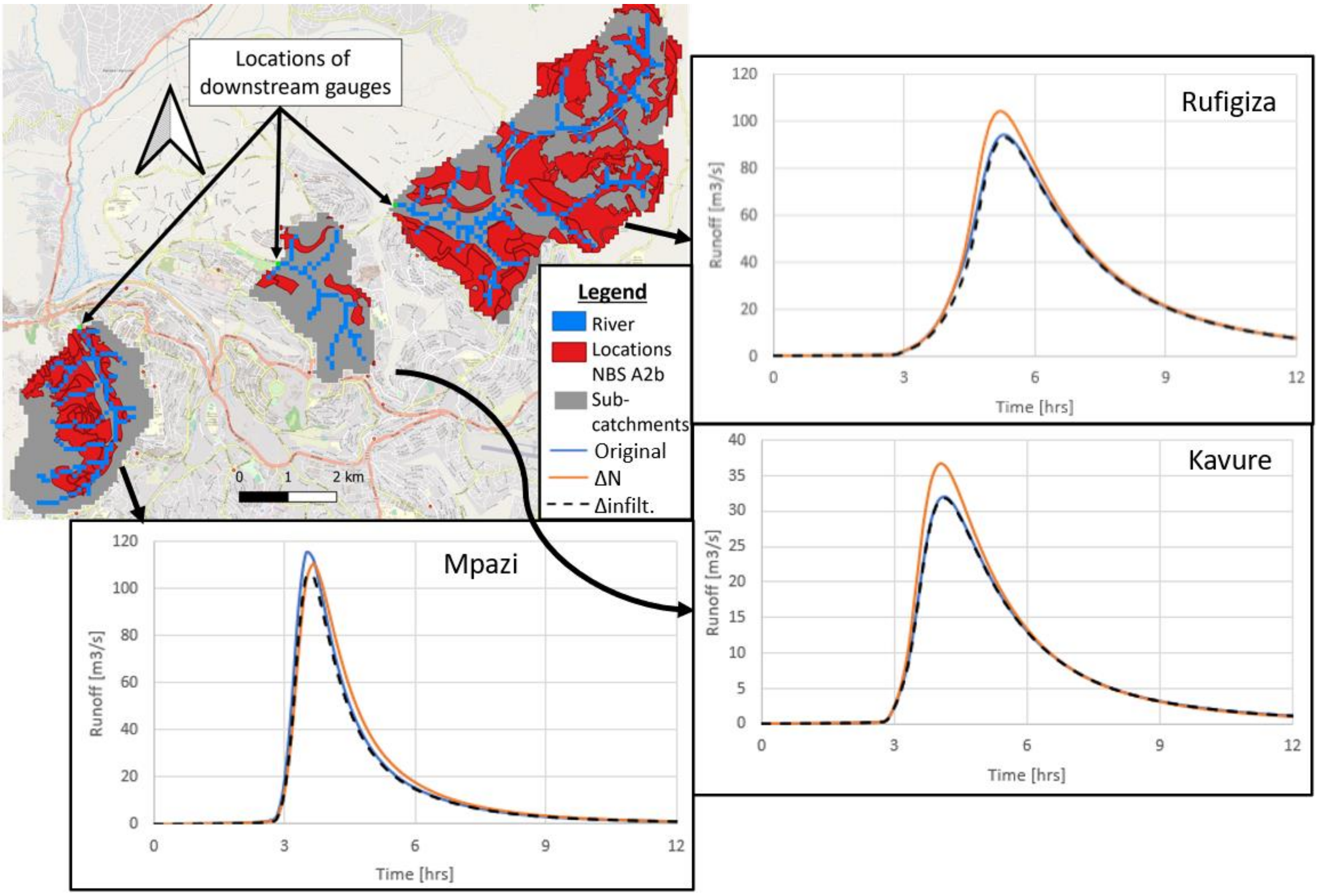

Figure 19 - downstream runoff for the three sub-catchments when changes in the infiltration rate and surface roughness of NBS A2b (contour planting) are compared to the original runoff when the return period is 100 years

However, as shown in this animation[14], the runoff mainly increases in upstream areas, where no roughness changes are made. It is uncertain what causes this runoff increase when increasing the surface roughness. Several hypotheses are tested, but were rejected:

- Runoff is re-routed around the rough areas such that it follows the path of the least resistance. It was believed that this could have been a result of using the Kinematic Wave approach

[14] see animation

(Miller, 1984). However, this hypothesis is rejected, because wflow-SBM uses a fixed LDD map to route runoff. It is impossible that the runoff routing has changed.

- Runoff accumulation occurs near the downstream boundary (Helming et al., 1998; Vermang et al., 2015). This does not occur in the model, because the increase runoff is initiated upstream[14].
- It is caused by the combined effect of infiltration and surface roughness. Figure 19 rejects this hypothesis.
- Wave coincidence due to delay of internal flood peaks occurs (World Bank, 2021). However, since only a single flood wave is observed in Figure 19, this does not occur.

Therefore, the most plausible explanation is that it is caused by a model anomaly. Though various attempts were made, it remains uncertain what causes this anomaly. The effect of the model anomaly is expected to be larger when considering the individual effects than combined effects. This is because no negative effects are observed in the sensitivity analysis of Paragraph 4.3.1 when surface roughness increases in an entire sub-catchment.

Combined effects of NBSs

Figure 20 shows that the maximum runoff and runoff volume decrease in all catchments, because of the implementation of retention areas and highly permeable soils. The combination of NBSs delays the runoff peak in Rufigiza and Mpazi, but not in Kavure. This is probably again caused by model anomaly in flat catchments.

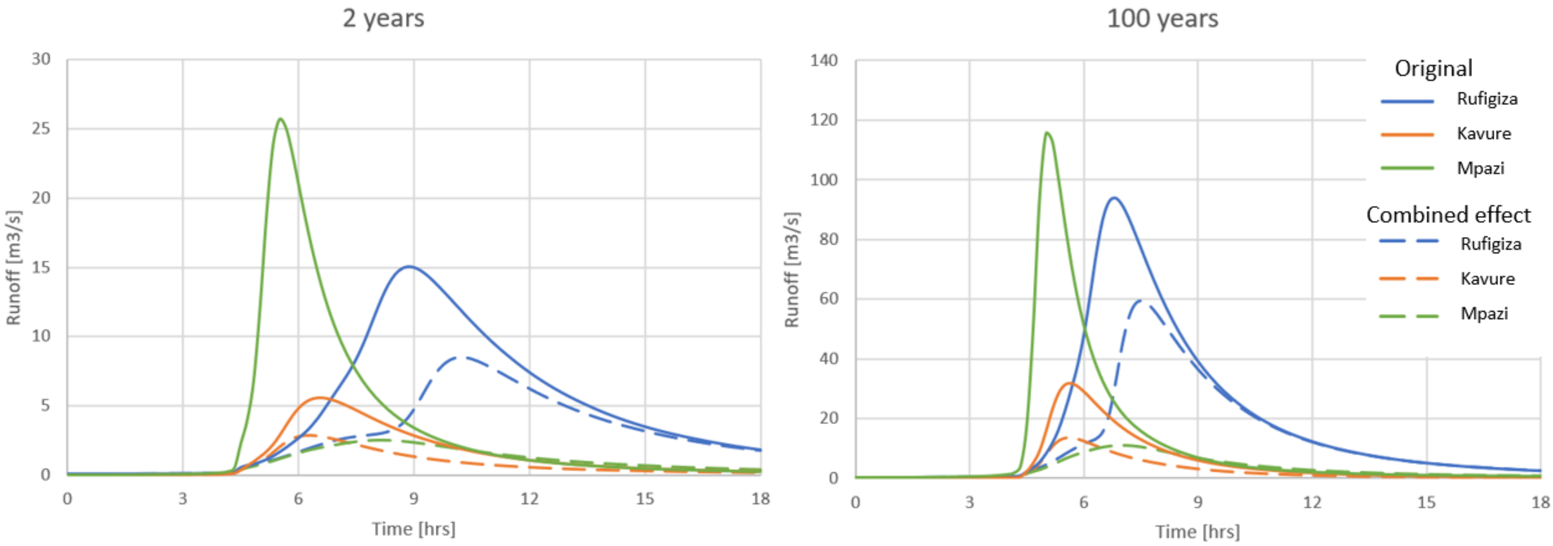

Figure 20 - combined effects of NBSs per sub-catchment for different return periods

NBSs are most effective in Mpazi. Since its terrain is steep, storage measures are relatively more effective in Mpazi than in the other sub-catchments. Also, NBSs increasing the infiltration capacity are more effective in Mpazi, due to its initially large, paved fraction. It is also shown that NBSs mainly decrease the maximum runoff and only have a small effect on the peak runoff volume (see Table F-4). This means that NBSs effectively delay stormwater runoff, but that only a small portion is stored or infiltrated.

In addition, NBSs have a similar effect on the maximum runoff for both return periods. Infiltration and/or surface water retention play a more important role in decreasing the runoff for larger amounts of rainfall, since the damping effect of surface roughness decreases with water depth (George et al., 1989). This result suggests that it is unlikely that the maximum infiltration and/or surface water retention capacity are reached.

4.4.4. Sensitivity of peak runoff to rainfall duration

The individual effects of one NBS per cluster for a long and short rainfall event with a return period of two years are shown in Figure 21.

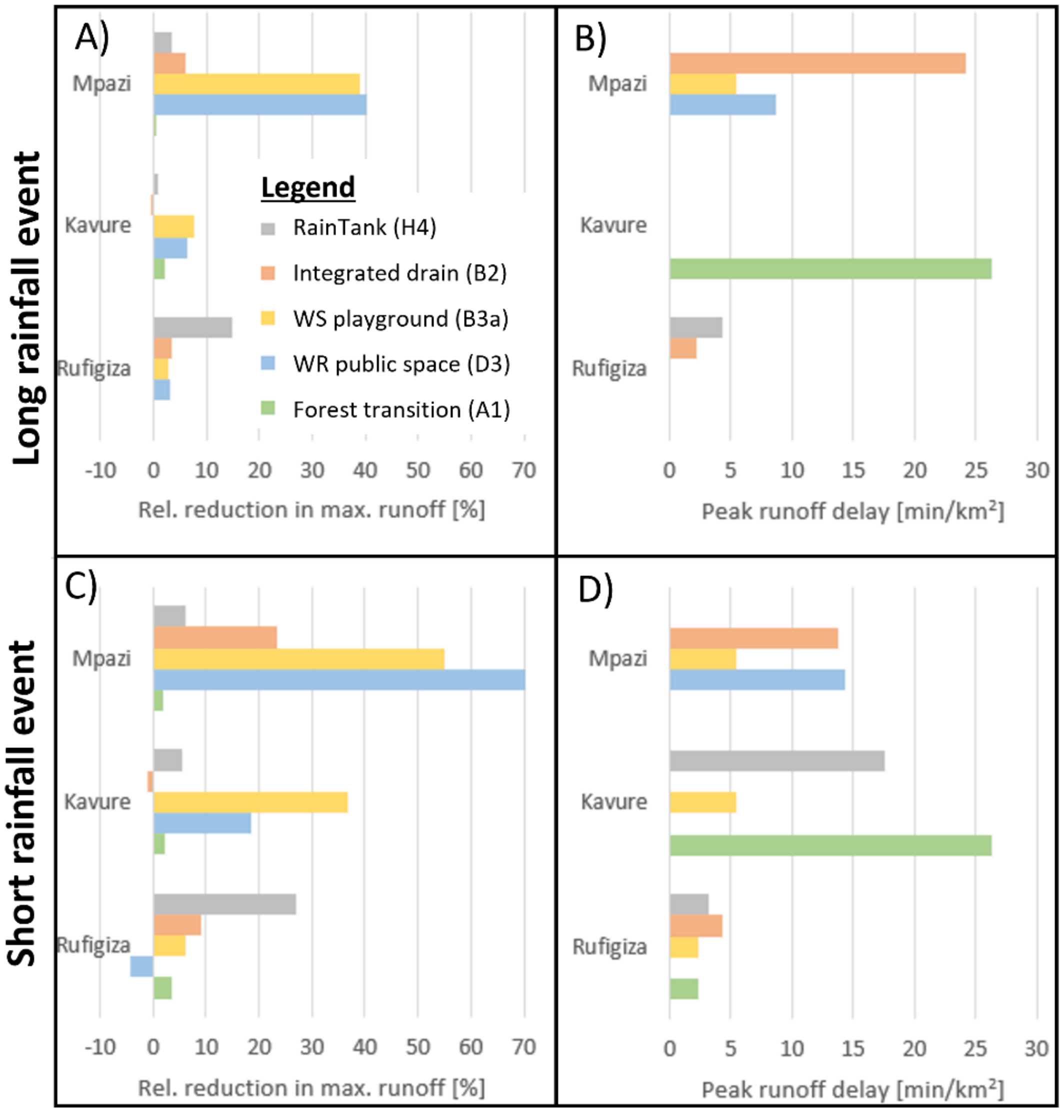

Figure 21 - NBS effects for a long (A, B) and short rainfall event (C, D) in terms of relative reduction in maximum runoff (A, C) and peak runoff delay (B, D) for a two-year return period

These results show that NBSs are generally more effective in decreasing the maximum runoff during short rainfall events. This is desirable because urban flooding primarily occurs due to high intensity short rainfall events (World Bank, 2021). During a short rainfall event, a NBS could delay the runoff until after the rainfall event. During long rainfall events, where the intensity is lower but the duration longer, this is not the case. Therefore, the relative effect of NBSs is smaller for long rainfall events.

In addition, Figure 21 shows that surface runoff storage NBSs, such as water retaining public spaces (D3) and water storing playground (B3a), significantly decrease the maximum runoff in Mpazi during both long and short rainfall events. During a long rainfall event, stored water has more time to infiltrate into the soil or evaporate (e.g., the average difference in rainwater that is infiltrated is two millimetres). However, these measures are more effective during short rainfall events, because the maximum runoff without these NBSs would be much larger than during a long rainfall event. In Rufigiza and Kavure the maximum runoff reduction during long rainfall events is significantly lower than in Mpazi.

Lastly, the negative effects of NBSs are less pronounced during long rainfall events (see D3 in Rufigiza and B2 in Kavure). This suggests that if further research points out that the negative effects are caused by a physical phenomenon, it is less notable for long rainfall events.

4.5. Research question 5 – comparison of effects of NBSs

In this section, the individual and combined effects of the new and the old approach are compared, as well as the results for long and short rainfall events. This is done using figures of the average NBS effects and representative flood waves. The complete comparison of the quantitative effects is included in Appendix F.5.

Individual effects

The individual effects computed in this study are completely different from the effects obtained by HKV (World Bank, 2021), because no separate model runs were used in HKV's approach. Therefore, the old approach is repeated in this study such that each individual NBS uses a separate model run. The average individual effects for the maximum runoff are shown in Figure 22. The peak runoff volume and delay are less relevant for urban flooding events and are therefore included in Appendix F.

The individual effects of NBSs are much larger in the new approach than in the old approach. This is caused by the following differences between the two approaches:

- Infiltration is included in the new approach and not in the old approach.
- Larger parameter value changes in the new approach than in the old approach when implementing NBSs (see Table 13 and Table E- 2). The parameter value changes are likely to be conservative in the old approach.
- The use of the paddy area function in the new approach rather than using a tree trunk interception parameter (Swood) which is dependent on the LAI. As shown in Figure 16 and Figure 17, this has the largest effect in Mpazi. In the old approach, only direct rainfall was stored, while in the new approach, overland flow may also be stored by the NBSs, and infiltration and open water evaporation occur over time.

These differences are illustrated by taking the Green Urban Park (NBS A3) as an example. At a return period of two years, the maximum runoff reduction is nearly 70% in Mpazi for the new approach, while the old approach suggests a reduction of less than 1%. These differences can be explained by the three arguments listed above. As shown in Figure 19, the effect of the inclusion of infiltration is relatively small. The larger changes in parameter values in the new approach than in the old approach is presumed to be mainly responsible to the large difference in maximum runoff reduction between the two approaches. The differences in storage capacity and roughness between both approaches are shown in Table 14.

Table 14 - differences in parameter value changes for the new and the old approach for NBS A3 (Green urban park)

Approach	Storage capacity [mm]	Manning roughness increase
Old	+ 2	x 1.01
New	+ 100	+(0.15 – X)

This table shows that the implemented storage capacity is much larger in the new approach than in the old approach. Two millimetres of additional storage is conservative, when assuming that the green urban park includes ponds and bioswales which can store a significant amount of water. In addition, the Manning roughness in the old approach is negligible, especially when implemented in urban areas with low initial roughness values. In the original model, the Manning roughness for paved areas is approximately 0.02 $s/m^{1/3}$, which is equal to the realistic roughness value used in the new approach. In these paved areas, the roughness only increases to 0.022 $s/m^{1/3}$ using the old approach, while when using the new approach, it can increase up to 0.13 $s/m^{1/3}$. For these reasons, the individual effects of NBSs shown in Figure 22 are generally larger for the new approach than for the old approach.

Furthermore, Figure 22 shows that NBSs are more likely to have a negative effect using the new approach. This can again be explained by the fact that the new approach generally allows larger roughness increases. This greater increase in roughness in the new approach is more likely to result in negative effects due to the model anomaly.

NBS-cluster InfRiv is the only cluster in which the effect on the maximum runoff of the new approach is generally lower than that of the old approach. In the old approach, all measures in the drains are assumed to increase the roughness by a factor of 1.5. In the new approach, substantiated assumptions are made resulting in smaller roughness increases in the drains.

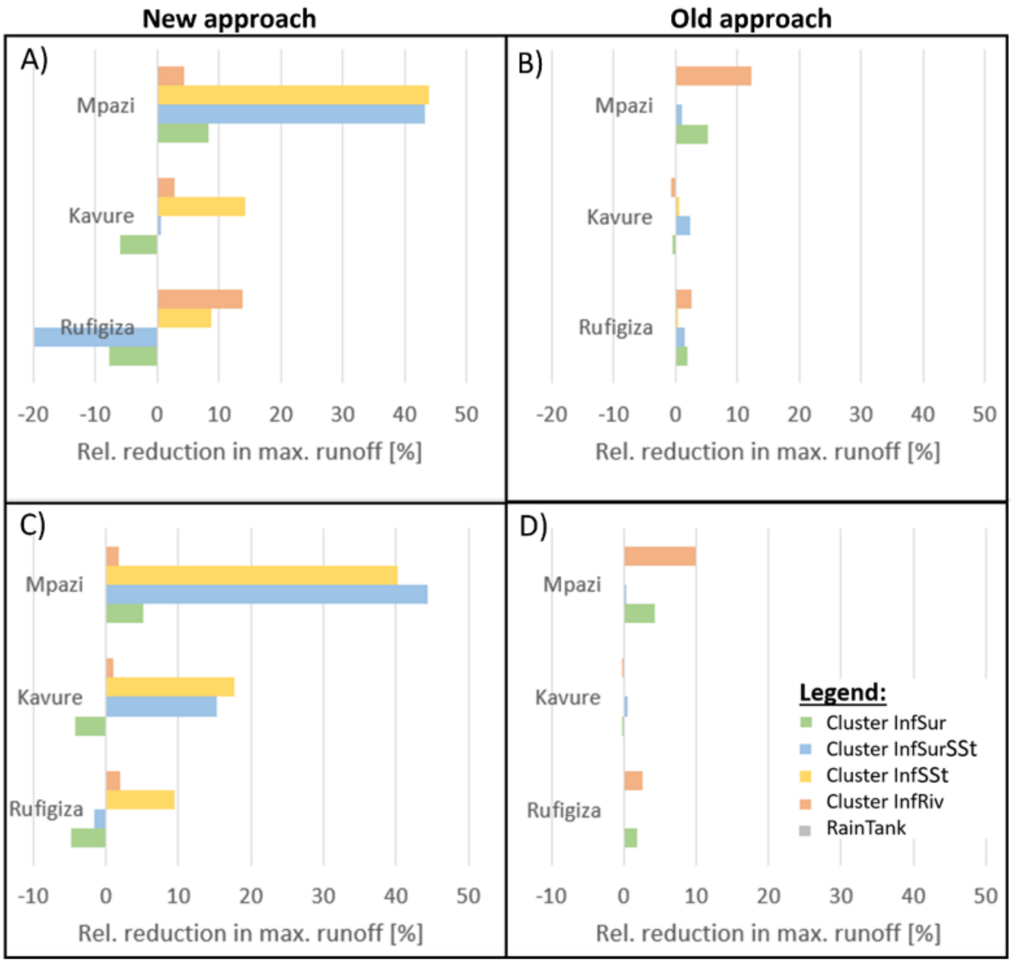

Figure 22 - average individual effects of NBSs for the new (A, C) and old approach (B, D) for return periods of two years (A, B) and 100 years (C, D)

Considering a return period of two years, NBS-cluster InfRiv is most effective in Rufigiza for both approaches. However, for Kavure and Mpazi, there is no agreement between the approaches about which NBS-cluster is most effective. Idem for when the return period is 100 years.

Lastly, changing the return period has a small effect on maximum runoff reduction. NBSs become slightly less effective when the return period increases. This applies to both approaches.

Combined effects

In Figure 23, the combined effects of NBSs in terms of runoff reduction over time of both approaches are compared. It shows that the combined effect of the new approach is much larger than that of the old approach. The combined effects of the old approach as computed in this study are nearly identical to what was found by HKV (World Bank, 2021). The differences are caused by the exclusion of certain NBSs described in Appendix G.

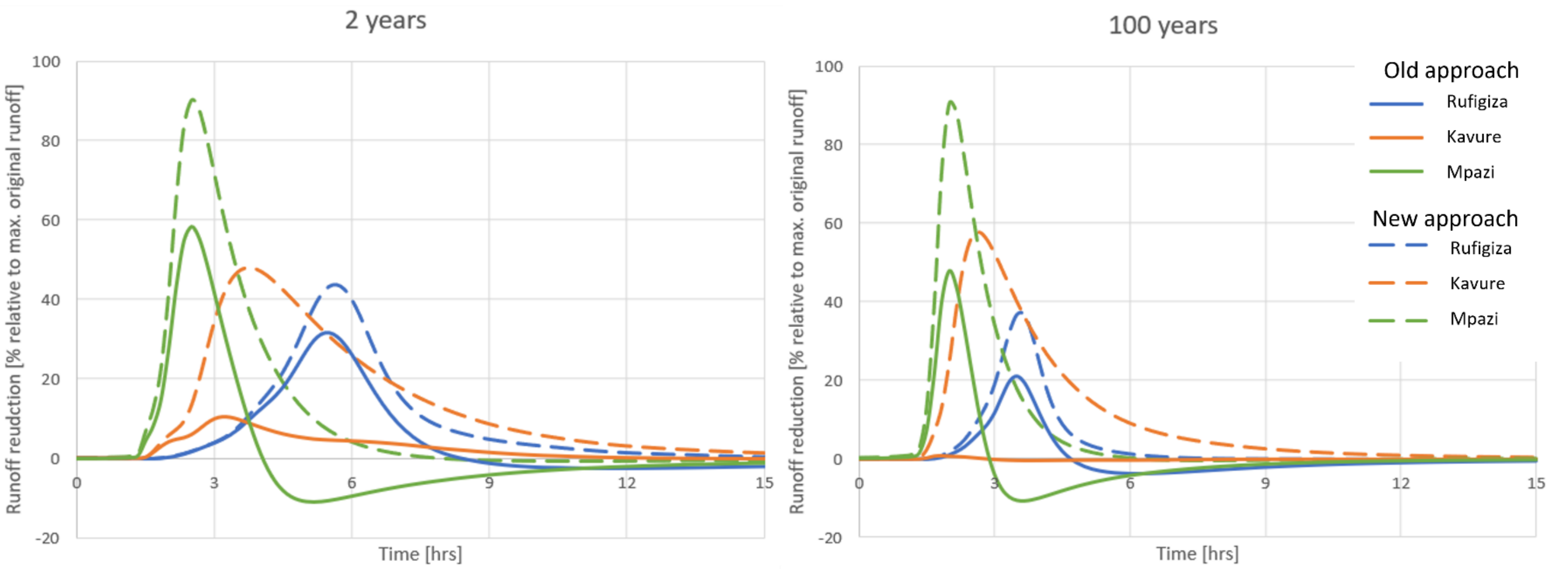

Figure 23 - comparison of combined effects of NBSs for the old and new approach for different sub-catchments and return periods

In Mpazi and Kavure, the largest differences in runoff reduction are observed. Both sub-catchments mainly consist of paved areas and therefore, the relative increases in surface roughness and infiltration capacity are larger than in the other two catchments. Infiltration is only included in the new approach. Also, as shown in Figure 17, the average LAI are the lowest in Mpazi. For that reason, the effect of increasing Swood is relatively small. Since the average LAI is the highest in Rufigiza, the differences between the new and the old approach are the smallest.

Using the old approach, HKV concluded that a combination of NBSs could lead to a small reduction of the flood hazard in the 2050 situation (World Bank, 2021). It is however possible that this approach underestimates the effects of NBSs. According to the new approach, NBSs are effective measures to decrease the urban runoff, even when the return period is 100 years. The maximum runoff may be reduced by 90% in Mpazi and by at least 35% in Kavure and Rufigiza.

The differences in the combined effects of NBSs between the two approaches are large, but smaller than the differences in the individual effects. This can be explained by the rules explained in Paragraph 3.4.3 when multiple NBSs are combined in a grid cell. The maximum roughness on the surface and in rivers is lower in the new approach than in the old approach.

Effects for short and long rainfall events

Like the new approach, when using the old approach, NBSs are generally more effective in decreasing the maximum runoff during short rainfall events. However, the differences are much smaller for the old approach. This can again be explained by the fact that the computed effects of NBSs are smaller in the old approach due to lower parameter value changes, use of Swood for storage measures and the neglection of infiltration. The comparison of the quantitative effects is displayed in Table F- 2.

5. Discussion

The methodology and results of this study are interpreted and discussed in this chapter.

5.1. Limitations

Some elements affecting the practical relevance of this study are described in this section.

Overestimation of NBS effects

Extreme soil erosion may occur due to abundant rainfall and agricultural expansion on steep slopes near Kigali (Karamage et al., 2016). Soil erosion results in the formation of a crust on the soil (Majoro et al., 2020). The infiltration rate decreases due to soil crusting, while the surface runoff increases (Majoro et al., 2020). The NBS effects are expressed in terms of peak runoff reduction or delay. Therefore, the NBS effects computed in this study are overestimated when soil crusting occurs.

In addition, the modelled surface area of small-scale storage NBSs is larger than in reality. The storage depths of small-scale NBSs (smaller than the size of a grid cell) are scaled using their estimated surface areas. In this way, the total storage volume per grid cell is equal to the storage capacity of the NBS. Therefore, open water evaporation and the captured overland flow volume are overestimated for these NBSs, because the surface area of small-scale storage NBSs is larger than in reality. Using the current model resolution, this problem cannot be avoided. The NBSs effects are expressed in terms of the reduction in the peak runoff volume and maximum runoff. The effect of evaporation is small compared to the peak runoff and can therefore be neglected in this study. The overestimation of the captured overland flow can however be important to the peak runoff, as it affects processes such as infiltration.

Potentially adverse effects of NBSs

It needs to be questioned whether the increased runoff due to the implementation of some individual NBSs is a result of a model anomaly or not. The kinematic wave approach is used in the wflow-SBM concept to route runoff. This approach simplifies the shallow water equations by neglecting the pressure and inertial terms, assuming that topography controls the water flow. This assumption holds in steep areas, but can cause inaccuracies in the subsurface, overland and channel flow in flat areas (Schellekens, 2019). In the case of subsurface flow, the hydraulic gradient is likely not equal to the surface slope and for overland and channel flow, pressure differences and inertial momentum should not be neglected. A more accurate alternative is the diffusive wave approach, which can be used in the Julia version of wflow-SBM. The diffusive wave approach considers the pressure term and neglects the inertial term (Collier et al., 2011).

Previous research has shown that the coincidence of flood waves due to the unbalanced implementation of NBSs within a sub-catchment can also result in an increased maximum runoff (World Bank, 2021). This effect is not observed in this study but should be considered when implementing NBSs in Kigali.

In addition, the local water levels could increase when applying measures in the drains by increasing their roughness, giving rise to an increased risk of flooding (World Bank, 2021). To avoid flooding while also lowering the maximum runoff using the surface roughness, the NBSs should be designed in such a way that they can temporarily store or convey more water. For the majority of NBSs in this study, this aspect is considered (e.g., an integrated neighborhood drain).

Spatial and temporal variability of the NBS effects

The effects of NBSs on hydrological processes depend on where they are implemented. For example, when trees are placed in a floodplain, they can significantly slow down the flow velocity. However, when they are positioned on a hillslope, their effect on the flow velocity is much smaller (Russell, 2021; Sanz-Ramos et al., 2021). In this hydrological modelling study, the friction is only caused by flow-boundary interactions. In reality, vegetation also causes turbulence, which increases the friction and dissipates energy from the flow (Sanz-Ramos et al., 2021). Turbulence may be neglected in steep areas. However, in more gently sloping areas, neglecting turbulence may lead to a rainfall-runoff response which is much quicker than in reality (Sanz-Ramos et al., 2021). Unrealistically high Manning values are often used for compensation (Sanz-Ramos et al., 2021). This is also observed in the wflow-SBM of Kigali. To obtain more representative effects of NBSs, the surface roughness increase should be expressed as a function of the slope and land use/cover. NBS effects are currently independent of the slope for both approaches. Figure 23 shows that the combined effects of NBSs are most pronounced in Mpazi and Kavure because these sub-catchments mainly consist of paved areas. The average slopes in these sub-catchments are significantly different, so it is assumed that the dependence of NBS effects on the slope plays a minor role in determining the combined effects of NBSs compared to the dependence on land cover. The dependency on the slope is expected to be larger when considering individual effects of NBSs. For instance, some individual NBSs such as contour planting are always positioned on a hillslope. This is also supported by Figure 22, which shows that the individual effects are much larger in Mpazi than in the other two sub-catchments. Therefore, parameter value changes for individual NBSs should be corrected for the dependency on the slope.

In addition, the observed effects of NBSs may also change over time. In the case of forestation, the trees may lose their leaves and therefore some of their hydraulic effectivity. This can be neglected in this study though as Kigali is located in the tropics. Trees also grow on an annual basis and thus their effects are expected to increase over time. Some NBSs may also become less effective over time due to erosion and sedimentation. In other words, expressing NBS effects in terms of static variables may result in an over- or underestimation of the results.

Furthermore, the actual rainfall intensity varies both in time and in space. In the model, only the magnitude of the maximum rainfall differs between grid cells. The timing is identical in all grid cells. In reality, clouds propagate over a catchment at the wind speed (Helfer, 2019). The timing of the maximum rainfall depends on the location of the cloud. It could therefore be that delaying runoff using NBSs causes a downstream coincidence of flood waves, resulting in an increased maximum runoff. Though it should be noted that rainclouds generally propagate about ten times faster than water travelling over land (Blöschl & Sivapalan, 1995), this phenomenon is likely to play a role in Mpazi and Kavure as he main flow direction is the same as the annual mean wind direction in Kigali (Onyango et al., 2015). In Rufigiza, the main flow direction is not equal to annual mean wind direction. Therefore, moving rainclouds are likely to result in a reduction of the maximum runoff. It should however be questioned whether this is relevant, since the sub-catchment considered in this study are small. For large sub-catchments, moving clouds are recommended to be used in the hydrological model.

5.2. Practical relevance

Validation of NBS effects

Ideally, the effects of NBSs are validated. Quantitative data of the measured ranges of runoff reduction are available for some NBSs. These NBSs include water storing ponds, green roofs, permeable pavement, bioswales and contour planting (Farahani et al., 2016; Ruangpan et al., 2020). For example, permeable pavement reduced the maximum runoff by approximately 20% during a case study in Texas and the maximum runoff reduction was almost 45% for a water storing pond in Malaysia (Ruangpan et al., 2020). The individual effects determined in this study are in the same order of magnitude but are slightly lower. The NBSs are only implemented at specific locations in the Kigali model and not for the entire catchment. The available data of NBS effects mainly consist of measurements taken at a local scale and are not available at a catchment scale. These local effects cannot be upscaled to the catchment scale, where NBSs are implemented at specific locations.

Also, validation data have not been obtained in Kigali. This study shows that the effects of NBSs depend on characteristics of a sub-catchment such as slope, land use, prevalence of paved surfaces and the network of drains and rivers. Thus, the validation data are unrepresentative and cannot be used. The data can be used to validate the methodology employed in this study when all steps are applied at the location where the validation data are available. However, this requires a new hydrological model to be built at this location.

Suitability of wflow-SBM in Kigali

Wflow-SBM is a suitable hydrological model in data-scarce environments (Gebremedin et al., 2020). So, even though little reliable field data is available for Kigali, no additional field measurements were taken to develop the model. Field measurements are often expensive and take much time. Therefore, the wflow-SBM concept is suitable for Kigali.

Practicality of applied methodology to implement NBSs

More insight is gained in the expected hydrological effects of the set of NBSs in Kigali by describing NBSs in terms of hydrological processes. This methodology prevents important hydrological processes from being omitted and allows NBSs to be schematized using land use and land cover changes. This causes the methodology to be transparent and reproducible for further research in both Kigali and in other catchments.

5.3. Generalisation

The research goal was to determine the NBS effects for Kigali and to develop a methodology which can be applied in NBS-studies for other catchments using different hydrological models. Therefore, this section discusses the elements of this research which can be used for other urban NBS studies. Also, the elements, which should not be generalised, are discussed. The methodology used in this research to parametrise NBSs can be generalised to other catchments and different fully distributed physically based hydrological models.

This study has shown that the positioning of NBSs within a catchment determines their effects. Hence, for an accurate effectivity assessment of NBSs, a hydrological model and an evaluation on sub-catchment scale are required. The hydrological effects of NBSs in Table 7 and the quantification of the hydrological processes resulting from the implementation of NBSs in Paragraph 4.4.1 apply to other catchments and different physically based hydrological models. These models must be fully distributed and include the same hydrological processes. Examples of suitable hydrological models are MIKE SHE, LISFLOOD, D-Hydro and HydrGeoSphere (Islam, 2015). Like wflow-SBM, these hydrological models use orthogonal grids. Implementing NBSs in semi distributed or lumped models introduces additional uncertainty in the parametrisation of NBSs and does not allow for implementation at specific locations in a catchment (Qiu et al., 2021). Thus, to make the modelling results more accurate and credible, the use of a physically based and fully distributed hydrological model is recommended.

In addition, it is recommended not to generalise the estimated effects of NBSs based on the areal characteristics of a catchment. The effects of NBSs depend on the slope, land use and their interactions with the catchment's drainage network. These factors are different for another catchment and so, the extrapolation of runoff reduction values between catchments is meaningless (Mayor et al., 2011). The computed effects of this study can however be used to qualitatively substantiate which NBSs are expected to be effective given the areal characteristics. The following generalised rules of thumb can be adopted regarding the effectiveness of NBSs in reducing the maximum runoff:

- Surface runoff storage NBSs are more effective measures to decrease the maximum runoff than NBSs which increase the surface roughness.
- NBSs which cause an increase in the surface roughness and infiltration capacity are most effective in paved areas.
- NBSs which cause a surface roughness increase are most effective in upstream areas, while delaying NBSs in drains and rivers can be applied to the entire catchment (see Appendix H).
- Surface runoff storage is most effective in steep areas. It should however be noted that the slope is a key limiting factor to water storage. It may not be economically beneficial to place surface runoff storage NBSs in steep area, because they require much earth excavation in areas with limited accessibility.

6. Conclusion and recommendations

6.1. Conclusion

The main aim of this research was to compare the effects of NBSs on urban runoff simulated with old implementation into wflow-SBM and a new physically based approach. The main conclusion is that the old approach probably underestimates the effects of NBSs in Kigali. By focussing on the parametrisation of NBSs, the possibilities and limitations of the wflow-SBM concept for implementing NBSs are assessed and the unit effects of NBSs in Kigali are updated. In addition, more insight is gained in the effectiveness of NBSs in different types of urban catchments. In the following section, the answers to the five research questions are provided.

The SWOT analysis shows that the main limitations of the old approach are the use of unrealistically high Manning values, the omission of infiltration, and the parametrisation of surface runoff storage and small-scale NBSs. Also, the individual effects are determined using the combined effects. These limitations have a significant effect on the simulated urban runoff due to the implementation of NBSs.

Using common conceptual effects of NBSs on the hydrological cycle, all NBSs are clustered into groups. NBSs in the same cluster can be implemented using the same model parameters.

Sensitivity analyses showed that infiltration is a hydrological process that needs to be included, but that it is plausible to neglect transpiration, interception and evaporation when assessing the peak runoff. 70% of the rainfall is infiltrated to soil during a rainfall event with a return period of 2 years. However, the effect of changing the maximum infiltration capacity when implementing NBSs is usually less than 10%, depending on the characteristics of the sub-catchment and the NBS. The parametrisation of surface runoff storage NBSs was improved using the function for paddy areas instead of increasing the branch trunk storage (Swood). The limitations of Swood include the inability to capture overland flow, the dependency on the leaf area index and the failure to capture rainwater infiltrating into the soil.

In general, surface runoff storage NBSs are more effective than NBSs which increase the surface roughness. Individual storage NBSs can decrease the maximum runoff up to 40%, while the maximum runoff reduction of delaying NBSs is generally below 10%. Surface runoff storage NBSs are equally effective for both return periods considered in this study, suggesting that the maximum storage capacity is not reached during extreme rainfall events. NBSs increasing the surface roughness are most effective in upstream areas, while delaying NBSs in drains and rivers are also effective in downstream regions. It was shown that not only the slope and land cover of a catchment are crucial for the effects of NBSs, but also the positioning of a NBS relative to the catchment's drainage network are crucial for the effects of NBSs. This emphasises the importance of using a hydrological model. Both the individual and combined effects of NBSs are most noticeable in Mpazi. Large effects are observed when implementing NBSs in steep and paved areas due to two reasons. Firstly, the contributions of infiltration and roughness are relatively more important in paved areas than in unpaved areas. Secondly, due to the high slope and the low surface roughness, the runoff can become large without the presence of NBSs. Hence, in Mpazi, the combined effects of NBSs could decrease the maximum runoff by more than 90%, even if the return period is 100 years. Though the model's validity and thereby the absolute effects of NBSs are debatable, it can be said that NBSs likely reduce the risk of flooding in Mpazi. In the other two catchments, the effects of NBSs are smaller, but NBSs still reduce the maximum runoff significantly. The effect on the runoff volume is less pronounced in all sub-catchments.

The effects of the new implementation were compared to the effects of the old approach. It is shown that the NBS effects of the new approach are significantly larger than those of the old approach for all sub-catchments and return periods. This is due to smaller parameter value changes, use of Swood for storage measures and neglecting infiltration in the old approach. The new approach includes all relevant hydrological processes and is more detailed. However, since the results are not validated, it is impossible to say which approach represents reality best. Therefore, the results of this research should not be used as generalised effects of NBSs. Nevertheless, since the new approach uses all relevant hydrological processes and carefully chosen parameter value changes, its results can be used to explain why the old approach is likely to underestimate the effects of NBSs. Also, the methodology used in this research to parametrise NBSs can be generalised to other catchments and different fully distributed physically based hydrological models.

6.2. Recommendations for practice and future research

The practical recommendations can be used by stakeholders involved in NBS-projects in Kigali and other urban catchments. The recommendations for future research are meant to gain more insight in the general process of determining the effects of NBSs.

6.2.1. Practical recommendations

Optimisation

This study shows that finding the optimum locations of NBSs is critical. Though this lies outside the scope of this research, attempts to optimise the runoff reduction, by changing the roughness in upstream and downstream roughness, are shown in Appendix H. However, this optimisation procedure is complex because the drainage network of each sub-catchment is unique. Therefore, an optimisation study is recommended to find the optimal set of NBSs and their locations for each sub-catchment. This study should include the following steps:

1. Define the hydrological processes which are affected by the implementation of each NBS (refer to Paragraph 4.2).
2. Determine the corresponding model parameters and their physically plausible ranges (refer to Paragraph 4.4.1).
3. Optimise the value of each relevant model parameter using an optimisation algorithm (e.g. genetic) in all grid cells such that the runoff reduction is maximised (Zemmari & Benois-Pineau, 2020). This can for instance be applied in Matlab using the global optimisation toolbox or in Phyton using the PyGAD library.
4. Associate the parameter value changes with NBSs.
5. [Optional] Extend the optimisation study by combining it with the costs and benefits of NBSs in cooperation with Ecorys (company responsible for cost-benefit analysis is the NBS project of Kigali).

Obtaining local field measurements

A challenge in the parametrisation of NBSs is the lack of quantitative data. If data are available, their quality is often poor. In addition, data obtained in areas other than Kigali are unrepresentative for the study area, because measurements are obtained in areas that have significantly different soil and vegetation characteristics and precipitation patterns. To obtain a more accurate parametrisation for Kigali, local field measurements are required. Measurements should for example include the infiltration capacity and surface roughness of different land use types, e.g., to determine whether soil crusting occurs or not. Alternatively, measurements of the effects of local NBSs can be used to validate the computed effects of these NBSs implemented at the same locations. The infiltration capacity can be measured using a double ring infiltrometer (Eijkelkamp, 2012) and the Manning roughness can be calculated after measuring the flow velocity, hydraulic radius and slope. Note that multiple measurements per grid cell are required to obtain reliable data.

In addition, it is also recommended to monitor the hydraulic effectivity of NBS-elements in space and time. It should be measured to what extent there is a difference in the flow velocity reduction when NBSs are positioned at different locations (e.g., floodplain and hillslope). Also, annual measurements should be obtained to investigate whether this effect changes over time as NBSs adapt to their environment. These measurements may not only stress the importance of the implementation of NBSs but can also be used in decision making for local authorities applying NBSs.

6.2.2. Recommendations for future research

Parametrisation of small-scale NBSs

It is recommended to do further research on the parametrisation of small-scale NBSs in hydrological models. The spatial resolution of most hydrological models is insufficient to implement small-scale interventions. So, their parametrisations require grid-based assumptions to be made. This research shows a promising coupling of wflow-SBM to the Adaptation Support Toolbox, which allows measures to be schematised in much more detail. However, the resulting parameter value changes remain uncertain, as they require weighted averaging of the hydrological effects. Therefore, research should be done either to a more accurate implementation of small-scale interventions in hydrological models with a limited spatial resolution, or to the use of hydrodynamic models in NBS-studies. A hydrodynamic model allows a more accurate implementation of small-scale measure because its spatial resolution is often high (<10m pixels). A suitable hydrodynamic model is HECRAS, because it is freely accessible. However, a model with a higher spatial resolution requires more data. The trade-off between the availability of data and model complexity should be considered. Therefore, the comparison of the effects of small-scale NBSs in a hydrological model and a hydrodynamic model should be made in an urban catchment where more data is available.

Model anomaly

In addition, more insight in the causes of the model anomaly, resulting in an increase of the maximum runoff, should be gained. The model anomaly should be communicated to Deltares and tested in the Julia version of wflow-SBM. If the negative effects of individual NBSs are still observed, a different physically based model (e.g., D-Hydro) can be used to determine the effects when increasing the roughness at the same locations. This model would need to be built however, as no fully distributed physically-based hydrological model are available for the Nyabugugo catchment apart from wflow-SBM (Mindje et al., 2021). If an increase in the maximum runoff is observed in all cases, it is likely to be caused by a physical phenomenon which could also occur in nature. Further research to the underlying causes of this phenomenon should then be done.

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Appendices

Appendix A – relevant look-up tables

This appendix contains relevant look-up tables which are mainly used in the small-scale calculations of research question 2 and 4.

Table A- 1 - look-up table for specific leaf index (SI), total storage in the woody part of the vegetation ($C_{max,wood}$) and the coefficient k for different land cover characteristics (Schellekens, 2019)

SI	$C_{max,wood}$	Land cover characteristics
0.1272	0.01	Mosaic cropland (50-70%) / vegetation (grassland/shrubland/forest) (20-50%)
0.03926	0.5	Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)
0.036	0.5	Closed (>40%) broadleaved deciduous forest (>5m)
0.09	0	Closed to open (>15%) herbaceous vegetation (grassland or savannas)
0.04	0.04	Sparse (<15%) vegetation
0.04	0.01	Artificial surfaces and associated areas (Urban areas >50%)
0.04	0	Bare areas
0.04	0	Water bodies

Table A- 2 - Manning n values for channels (V. T. Chow, 1959)

Type of Channel and Description	Minimum	Normal	Maximum
1. Main Channels			
a. clean, straight, full stage, no rifts or deep pools	0.025	0.03	0.033
b. clean, winding, some pools and shoals	0.033	0.04	0.045
c. sluggish reaches, weedy, deep pools	0.05	0.07	0.08
d. very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.1	0.15
2. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
a. bottom: gravels, cobbles, and few boulders	0.03	0.04	0.05
b. bottom: cobbles with large boulders	0.04	0.05	0.07
3. Floodplains			
a. Pasture, no brush			
1.short grass	0.025	0.03	0.035
2. high grass	0.03	0.035	0.05
b. Cultivated areas			
1. mature row crops	0.025	0.035	0.045
2. mature field crops	0.03	0.04	0.05
c. Brush			
1. scattered brush, heavy weeds	0.035	0.05	0.07
d. Trees			
1. dense willows, summer, straight	0.11	0.15	0.2

Table A- 3 - Manning n values for flow over the surface (V. Te Chow et al., 1988; Jung et al., 2011; Vieux, 2001)

Wflow Land use Class	Description	Manning n [$s/m^{1/3}$]
1	Forest	0.180
2	Open areas or grass	0.080
3	Agriculture (seasonal)	0.100
4	Bare soil	0.035

5	Settlement and buildings	0.020
6	Water bodies	0.030
7	Wetlands	0.050
10	Sparse forest	0.100
11	Agriculture (perennial)	0.100

Table A- 4 - hydraulic conductivities of different soil textures (Carsel & Parrish, 1988)

Texture	Hydraulic conductivity [cm/d]
Sand	712.8
Loamy sand	350.2
Sandy loam	106.1
Loam	24.96
Silt	6.00
Silty clay	0.48
Clay	4.80
(Concrete) pavement	0.00

Table A- 5 - Curve Numbers for different cover types, hydrological soil groups and hydrological conditions (V. Te Chow et al., 1988; HEC-HMS, 2021)

Cover description		**Curve numbers for hydrological soil group**			
Cover type	**Hydrological condition**	**A**	**B**	**C**	**D**
Urban areas					
Impervious areas (paved parking lot, roofs, driveways, etc.)	-	98	98	98	98
Paved; open ditches	-	83	89	92	93
Cultivated agricultural lands					
Bare soil	-	77	86	91	94
Straight row crops	Poor	72	81	88	91
	Good	67	78	85	89
Contoured row crops	Poor	70	79	84	88
	Good	65	75	82	86
Other agricultural lands					
Pasture, grassland, or range	Poor	68	79	86	89
	Good	39	61	74	80

Table A- 6 - hydrological soil groups (Stone, 2015)

Soil group	Soil texture	Description	Infiltration rate [mm/h]
A	Sand, loamy sand or sandy loam	Lowest runoff potential, deep soils	8-12
B	Silt loam or loam	Moderately low runoff potential	4-8
C	Sandy clay loam	Moderately high runoff potential	1-4
D	Clay loam, Silty clay loam, sandy clay, silty clay or clay	Highest runoff potential, shallow soils	0-1

Appendix B – interviews

This appendix corresponds to the first research question. First, the interview protocol and an overview of the interview questions are provided. In Appendix B.3 – B.6, the transcripts of the four interviews are attached.

B.1. Interview protocol

Step 1 - Before the interview:

- Invite the interviewees. To get a balanced view on the current implementation of NBSs into wflow-SBM, people with different extents of involvement in the project are interviewed:
    - Geerten Horn – responsible for the NBS implementation in wflow-SBM by HKV for Kigali.
    - Bobby Russell – product manager of wflow (manages the development process) and team leader of the development team of the wflow-SBM of Kigali.
    - Mark Hegnauer – former product owner of wflow (lead programmer), but not involved in the Kigali project.
    - Jerom Aerts – PhD candidate, who is using wflow-SBM to investigate the effects of spatial resolution on the model accuracy. He is not involved in the Kigali project.
- Prepare open-ended questions relevant to each interviewee. For each interview, a slide show is made containing all the questions, and supporting figures and tables. The questions are prepared by critically examining the current implementation of NBSs into the wflow-SBM and reading relevant documents. Documents that were used are the wflow documentation (Schellekens, 2019), the Flood Model and Hazard Assessment Report of Kigali (Gebremedin et al., 2020) and the final report of the World Bank for the NBS assessment in Kigali (World Bank, 2021). Also, spreadsheets and scripts used by HKV to implement NBSs are examined. Lastly, questions are also prepared by investigating which parameters have been adjusted to implement NBSs in the current approach by visualising relevant wflow files using QGIS.
- After having set up the interview, perform a test interview. This does not only give an indication of the time required for each interview, but also allows the order of the interview questions to be changed prior to the interviews.

Step 2 - During the interview:

- Start by introducing myself and the topic of my master thesis (only when relevant).
- Mention the goal of the interview.
- Give an overview of the different topics that will be discussed during the interview and give an indication of the time it is expected to take.
- Ask for consent to record the interview.
- Start the recording and begin the interview. Each interview starts with some introductory questions (e.g., position, role in the project). After that, different topics are discussed depending on the interviewee. An overview of all the interviewee questions is shown in Table B- 1.
- Close the interview by thanking the interviewee for his time.

Step 3 - After the interview:

- Use the recording of the interview to write a transcript and send it to the interviewee for feedback.
- Improve the interview questions, if necessary, prior to re-using them for the next interview.
- Process the results by adding them to the SWOT analysis matrix in Figure 11.

B.2. Overview of interview questions

Table B- 1 - overview of the interview questions asked to the different interviewees

Interview question	Interviewee
Introduction	
What is your role with Deltares/HKV?	Geerten Horn, Bobby Russell, Mark Hegnauer
What is the topic of your PhD?	Jerom Aerts
In which ways were you involved in the flow project for Kigali?	Bobby Russell, Geerten Horn
Which wflow projects have you been involved?	Mark Hegnauer
For which purposes have you used wflow?	Jerom Aerts
Development goals of wflow	
Why did Deltares decide to develop wflow?	Bobby Russell, Mark Hegnauer
Do you have any idea why there are few scientific articles available which address modelling studies using wflow?	Bobby Russell, Mark Hegnauer
Model validation	
For the Kigali model, the discharge was only validated using discharge data at Nemba. What can be said about the resulting validity of the model?	Bobby Russell
Representation of the hydrological cycle	
What is the canopy gap fraction? And how does this influence interception, soil evaporation and transpiration?	Mark Hegnauer
How is drainage from the canopy after interception taken into account by the SBM concept?	Mark Hegnauer
How is transpiration included in the model? And is it proportional to the amount of vegetation?	Bobby Russell, Mark Hegnauer
Which parameters influence the infiltration into the saturated and unsaturated store?	Mark Hegnauer
How is open water evaporation accounted for?	Mark Hegnauer
How could I increase the evapotranspiration in the system? Should I increase the PET forcing or is this included in wflow parameter e.g. land cover?	Mark Hegnauer
Which hydrological processes are not taken into account when using land cover changes?	Mark Hegnauer
To what extent are certain hydrological processes negligible to the surface runoff simulated by wflow?	Mark Hegnauer
To what extent has research been done to investigate the runoff effects of using the kinematic wave approach for a terrain with a mild slope?	Mark Hegnauer
How does the waterdem = 1 option limit the inaccuracy of the model in mildly sloping terrain? Should this option be included in for Kigali?	Mark Hegnauer
Spatial mask	
How is the spatial mask determined for each NBS?	Geerten Horn
What are the applicabilities of NBSs for different population densities based on?	Geerten Horn
Why has the decision been made to exclude certain measures (not implementing them into wflow)?	Geerten Horn
Spatial scale	

Why does a model not always become ‘better’ at a higher resolution?	Jerom Aerts
A higher resolution causes a gentler slope in relatively flat areas. Can you explain this using the Kinematic Wave approach?	Jerom Aerts
To what extent has research been done on relevant spatial scales of hydrological processes, e.g. interception, infiltration and transpiration?	Jerom Aerts
How have you investigated changes of different fluxes in wflow?	Jerom Aerts
Implementation of NBSs	
How did HKV adjust the quantified effects from Defacto?	Geerten Horn
How have the values in column ‘value’ been determined given the data from Defacto?	Geerten Horn
How could small-scale measures (smaller than the grid size) be implemented into wflow?	Mark Hegnauer, Jerom Aerts
Is it possible to locally refine the model? And if so, how?	Mark Hegnauer, Jerom Aerts
How did Deltates conclude that 90x90 m was a suitable grid size for the wflow model of Kigali?	Bobby Russell
Why is it difficult to implement storage measures into wflow using only its model parameters?	Bobby Russell, Mark Hegnauer
What are the disadvantages of using the Swood parameter to represent storage measures	Geerten Horn, Mark Hegnauer
What are your thoughts on the following wflow improvement to represent storage measures? [show image of additional storage layer for the SBM concept]	Bobby Russell, Mark Hegnauer
Why are the Swood parameters not adjusted after running the script NBS_all.py?	Geerten Horn
Are there, apart from using N and N_{River}, other parameters that could possibly be used to implement surface and drain measures?	Geerten Horn
Quantifying the effects	
What is the output of the model used to quantify the effects of NBSs?	Geerten Horn
How did you determine the unit effects of NBSs?	Geerten Horn
Limitations and improvements	
What are other limitations of the Kigali wflow model?	Geerten Horn, Bobby Russell
Which improvements can be made to wflow model?	Jerom Aerts

B.3. Geerten Horn – HKV – 22-11-2021

[Note, the interview was set-up in Dutch, because the interviewee and I both speak Dutch]

Inleiding:

[Q]: Wat is je rol binnen HKV?

[A]: ik ben adviseur binnen HKV. Daarbinnen kan ik een hoop verschillende dingen doen, waaronder hydraulisch modelleren, voorspelsystemen en overstromingsmodelleren. Ik heb redelijk veel in Afrika gewerkt, met name in Ghana. Ook in Togo, Burkino Fase en Ivoorkust. Rwanda is ook Afrika, dus dat zorgt voor een snellere link. Ik heb veel met Job samengewerkt, dus dat ik ook reden dat Job mij vroeg om hierbij te helpen. Daarnaast heb ik eerder met wflow gewerkt. Het wflow model van Kigali is gemaakt door Deltares. Wij moesten de NBSs er in implementeren. We hebben het model niet doorgerekend, maar het toch wel handig als je een beetje een beeld hebt van wflow.

[Q]: Op welke manieren ben je betrokken geweest bij het NBS project in Kigali?

[A]: Binnen dit project ben ik project medewerker. Samen met Job bespreek ik wat er moet gebeuren en dat doe ik. Job is projectleider vanuit HKV. Hij weet meer over de achtergrond. Ik probeer daar niet teveel over te weten. Naast ons is er niemand direct betrokken. Alleen Abbe Klaas is deels betrokken geweest in het genereren van de shapefiles, relevant voor de spatial masks. Vanuit Defacto hadden ze namelijk alleen .dbg-bestanden (autocad files).

Spatial mask:

[Q]: Hoe is bepaald waar welke NBSs effectief zijn en dus geïmplementeerd zullen worden? Hoe is de spatial mask per NBS bepaald (toolbox van Defacto bijv.)?

[A]: Er is een mask per gebruikstype. Je hebt daar een tabel met verschillende gebruikstype. Per gebruiktype is er een kaart met dit gebruikstype valt daaronder. Er zijn ook nog een paar andere kolommen in deze tabel, waaronder de Urban Upgrading. Dat is een gebied dat aangemerkt is als een die in de toekomst geurbaniseerd of geupgrade gaat worden. Dat zijn de verschillende masks die er zijn. Dan jouw vraag: hoe zijn de masks gemaakt. Dat weet ik eigenlijk niet. Dan kom je uiteindelijk bij Defacto uit. Zij hebben de masks gemaakt. Voor een deel kan ik het wel uitleggen. Bijvoorbeeld de typologies. Er zijn natuurlijk bronnen waarin staat aangegeven wat een bepaald gebied is, bijvoorbeeld OpenStreet maps. Die bronnen, in combinatie met bronnen van het land zelf, combineer je met open datasets en daar zijn wat dingen uit te halen. De Urban Upgrading komt uit plannen van de overheid. Het is wel een belangrijk onderdeel. Per maatregel zijn er best wat verschillende keuzes gemaakt over wat waarop wordt toegepast. Dit zijn keuzes die allemaal gemaakt zijn door Defacto in dit geval.

[Q]: oke, dus de informatie in de tabel is opgesteld op basis van bronnen en op basis van kennis van NBSs over waar ze wel of niet effectief zijn?

[A]: Ja. En ook als je bijvoorbeeld kijkt naar de drains. Als je kijkt naar kaarten, kan je zien dat er gebieden zijn waar gewoon geen drains aanwezig zijn. Als je in dit gebied een drain maatregel zou nemen, heeft dat geen zin. Neem bijvoorbeeld een forest-area, daar zullen drain maatregelen minder snel genomen worden.

[Q]: Waar is de geschiktheid van NBS op verschillende bevolkingsdichtheden op gebaseerd?

[A]: Deze zijn ook van Defacto. Er zijn verschillende mogelijkheden waar ze op gebaseerd kunnen zijn, bijvoorbeeld op de bevolkingsdichtheden of op de fractie groen. Dit is meestal ook een goede indicatie van hoeveel mensen er wonen. Ik denk dat het zeer aannemelijk is dat ze dat hebben gedaan.

[Q]: Ook daarin hebben ze dan waarschijnlijk weer gekeken naar andere projecten waar de NBSs dan meer toepasbaar zijn?

[A]: Ja, dat, maar ook een deel logica en beredenering. Neem bijvoorbeeld water storing tanks maatregelen. Die zijn makkelijker toepasbaar in een bepaald type wijk. Wat kan wel, wat kan niet.

[Q]: Waarom is er besloten sommige maatregelen niet mee te nemen? (excl. Mea.) (of omdat ze al op een andere manier worden meegenomen?)

[A]: Durf ik zo eigenlijk niet te zeggen. Een aantal van die maatregelen hebben we wel meegenomen.

[Q]: Belangrijker voor mij, ik neem aan dat ik naar alle maatregelen in deze tabel moet kijken?

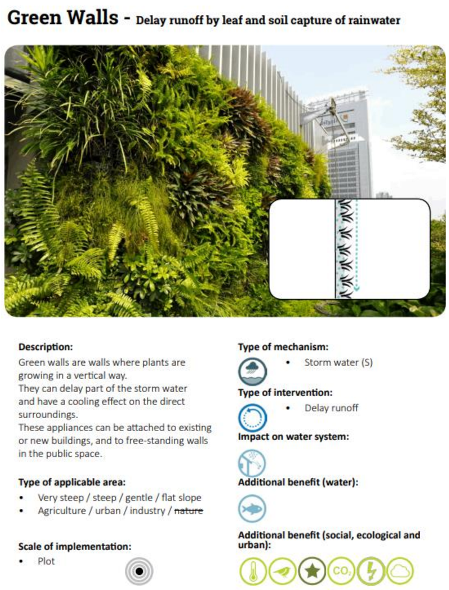
[A]: Ja, ik zou je daar niet door laten beperken. Wij hebben wel besloten om sommige maatregelen niet mee te nemen in wflow. Water storing en green walls bijvoorbeeld. Het doet wel iets, maar op deze schaal en met deze onzekerheid, kan je het beter niet meenemen. Deze maatregelen hebben ook andere functies natuurlijk. Het kan naast stormwater runoff verlagen bijvoorbeeld ook verkoelend werken. Dus er zijn meer redenen om NBSs toe te passen.

[Q]: Hoe kan ik dan onderbouwen dat die maatregelen geen effect hebben?

[A]: Dat hebben we beredeneert, niet daadwerkelijk getest of iets dergelijks. De lijst met niet meegenomen maatregelen heb ik zo niet bij de hand, maar kan ik nog wel een keer opzoeken.

			Type (hydrology)				Urban typologies						Residential areas				Urban Upgrading		
		Excl. Mea	Store	Surface	Drain	Comment	Agriculture & rural housing	Parks & open	Forest area	Wetlands	Commercial & mixed use	Public facilities &	Low & medium	High density	Densificatio n area	New developmen	Defined areas (RUDP-	Potential areas	Excluding measures
A3.2	Vegetated pond																		
A4	Forest protection/ demarcation					-			x										
B1	Green blue spine				x												x	x	
B2	**Integrated neighboorhood drain**	x			x		x						x				x	x	F3
B2.1	Foothpath concrete																		
B2.2	Stone pavement vegetated																		
B3a	Water storing playground	x	x									x	x		x	x			G1
B3b	Water storing playground (apply 70%)	x	x														x	x	G1
B4	Street profile regulations	x		x							x		x	x	x	x	x	x	C5, D5
B5	Water storage tank	?	x				x						x				x	x	H4?
C1a	Water storing pond	I x	x								x	x		x		x			D1, D2
C2a	Green roofs	I	x								x	x		x		x			
C3a	Green façade	I				?					x	x		x		x			
(C1-3)b	Water storing pond	I	x														x	x	
C4	**Linear park**		x	x							x	x		x		x			
C4.1	Rain garden																		
C4.2	Water retention area																		
C5	**Integrated road profile**	x		x		Can only be drain, if it is modelled as a drain in the wflow					x	x		x	x	x			B4, D5
C5.1	Green swales																		
C5.2	Permeable Pavement																		
C6	Permeable Parking			x							x	x		x					
D1a	Guidelines private waterstorage	I x	x								x	x	x	x	x	x			C1-3, D2
D1b	Guidelines private waterstorage (lower de	I x	x														x	x	C1-3, D2
D2a	Water storing walls	x	x											x	x				C1-2, D1
D2b	Water storing walls (lower density)	x	x														x	x	C1-2, D1
D3*	Water retaining public space	x	x	x									x		x	x	x	x	A3

Figure B- 1 - Screenshot of suitable locations for NBSs composed by Defacto and used by HKV



Green Walls - Delay runoff by leaf and soil capture of rainwater

Description:
Green walls are walls where plants are growing in a vertical way.
They can delay part of the storm water and have a cooling effect on the direct surroundings.
These appliances can be attached to existing or new buildings, and to free-standing walls in the public space.

Type of applicable area:
- Very steep / steep / gentle / flat slope
- Agriculture / urban / industry / ~~nature~~

Scale of implementation:
- Plot

Type of mechanism:
- Storm water (S)

Type of intervention:
- Delay runoff

Impact on water system:

Additional benefit (water):

Additional benefit (social, ecological and urban):

Figure B- 2 - Screenshot of a page of the NBS toolbox from Defacto

Implementatie NBS:

[Q]: Je noemde dat HKV de NBS effecten van Defacto heeft aangepast. Hoe is dit precies gebeurd? En waarom is dat gedaan? Kan je een voorbeeld geven?

[A]: We zijn begonnen bij de Storage maatregelen. We hebben gekeken naar wat ze hebben opgeschreven, dus hoeveel m^3/km^2 hebben ze aangegeven. Dus uiteindelijk om hoeveel millimeters gaat het. In die tabel staan een aantal waardes die niet realistisch zijn. Als ze niet realistisch zijn, hebben we ze besproken met Defacto en vervolgens verlaagd. Dus bijvoorbeeld de 45000 van de Bioswales, staat bij ons er als 9 millimeter storage erin. Het is dus een factor 5 lager. Een bepaalde storage maatregel is voor een aantal zoekgebieden toepasbaar. We gaan de maatregel voor het gehele zoekgebied toepassen. Wat zij zeggen hier (wijst aan op scherm): 2000 m^3/km^2 storage gaan we hiermee creëren in het zoekgebied, dus over het hele zoekgebied 2 mm storage. Bij die andere hebben we 45 mm storage over het hele zoekgebied. Dat kan helemaal niet. Daarom is er overleg geweest om samen tot realistischere getallen te komen. Er staat ook nog een van 360 mm, die is ook verlaagd. Volgens mij zijn dat de water storing tanks.

[Q]: Hoe zijn de waardes in de kolom 'value' ('aanpassing' in script) bepaald o.b.v. de data van Defacto?

[Q]: Welke waardes zijn dan maatgevend voor mijn onderzoek? Die in de originele tabel van Defacto of die in de kolom 'values'?

[A]: die in de kolom 'values', tenzij je andere dingen vindt die een betere inschatting geven. Bij die storage maatregelen is het redelijk recht toe recht aan. Er kunnen wel meerdere storage maatregelen genomen worden in een zoekgebied. Wanneer dit het geval is, tellen we ze bij elkaar op.

[Q]: je telt het bij elkaar op als de shapefiles overlappen?

[A]: Ja. Voor elke maatregel maak je een eigen raster en die tel jij bij elkaar op. Of dat in werkelijkheid klopt is natuurlijk een tweede. Je hebt het over cellen van 90mx90m, dus in die zin zouden er meerdere maatregelen kunnen zijn, maar het is misschien niet realistisch dat er op 1 locatie zowel een water storage tank, water storage pond en ook nog eens een bioswale. Dat kan misschien niet allemaal op dezelfde plek. Je bent echter aan het kijken naar een hydrologisch model.

[Q]: Wat gebeurt er als surface en drain measures overlappen? Tel je die ook bij elkaar op?

[A]: Ook daar worden ze dan beide toegepast. Je telt ze alleen niet bij elkaar op voor de surface en de drain, want we passen het toe op verschillende parameters. Dat is wat je op de volgende sheet op ziet. Voor de surface en drains measures: een bepaald type maatregel levert een toename in ruwheid op. Vaak is het een vermenigvuldiging. Heel vaak zie je het getal 1.5 daar staan. Dat betekent dat de ruwheidswaardes met 1.5 wordt vermenigvuldigd. Het kan zijn dat je dat 5x doet, omdat maatregelen overlappen. Er zijn ook nog wat andere maatregelen, zoals maatregel A2b, de counter planting in agricultural areas. Het werkt natuurlijk wel voor een deel, maar het is ook niet zo dat het de ruwheid van het hele gebied met een factor vermenigvuldigd. Dus wat we daar hebben gezegd is, als de ruwheid daar lager is dan een bepaalde waarde, dan vullen we die waarde in. Dus dan krijg je in dit geval een waarde van 0.6. Als die waarde hoger wordt dan 1, dan moet het naar 0.99 worden gezet, want zo'n hoge Mannings waarde is heel raar.

[Q]: Ik neem aan dat dat ook te zien is in dit screenshotje van het script?

[A]: Ja, klopt.

[Q]: neem bijvoorbeeld maatregel A1. In het eerste bestand van Defacto heeft de surface maatregel een waarde van 0.5 km^2/km^2. In de kolom value staat een waarde van 1.5. Hoe kom je uit op deze waarde?

[A]: Dit is niet altijd 1 op 1 te koppelen. Vaak is er wel op deze manier gedacht. Bijvoorbeeld bij maatregel C4, die is 0.02 en die we hebben we 1.02 gemaakt. Dat is geen toeval. Voor C5 geldt dat ook. Dat is ook weer keuze soms. In dit geval is het niet echt beargumenteerbaar. Het is een beetje natte vinger werk.

[Q]: Oke, het betekent dus niet zo dat je op basis van de tabel van Defacto al precies kan bepalen hoeveel ruwer het wordt?

[A]: Nee, dat is dus niet zo. Wat je in die tabel van Defacto ziet is dat het over zoveel km^2 per km^2 ruwer wordt door een maatregelen. Soms zijn het zelfs kilometers, bijvoorbeeld bij Countour planting. Het is natuurlijk heel lastig om dat in je model te zetten. Daarom zeggen we gewoon, we verruwen de hele cel met zo'n factor. Die factor zal wel reletief laag zijn. Bij forest transition is die wel iets hoger. Of dit uiteindelijk helemaal goed gaat is natuurlijk de vraag.

Laten we het ook nog maar even hebben over de drain maatregelen. Binnen dat zoekgebied verruwen we alle drains en daar zit dan ook een bepaalde factor achter. Daar hebben we het nog eenvoudiger gedaan: elke maatregel zorgt gewoon voor 50% meer verruwing. Dus een factor van 1.5. De waardes uit de tabel van Defacto zijn daar helemaal niet in meegenomen.

[Q]: Er zijn veel manieren om storage measures te modelleren in wflow. Waarom is er gebruik gemaakt van de Swood parameter? Welke effecten heeft dit potentieel op de rest van het model?

[A]: Wat je wil doen is storage creëren. Er zijn natuurlijk verschillende manieren. Een water storage tank is vrij duidelijk. Je koppelt een dak aan een tank. Water stroomt in tank, totdat die vol is. Wanner dit gebeurt, stroomt het er gewoon af. Hoe zou je dit kunnen doen? Je kan de neerslag verlagen met een bepaalde waarde. Dat moet je dan vanaf het begin van de bui doen, want het eerste water valt je tank in. Of je zou retentiegebieden moeten maken in het model. Het is mogelijk om dat in wflow te doen, maar dat is heel lastig. Wat wij nu hebben gedaan is Swood pakken. Swood is de interceptie van bomen. Dus wat is de hoeveel water dat op het hout van de bomen blijft liggen. Interceptie is wat dat betreft hetzelfde als neerslag die direct wordt opgevangen. Op een gegeven moment zal het nu wel verdampen, wat het anders niet zal doen. Maar de verdamping voor een hydrologisch model dat voor een event draait is erg weinig. Dus daarom hebben we Swood gebruikt. Die kan je gewoon per cel opleggen. Alle storages hebben we daarin gezet. Water wordt dus opgevangen en komt niet in je model terecht. Je hebt ook storage maatregelen die meer verzamelend zijn, dus dat water van verschillende kanten ergens naartoe stroomt en dat het daar dan blijft hangen. Dat neem je in feite niet helemaal op de juiste manier mee, omdat we hier alleen kijk naar wat gebeurt er met die neerslag. Qua volume klopt het wel ongeveer, maar ruimtelijk zal het niet helemaal hetzelfde zijn. Benedenstrooms zal het ongeveer op hetzelfde neerkomen, maar bovenstrooms zal het er waarschijnlijk net iets anders uitzien, wanneer je het als een retentiegebied implementeert. Je hebt het hier namelijk over best veel verschillende maatregelen. Daarnaast is zo dat elke maatregel in een ander gebied toegepast wordt. Dan kan ook niet kiezen op welke plekken je een reservoir wil inzetten. Daarom kijk je op een iets pragmatischere manier naar het probleem en is er gekozen om gewoon een deel van de neerslag eraf te halen m.b.v. de Swood parameter.

Maatregel	Type	Values	Actie	Shapes	UrbUpgrade
A1	Surface	1.5	MultiplyL	3	
A2b	Surface	0.6	ReplaceL	1,8	
A3	Surface	1.01	MultiplyL	10,11,12	A3-Urban Upgrading area_clip.shp
A3	Store	2	AddH	10,11,12	A3-Urban Upgrading area_clip.shp
B1	Drain	1.5	MultiplyL	12	B2-Urban Upgrading area_clip.shp
B2	Drain	1.5	MultiplyL	1,8,12	B2-Urban Upgrading area_clip.shp
B3a	Store	3.5	AddH	7,8,10,11	
B3b	Store	3.5	AddH	12	B3b-Urban Upgrading area_clip.shp
B4	Surface	1.03	MultiplyL	6,8,9,10,1:	B4-Urban Upgrading area_clip.shp
C1	Store	25	AddH	6,7,8,11,1:	D3-Urban Upgrading area_clip.shp
C4	Store	14	AddH	6,7,9,11	
C4	Surface	1.02	MultiplyL	6,7,9,11	
C5	Surface	1.08	MultiplyL	6,7,9,10,11	
C6	Surface	1.25	MultiplyL	6,7,9	
D1	Store	15	AddH	9,10	
D3	Store	2	AddH	8,10,11,12	D3-Urban Upgrading area_clip.shp
D3	Surface	1.01	MultiplyL	8,10,11,12	D3-Urban Upgrading area_clip.shp
D5	Drain	1.5	MultiplyL	8,10,11	
D6	Surface	1.01	MultiplyL	1,2,4,8,12	D6-Urban Upgrading area_clip.shp
E1	Surface	1.5	MultiplyL	2,5	
F1	Store	9	AddH	8,12	F1-Urban Upgrading area_clip.shp
F3a	Surface	1.013	MultiplyL	8,12	F3-Urban Upgrading area_clip.shp
F4	Drain	1.5	MultiplyL	8,12	F1-Urban Upgrading area_clip.shp
G1a	Store	1.5	AddH	7,8,9,10,11	
G1b	Store	1.5	AddH	12	A3-Urban Upgrading area_clip.shp
H1	Surface	1.014	MultiplyL	1	
H2	Surface	1.75	MultiplyL	4	
H3	Store	2.2	AddH	1,8	

Figure B- 3 - quantified effects by HKV of the different NBSs used in the model

Area Calculation (per 1 sq.km.)

	NBS	Area (per km²) Store	Surface	Drain
Parks and vegetation				
A1	Forest transition		0,5 km²/km²	
A2a	Contour planting in the forest and openspace		2 km/km²	
A2b	Contour planting in agriculture areas and housing areas		6,5 km/km²	
A3*	Green urban parks	2,000 m³/km²	0,01 km²/km²	
D3*	Water retaining public space	2,000 m³/km²	0,01 km²/km²	
C4	Linear park	14,000 m³/km²	0,02 km²/km²	
H1	Coutour planting (with trenches)		0,014 km²/km²	
H2 + D4	Reforrestation + slope park		0,75 km²/km²	
G2a	Wall with planter boxes in urban upgrading area		0,002 km²/km²	
G2b	Wall with planter boxes in parks, public facility, low and medium residential areas		0,001 km²/km²	
Access ways roads and pedestrian paths				
B4	Street profile regulations		3 km/km²	
C5	Integrated road profile		7,5 km/km²	
C6	Permeable Parking		0,25 km²/km²	
F1	Bioswales and water buffer	45,000 m³/km²		
F3a*	Stepped foothpath with planters		6,5 km/km²	
F3b	Climbing plants with archs		2 km/km²	
H3	Water storage ponds along road	2,200 m³/km²		
Drain				
B1	Green blue spine			1 km/km²
B2	Integrated neighboorhood drain			1 km/km²
D5	Green integrated Drain			4 km/km²
D6*	Gabions		4 km/km²	
F4	Stepped drain			8 km/km²
Community facility – playground				

Figure B- 4 - screenshot of table obtained from Defacto to quantify the effects of NBSs

[Q]: Door de NBS measures zouden de Swood waardes in het model aangepast moeten worden. Dit is het geval in het model dat Pieter mij heeft gestuurd, maar niet als ik jou script gebruik. Weet jij wellicht waar dit aan zou kunnen liggen? Wordt het bestand niet ongeveer gewoon overgeschreven (zie script)?

[A]: Dan is er iets niet goed gegaan met het draaien van het script. Het ligt niet aan het screenshotje van het script, want dat past die niet toe voor storage maatregelen. Die regels gaan over wat we eerder besproken hebben.

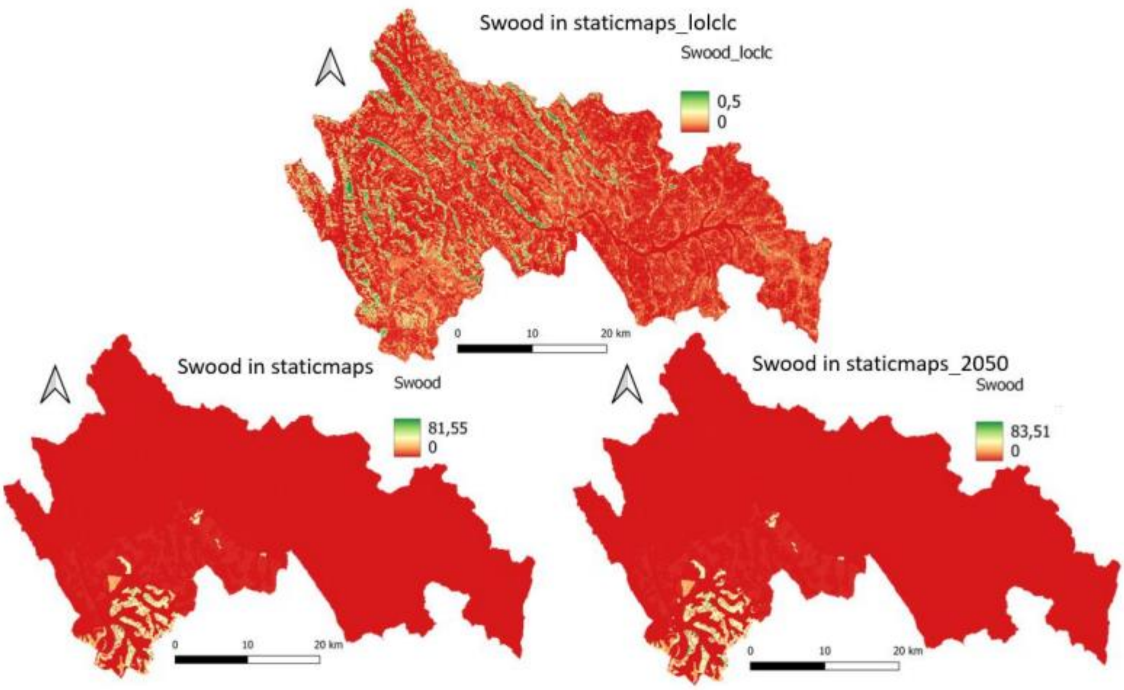


Figure B- 5 - resulting Swood parameter values after applying NBSs in different model scenarios (upper = current without NBS, bottom left = current with NBS, bottom right = future with NBS)

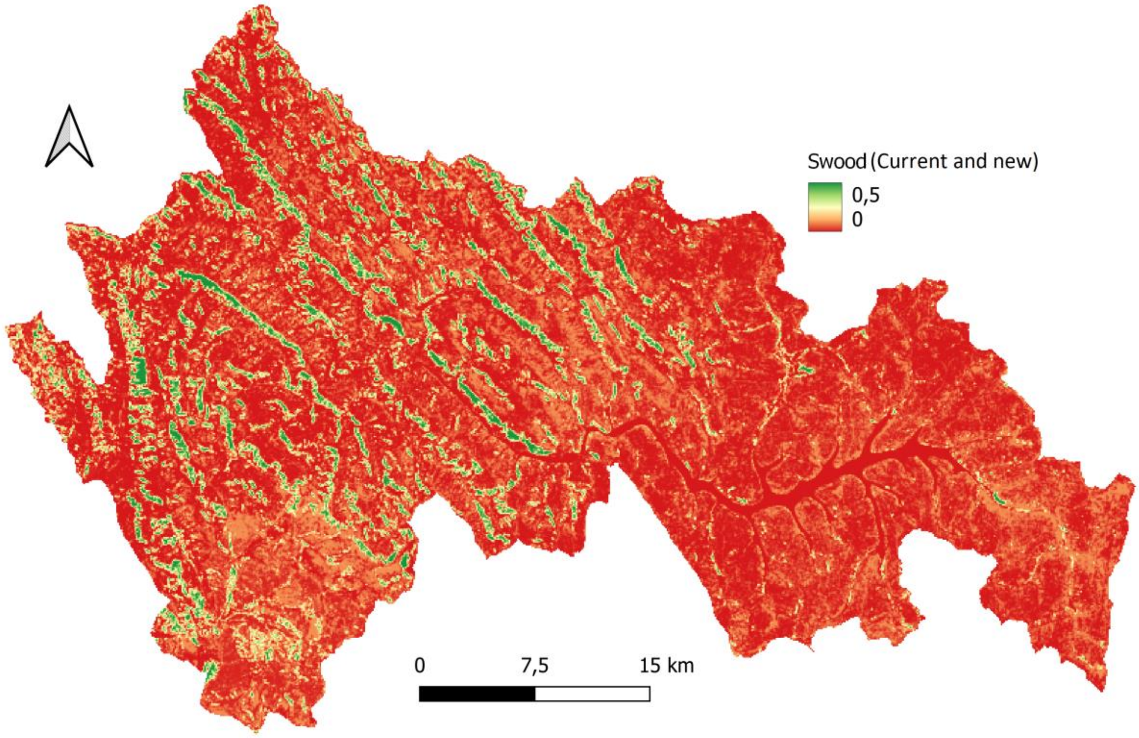


Figure B- 6 - prove that there is no change in the Swood parameter values after running the script

```python
    else:
        idx=Shapes[Shapes.ID==j].Shapefile.index[0]
        Shape=Shapes[Shapes.ID==j].Shapefile[idx]
        ShapePad=ShapesPad+"/NBS-"+Type+"/"+Shape
        if Type=='Surface':
            Var='N'
            CreateNewMap_v2(NewModel_pad,ShapePad,Var,Actie,Value,Value)
            CreateNewMap_v2(NewModel_pad,ShapePad,Var,'ReplaceH',0.99,0.99)
        elif Type=='Drain':
            Var='N_river'
            CreateNewMap_v2(NewModel_pad,ShapePad,Var,Actie,Value,Value)
            CreateNewMap_v2(NewModel_pad,ShapePad,Var,'ReplaceH',0.99,0.99)
        else:
            Var='Swood'
            CreateNewMap_v2(NewModel_pad,ShapePad,Var,Actie,-999,Value)
if isinstance(UrbUpgrade,str):
    ShapePad=ShapesPad+"/NBS-"+Type+"/"+UrbUpgrade
    if Type=='Surface':
        Var='N'
        CreateNewMap_v2(NewModel_pad,ShapePad,Var,Actie,Value,Value)
        CreateNewMap_v2(NewModel_pad,ShapePad,Var,'ReplaceH',0.99,0.99)
    elif Type=='Drain':
        Var='N_river'
        CreateNewMap_v2(NewModel_pad,ShapePad,Var,Actie,Value,Value)
        CreateNewMap_v2(NewModel_pad,ShapePad,Var,'ReplaceH',0.99,0.99)
    else:
        Var='Swood'
        CreateNewMap_v2(NewModel_pad,ShapePad,Var,Actie,-999,Value)
```

Figure B- 7 - screenshot of Python script written by Geerten to edit .map files

[Q]: N en N_river zijn gebruikt voor de surface en drains measures. Zijn hiervoor ook nog andere mogelijke parameters onderzocht? Zo ja, welke?

[A]: we hebben ervoor gekozen om het zo pragmatisch mogelijk te doen. Er is een gigantische lijst aan parameters, dus er zullen zeker nettere manieren zijn. Dat zou je dan per maatregel moeten benaderen. Ruwheid zal er zeker een zijn, maar je hebt ook infiltratiecapaciteiten. Voor veel maatregelen zou het verhogen van infiltratiecapaciteit een hele logische parameter zijn. Vegetatie hebben we niks mee gedaan. Forestation is een van de maatregelen die ertussen zit. Vervolgens passen wij niet de vegetatie of landgebruik aan, maar alleen de ruwheid en de storage worden aangepast.

[Q]: Infiltratie wordt op dit moment dus niet meegenomen als maatregel?

[A]: Het zit wel in het model, maar we passen het niet aan. De vraag is, in hoeverre maakt dat wat uit? We kijken naar een piekbui. Er gaat misschien door de maatregel wel meer de grond in, maar dat is zo klein vergeleken met hoeveel er valt. Ik zou wel zeker aanraden om naar die parameters te kijken en bedenk een manier om het te implementeren. Het kan verfijnder dan de manier waarop wij het nu hebben gedaan. Bedenk welke parameters effect hebben op welk deel van de cyclus. Ik zou een schemaatje maken van welke parameters bij welk component van de cyclus horen en bouw het van daaruit op. Kijk hiervoor in de wflow manual. In de pdf staat nog meer dan in de webpagina (readthedocs). De manual is minder up-to-date, maar er staat wel heel veel in (google wflow documentation pdf, Schellekens 2021 of wflow techdoc). Alle vergelijkingen staan hierin.

[Q]: Goed om dat inderdaad ook nog door te nemen voordat ik met Bobby afspreek.

[A]: Ik wil er nog wel iets aan toevoegen. Die Swood kaart heb je natuurlijk ook voor de ruwheid. Wat ik zelf nog wel niet zo goed vind, is dat de N-waardes wel heel hoog worden. Dat komt omdat als je veel verschillende maatregelen gaat stapelen. Veel N-waardes gaan daarom richting de 1. Het maakt dan ook uit op welk punt je iets doet. Als je met stapelen dus als eerste iets doet, of wanneer je het als laatst doet. Daar hebben we nu heel weinig mee gedaan. Het is de vraag of de ruwheden nu nog realistisch zijn. Het is overigens ook de vraag of de ruwheden die initieel in het model zitten wel realistisch zijn.

[Q]: Komt dat doordat die waardes ook gekalibreerd zijn om het model te maken?

[A]: Ja, dus ik denk dat ze al vrij hoog zijn. Neem bijvoorbeeld de N-river waardes. Die zijn al niet meer realistisch vanuit een fysisch oogpunt. Dus daar zitten nog best wat gekkigheden in.

[Q]: Het model is alleen gevalideerd bij Nemba. Ik neem aan dat het model gewoon gekalibreerd is zodat de modelresultaten zo goed mogelijk zijn. Wat is dan het effect van onrealistisch hoge N-waardes? In hoeverre gaat dit ten koste van de modelresultaten?

[A]: We gaan er vanuit dat het model goed gekalibreerd is en dat de resultaten gewoon goed zijn. Die aanpassing van die waarde is om te compenseren voor iets dat ergens anders niet goed gaat. Dit ligt waarschijnlijk niet aan de onderdelen van wflow, maar er zijn waarschijnlijk andere dingen die ervoor zorgen dat water te snel wordt afgevoerd. Hiervoor wordt dan weer gecompenseerd met een hogere ruwheid. Wat je het liefst zou willen doen, bij bijv. forestation, de bomen hebben een ruwheid van 0.07, dus voor het gebied waarin ik dat toepas zet ik de ruwheid naar 0.07. Klaar. Ergens anders pas je een andere maatregel toe, met een andere ruwheid. Maar, als het daarvoor al hoger was, doe je niks, terwijl datgene wat het eerst had eigenlijk een lager ruwheid dan bos had. Dan wordt het lastiger. Als we zeggen, in dit zoekgebied passen we bos toe, dan is het niet zo dat overal de ruwheid precies 0.07 zal zijn. Er zullen een paar plekken zijn, maar dat weet je niet, dus voor het hele gebied. Daarom gebruik je een gewogen gemiddelde. Dus bijvoorbeeld, 10% van het gebied wordt bos, dus we passen het niet met 0.07 aan, maar we pakken het verschil tussen de huidige en de toekomstige ruwheid en dat vermenigvuldigen we met 1.1 en dat tellen we erbij op. Daarin maak je dan dus al keuzes. Voor bijvoorbeeld countour planting, dat kan simpelweg niet op de schaal van het model. De ruwheid die aan het begin erin zat, matcht eigenlijk al niet met wat er in het begin in zat. Daar zit natuurlijk wel wat wrijving in met hoe je het het liefst fysisch zou willen doen. Ik heb het antwoord er ook niet meteen op dus, anders hadden we het al wel gedaan, maar we hebben er wel een mening over. Het is niet helemaal zoals je het wellicht zou willen.

Geerten laat QGIS visualisatie van N en N-river zien

De maximale waarde van N-river is 0.1 en de laagste is 0.06. Dat is echt heel hoog, vergeleken met de representatieve manning waardes van Chow. Daar heeft een straight channel een waarde van 0.03 of zelfs nog lager. Zelfs een flood plain is het ruw zelfs met bomen die in bloei staan in de zomer. Dat vind ik opvallend. Het absolute verschil wordt daardoor veel groter dan wellicht de bedoeling is. Bij de oppervlakte N waardes zijn de verschillen kleiner, maar zijn ze alsnog hoog. Die waardes kunnen hoger zijn, rond de 0.5. Door de maatregelen kan het soms zelf rond de 1 komen te liggen. Als je maatregelen gaat stapelen, gaat dit erg hard oplopen. De vraag is of het niet te hoog is wat we nu hebben geïmplementeerd. Het stapelen klopt niet helemaal. Het probleem is alleen dat we niet meer weten op dit moment. Wat je natuurlijk kan doen straks, is dat je gaat kijken of maatregelen daadwerkelijk op deze groffe schaal geïmplementeerd moeten worden. Of zeg je voor dit type implementeer ik daar en met deze parameters. En dan heb je verschillende parametersets die je aanpast. Achteraf zou je ook nog kunnen zeggen: dit doe ik over het hele gebied en dan zwak ik mijn parameterwaardes nog iets af. Dat zijn natuurlijk wat oplossingsrichtingen.

<u>Effecten bepalen:</u>

[Q]: Wat is de output van het model dat gebruikt is voor om de effecten te bepalen?

[A]: Het is het piekafname effect dat op de piek gereduceerd is bij het uitstromen van de catchment op een puntlocatie. Deze wordt standaard weggeschreven in een CSV-bestand. Ik weet het niet 100%, maar 90% zeker. De grid-output kan ook gebruikt worden. Ik weet alleen niet hoe.

[Q]: Hoe zijn momenteel de eenheidseffecten bepaald? Is het model gerund voor alle verschillende maatregelen? In dat geval zijn er nieuwe .map bestandjes nodig voor elke model run toch? Of zou je mij een andere manier aanraden?

[A]: Ik heb een lijst gekregen van Job van afnames per outflow locatie en vervolgens ben ik gaan bepalen wat het eenheidseffect daarvan is. Dat is natuurlijk lastig, want je hebt heel veel verschillende maatregelen. In de rekensheet staan meer details. Ik heb geprobeerd om het afvoereffect te verdelen over de verschillende maatregelen op basis van de grootte van de implementatie. Als je bijvoorbeeld 3 maatregelen in hetzelfde gebied hebt die allemaal storage maatregelen zijn, dan kunnen we daar wat van zeggen. Op die manier zijn ze verdeeld. Echt heel goed is het niet.

[Q]: Kan je een voorbeeld geven met twee maatregelen waarvan eentje op een grote schaal is en eentje op een kleine schaal, bijv. contour planting?

[A]: De grootte van maatregeltoepassing is ook op hele kleine schaal gedaan, dus die heeft daarmee ook al een kleine bijdrage in de tabel. We hebben het effect per maatregel bepaald. Voor storage bijvoorbeeld, hebben we de afvoerreductie per m^3 bepaald voor 4 verschillende terugkeertijden. Hier hebben we uiteindelijk het gemiddelde van genomen.

[Q]: Dat is dan het gemiddelde van alle maatregelen per terugkeertijd?

[A]: Ja, die heb ik hier bepaald. Die pas ik dan weer op de maatregelen toe. Wat je zegt gaat trouwens niet helemaal op, want ik zit hier naar surface te kijken en die hebben we allemaal gelijk genomen. We hebben de waardes op basis van iets bepaald, maar daarvoor moet ik wel echt even graven in mijn geheugen. Die eenheidseffecten worden gebruikt om de effecten te bepalen. Zeg bijvoorbeeld, ik maak de maatregel groter, ik voeg hier meer m^3 toe, dan ga je in de blokkendoos nieuwe effecten bepalen. Het vervelende is dat ik niet meer durf te zeggen op basis waarvan we die bepaald hebben.

[Q]: Die getallen zijn dan gebruikt om het de tabel met de eenheidseffecten te bepalen en te verdelen over de catchments?

[A]: Wanneer je een ander terugkeertijd pakt, pak je een ander getal hieruit. Wanneer je het aantal m^3 in een catchment vergroot, dan vergroot het absolute effect in de catchment ook. Op die manier wordt het dus gedaan. De vraag is alleen even waar de getallen vandaan komen. Die heb ik bepaald uit de resultaten van de verschillende gebieden, maar hoe precies kan ik niet zo makkelijk achterhalen. Als je eenheidseffecten netjes zou willen bepalen, wat hier dus niet gedaan is, is de maatregelen uit elkaar te trekken. Doordat alle maatregelen gecombineerd zijn in de blokkendoos, kan je de gecombineerde effecten van de maatregelen runnen en individuele maatregelen groter of kleiner maken. Hiervoor moeten ze weer uit elkaar worden getrokken. Hierbij worden wel hele arbitraire keuzes gemaakt. Dat maakt het gewoon heel onnauwkeurig en onzeker wat hierin staat. Het zal niet zo zijn dat het een factor 10 scheelt (misschien lager, maar zeker niet hoger). Je probeert uiteindelijk iets complex om het vervolgens weer complex te maken. Je hebt daarvoor niet de juiste informatie.

[Q]: In hoeverre denk jij dat het een oplossing zal zijn om het model te runnen voor alle verschillende individuele maatregelen en dan later gaan kijken naar de gecombineerde effecten?

[A]: Ja, dat kost veel tijd en daarom hebben we het niet gedaan. Ze hadden een blokkendoos nodig. Dus toen deden we dat maar. Als je het netjes zou willen doen, zou je het op een andere manier moeten doen.

[Q]: Hoe is deze tabel (Figure B- 8) opgesteld? Is dit gebruikt als input voor de eenheidseffecten of andersom?

[A]: de screenshot is ingevuld. Die staat vast. Dat zijn de effecten per m^3, m^2 of m. Dit wordt gecombineerd met de terugkeertijd. En vervolgens worden de eenheidseffecten bepaald. Ga niet de exacte getallen gebruiken. Ze kunnen wel gebruikt worden om de eenheidseffecten te bepalen.

[Q]: Kan de modelimplementatie dan wel goed vergeleken worden aangezien er in deze sheet weer allerlei aannames worden gemaakt die losstaan van de wflow implementatie?

[A]: Nee dat niet nee. Dat is heel anders gedaan.

[Q]: Aan de andere kant zijn dit wel jullie resultaten die vervolgens weer gebruikt worden in andere delen van de studie. Dus misschien is het juist wel relevant om hiernaar te kijken?

[A]: Dit is gebruikt in de kostenberekening. Dus hoeveel een m^3 oplevert. Welke maatregel is het meest voordelig? Het wordt niet gebruikt om daadwerkelijk op te ontwerpen. Dat moet je ook niet doen. Je zou het eventueel wel kunnen doen om een beeld te krijgen, maar vervolgens zou je het eigenlijk altijd moeten doorrekenen.

[Q]: Gegeven alle onzekerheid in het model en in deze sheet, zijn de verschillen tussen de effecten dan nog wel significant?

[A]: Dit is misschien het beste wat je hebt. Het zou natuurlijk wel echt beter kunnen. Dit is alleen niet altijd een optie. Als je het wat netter zou willen doen, moet je per maatregel het effect moeten bepalen en het model heel vaak runnen. Of op z'n minst elke type maatregel. Daar wordt het wel echt beter van. Zoiets hebben we wel gedaan, maar niet echt doorgezet. Het zou best kunnen dat we daar die getallen vandaan hebben, maar dat weet ik niet meer zeker. Het idee is hetzelfde. Nadeel van de nettere implementatie is dat als er geen maatregelen van een bepaald type in een catchment worden toegepast, dan kan er ook geen eenheidseffect worden berekend. Eigenlijk komt het er op neer dat er een vaste verdeling is gemaakt tussen storage, surface en drain maatregelen en die zijn afhankelijk van de terugkeertijd. Dat is in feite hoe de daadwerkelijk opgetreden m^3 zijn verdeeld.

Eenheidseffecten Nyabugogo

2017

Catchment	T2 Storage per m3	T2 Surface per km2	T2 Drain per km	T10 Storage per m3	T10 Surface per km2	T10 Drain per km	T50 Storage per m3	T50 Surface per km2	T50 Drain per km	T100 Storage per m3	T100 Surface per km2	T100 Drain per km
2	1.05236E-05	0.303276	0.097298	2.41585E-05	0.696217	0.223362	2.46048E-05	1.418156	0.454976	5.97913E-06	1.723105	0.55281
3	2.18963E-06	0.063102	0.020245	6.1006E-06	0.175811	0.056404	6.05504E-06	0.348997	0.111966	1.38856E-06	0.400166	0.128382
4	4.06436E-09	0.000117	3.76E-05	2.06076E-06	0.059388	0.019053	7.99863E-07	0.046102	0.014791	4.59018E-08	0.013228	0.004244
5	6.03277E-06	0.173857	0.055777	1.52053E-05	0.438196	0.140583	1.50381E-05	0.866756	0.278075	3.59446E-06	1.035876	0.332332
7	4.19243E-06	0.12082	0.038762	9.40267E-06	0.270973	0.086934	7.37323E-06	0.424974	0.136341	1.68963E-06	0.486928	0.156217
8	2.93525E-06	0.08459	0.027138	7.33807E-06	0.211474	0.067845	7.08751E-06	0.408505	0.131058	1.90111E-06	0.547876	0.175771
9	6.71019E-06	0.193379	0.06204	1.58032E-05	0.455426	0.146111	1.53683E-05	0.885791	0.284182	3.73888E-06	1.077495	0.345684
11	2.41408E-09	6.96E-05	2.23E-05	-1.58863E-06	-0.045782	-0.014688	-2.06971E-06	-0.119293	-0.038272	-5.86796E-07	-0.169107	-0.054253
12	4.59804E-06	0.132509	0.042512	1.13073E-05	0.325861	0.104543	1.05624E-05	0.608788	0.195313	2.75288E-06	0.793345	0.254523
13	4.26428E-06	0.122891	0.039426	1.06568E-05	0.307116	0.09853	9.72926E-06	0.560769	0.179907	2.37582E-06	0.684679	0.21966
14	1.40315E-06	0.040437	0.012973	2.83811E-06	0.08179	0.02624	1.78932E-06	0.103131	0.033087	5.23557E-07	0.150882	0.048406
15	6.27593E-06	0.180864	0.058025	1.44597E-05	0.416709	0.13369	1.34549E-05	0.775507	0.2488	3.19606E-06	0.921063	0.295498
16	2.76111E-06	0.079572	0.025528	7.80917E-06	0.22505	0.072201	6.47262E-06	0.373065	0.119687	1.76771E-06	0.50943	0.163437
17	5.20513E-06	0.150005	0.048125	1.31216E-05	0.378148	0.121318	1.13219E-05	0.652564	0.209357	3.06562E-06	0.883473	0.283438
18	6.74118E-06	0.194272	0.062327	1.61297E-05	0.464837	0.14913	1.36831E-05	0.788659	0.253019	3.54581E-06	1.021856	0.327834
19	1.73842E-06	0.050099	0.016073	4.46026E-06	0.128539	0.041238	3.60666E-06	0.207878	0.066692	1.08034E-06	0.311341	0.099885
20	1.68006E-08	0.000484	0.000155	-9.08414E-07	-0.026179	-0.008399	-1.2842E-06	-0.074018	-0.023747	-5.05272E-07	-0.145613	-0.046716
22	7.51283E-06	0.21651	0.069461	1.84073E-05	0.530474	0.170188	1.83929E-05	1.060119	0.34011	4.69483E-06	1.352988	0.434069
23	2.64295E-07	0.007617	0.002444	-3.65453E-06	-0.105319	-0.033789	-2.89043E-06	-0.166597	-0.053448	-7.36908E-07	-0.212367	-0.068132
24	2.79042E-06	0.080416	0.025799	7.66464E-06	0.220885	0.070865	8.18806E-06	0.471938	0.151408	2.08623E-06	0.601224	0.192886
25	0	0.038238	0.012268	0	0.036306	0.011648	0	0.204423	0.065583	0	0.286171	0.09181
27	9.50953E-06	0.274052	0.087922	2.47263E-05	0.71258	0.228611	2.26287E-05	1.304256	0.418434	5.56237E-06	1.603001	0.514278
28	4.14119E-08	0.001193	0.000383	-6.49543E-07	-0.018719	-0.006005	-2.00865E-06	-0.115773	-0.037143	-5.31178E-07	-0.153078	-0.049111
29	8.44894E-06	0.243487	0.078116	1.86776E-05	0.538263	0.172687	1.81921E-05	1.048545	0.336397	4.41366E-06	1.271958	0.408072
30	1.85919E-06	0.05358	0.01719	5.09322E-06	0.14678	0.04709	6.50141E-06	0.374724	0.12022	1.35886E-06	0.391607	0.125636
31	6.52228E-06	0.187963	0.060303	1.77086E-05	0.510338	0.163728	1.62532E-05	0.936793	0.300544	3.91076E-06	1.127028	0.361576
33	7.86669E-06	0.226708	0	1.61381E-05	0.46508	0	1.51766E-05	0.874742	0	3.80277E-06	1.095908	0
34	1.5837E-07	0.004564	0.001464	2.14263E-06	0.061748	0.01981	4.02423E-06	0.231946	0.074413	1.17332E-06	0.338137	0.108482
35	9.29841E-07	0.026797	0.008597	3.82867E-06	0.110337	0.035399	3.84167E-06	0.221424	0.071038	1.10426E-06	0.318232	0.102096
36	7.94235E-06	0.228888	0.073432	1.85822E-05	0.535515	0.171805	1.59598E-05	0.919883	0.295119	3.94513E-06	1.136934	0.364754
37	1.44924E-06	0.041765	0.013399	5.17201E-06	0.149051	0.047819	6.2888E-06	0.36247	0.116288	1.79598E-06	0.517577	0.16605

2017e

Catchment	T2 Storage per m3	T2 Surface per km2	T2 Drain per km	T10 Storage per m3	T10 Surface per km2	T10 Drain per km	T50 Storage per m3	T50 Surface per km2	T50 Drain per km
2	1.76E-05	0.506086	0.162364	4.05E-05	1.168451	0.374865	3.49E-05	2.010514	0.645017
3	3.7E-06	0.106673	0.034223	1.01E-05	0.291221	0.09343	8.17E-06	0.470945	0.15109
4	1.22E-06	0.035153	0.011278	1.93E-06	0.055639	0.01785	-4.44E-07	-0.025587	-0.008209
5	9.63E-06	0.277436	0.089008	2.58E-05	0.744049	0.238707	2.22E-05	1.279129	0.410373
7	6.61E-06	0.190634	0.06116	1.25E-05	0.360231	0.11557	8.64E-06	0.497909	0.15974
8	4.89E-06	0.14089	0.045201	1.17E-05	0.335801	0.107732	1.01E-05	0.581892	0.186684
9	1.09E-05	0.314303	0.100835	2.43E-05	0.699783	0.224506	1.96E-05	1.130543	0.362704
11	-8.73E-07	-0.02516	-0.008072	-2.94E-06	-0.08459	-0.027138	-3.63E-06	-0.209337	-0.06716
12	7.41E-06	0.213518	0.068501	1.78E-05	0.513909	0.164873	1.39E-05	0.803329	0.257726
13	7.05E-06	0.20327	0.065214	1.59E-05	0.459278	0.147347	1.34E-05	0.774432	0.248455
14	1.95E-06	0.056255	0.018048	3.59E-06	0.103369	0.033163	2.18E-06	0.125936	0.040403
15	1.01E-05	0.291367	0.093477	2.18E-05	0.627741	0.201393	1.57E-05	0.90586	0.29062
16	4.26E-06	0.122842	0.03941	1.07E-05	0.308338	0.098922	1.05E-05	0.606505	0.19458
17	8.41E-06	0.242243	0.077717	1.92E-05	0.554551	0.177912	1.67E-05	0.96023	0.308063
18	1.05E-05	0.302793	0.097143	2.25E-05	0.649152	0.208262	1.95E-05	1.123027	0.360292
19	2.77E-06	0.079961	0.025653	6.75E-06	0.194465	0.062389	4.99E-06	0.287609	0.092271
20	-3.1E-07	-0.008937	-0.002867	-2.24E-06	-0.064424	-0.020669	-3.62E-06	-0.208934	-0.067031
22	1.25E-05	0.359156	0.115225	2.68E-05	0.773628	0.248197	2.48E-05	1.427093	0.457843
23	2.64E-07	0.007613	0.002443	-5.1E-06	-0.147109	-0.047196	-3.04E-06	-0.175226	-0.056217
24	4.8E-06	0.138192	0.044335	1.24E-05	0.356863	0.11449	1.14E-05	0.654265	0.209903
25	0	0.042695	0.013698	0	0.043144	0.013842	0	0.389574	0.124984
27	1.64E-05	0.472979	0.151742	3.55E-05	1.022923	0.328176	2.82E-05	1.622681	0.520592
28	4.14E-08	0.001192	0.000382	-2.9E-06	-0.083437	-0.026768	-3.55E-06	-0.20445	-0.065592
29	1.32E-05	0.380488	0.122069	2.86E-05	0.823157	0.264087	2.37E-05	1.368107	0.438919
30	2.61E-06	0.075142	0.024107	9.84E-06	0.283546	0.090968	8.31E-06	0.478953	0.153659
31	1.16E-05	0.334724	0.107387	2.48E-05	0.714042	0.229081	1.91E-05	1.099432	0.352722
33	1.15E-05	0.332517	0	2.39E-05	0.689886	0	1.81E-05	1.040587	0
34	9.87E-07	0.028442	0.009125	4.5E-06	0.12977	0.041633	7.27E-06	0.419221	0.134495
35	2.17E-06	0.06249	0.020048	6.71E-06	0.193333	0.062025	6.87E-06	0.396133	0.127088
36	1.21E-05	0.348991	0.111964	2.67E-05	0.768469	0.246542	2.3E-05	1.3279	0.42602
37	2.66E-06	0.076757	0.024625	8.56E-06	0.246733	0.079157	1.07E-05	0.61436	0.1971

Figure B- 8 - screenshot of unit effects of NBSs computed by HKV

<u>Verbeterpunten:</u>

[Q]: Waarin schiet de huidige NBS implementatie momenteel tekort?

[A]: Naast de dingen die we al besproken hebben… Ik zou gewoon kijken, welke parameters zijn voor welke hydrologische processen belangrijk. Dat lijkt mij het meest belangrijke. Dan nog iets, waardoor het hier heel lastig wordt, is omdat we niet precies weten waar welke maatregel precies wordt toegepast, alleen in welk gebied. Het wordt dan maar voor 10% van het gebied toe. Hoe ga je dat dan verwerken? Daar kan je nog wel even goed naar kijken. Daar zitten nog wel wat belangrijke onzekerheden in. Klopt het wel? Bijvoorbeeld, ik heb een gebied waar ik voor de helft van het oppervlakte 100 mm storage toepas. Is dat hetzelfde als ik het hele gebied pak en daarop 50 mm toepas? Is dat wel hetzelfde? Nee, dat is niet hetzelfde, maar belangrijk is natuurlijk hoe groot dat verschil is. Het verschilt natuurlijk of je dit boven- of benedenstrooms doet. Dit zorgt er natuurlijk wel voor dat je fouten maakt. Verder zijn er weinig parameters gebruikt. Er worden maar 3 parameters aangepast, terwijl er veel meer mogelijk is. Bijvoorbeeld forestation, doet meer dan alleen verruwen. Het zorgt heel veel meer.

[Q]: Is elke maatregel echt maar 1 type? Of kan het zowel verruwen en storage bieden?

[A]: Ga nog maar eens terug naar het lijst. Maatregel A3 is bijvoorbeeld surface en storage, waarbij de storage relatief klein is. Lokaal is niet zo veel, maar op catchment-schaal kan het wel significant zijn. Ook kan het uitmaken als het wordt geïmplementeerd op een flood hotspot. Nog een ding: gebruik het script. Het is niet eenvoudig om de map bestandjes aan te wijzigen als je dat niet doet. Dit kan ook gebruikt worden om de catchments te scheiden. Alle parameters moeten naar NaN waardes worden gewijzigd als je catchment niet wil meenemen. Dan is hij eruit. Misschien zou je 'm dan nog moeten croppen (alle cellen weggooien die je niet nodig hebt) om opslagcapaciteit te besparen, maar waarschijnlijk is dit niet nodig. De getallen van de meetsations komen overeen met de subcatchment nummers. Als je echt gaat runnen, zou je eventueel nog kijken of het op het rekencluster van HKV zou kunnen runnen.

B.4. Mark Hegnauer – Deltares – 24-11-2021

[Note, the interview was set-up in Dutch, because the interviewee and I both speak Dutch]

Inleiding:

[Q]: Wat is jouw rol binnen Deltares?

[A]: Ik ben hydroloog binnen Deltares. Ik werk nu 10 jaar bij Deltares. Daarvoor ben ik afgestudeerd aan de TU Delft. Binnen Deltares heb ik verschillende rollen gehad. Ik ben begonnen als junior onderzoeker, modeleur en hydroloog. Vanuit daaruit begonnen met gelumpte modellen en toen wflow meer in ontwikkeling kwam, ben ik steeds meer met wflow gaan werken voor heel veel verschillende opdrachten.

[Q]: Bij welke wflow projecten ben jij betrokken geweest?

[A]: In veel verschillende projecten op verschillende plekken op de wereld heb ik wflow toegepast. Ook heb ik een tijdje het product ownerschap gedaan. Ik heb nooit echt ontwikkeld. Ik ben meer een gebruiker. Ik zat ook o.a. in de organisatie van de gebruikersdagen en heb veel trainingen gegeven over het gebruik van wflow. Op dit moment is mijn rol daarmee weer iets minder en ben ik vooral gebruiker van wflow. De hydrologie gaat me nog steeds nauw aan het hart, dus ik bemoei me er nog wel regelmatig mee en weet er nog veel vanaf. Ook gebruik ik het nog veel in projecten. Eigenlijk weer steeds meer. Dat heeft ook te maken met het feit dat wflow ook weer aan het groeien is.

[Q]: Je zei dat je product owner was. Wat houdt dat precies in?

[A]: Dat houdt in dat je de ontwikkellijn in de gaten houdt en samen met het ontwikkelteam plannen maakt voor de ontwikkeling. Hiervoor kijk je ook naar het budget voor ontwikkelingen. Je helpt bij het maken van keuzes. Je bent naar de buitenwereld ook het aanspreekpunt. Je verzamelt wensen en bespreekt en prioriteert dat vervolgens met het ontwikkelteam.

Ontwikkelingsdoelen wflow:

[Q]: Waarom heft Deltares besloten om wflow te ontwikkelen?

[A]: Voor een deel heeft dat te maken met het feit dat Deltares een onderzoeksinstituut is en deels gefinancierd wordt door de Nederlandse overheid. Het doel daarvan is om een toonaangevend internationaal kennisinstituut te zijn en daarmee ook voor een deel een vlaggenschip te zijn voor Nederland. Elke twee jaar komt er een soort audit op bezoek dit Deltares tegen het licht houdt. 10 tot 15 jaar geleden is er tijdens zo'n audit gezegd dat het gek is dat Deltares als kennisinstituut geen eigen ontwikkellijn heeft, waarin je ook je onderzoek een plek kan geven. Dat was de trigger om na te denken over of er niet een eigen hydrologisch model moest komen. Het doel van wflow was daarmee dan ook om toonaangevend te kunnen zijn op het gebied van hydrologie. Ook proberen we hiermee onderzoek toepasbaar te maken voor o.a. consultants. Daarom is het heel prettig om een open source hydrologisch model te hebben. Wij kunnen er projecten mee doen, net als consultants, maar we kunnen er ook nieuwe kennis in stoppen.

[Q]: Het feit dat wflow open source is en dat er zo vanuit verschillende kanten nieuwe kennis ingestopt kan worden, is dat ook een belangrijke limitatie die jullie zagen bij andere modellen? Is dat een belangrijke ontwikkelvoorwaarde geweest voor wflow?

[A]: Er zijn heel veel hydrologische modelpakketten. Een heel aantal daarvan zijn gesloten en voor een bepaalde doelstelling ontwikkeld. Een mooi voorbeeld daarvan is het HBV model, die is ontwikkeld voor inflow forecasting van reservoirs in Scandinavië. Als je dat beseft, dan weet je dat dat een hele typische hydrologie is en daar zitten dus bepaalde processen niet of onvoldoende in die op andere plekken in de wereld wel relevant. We hebben daar wel een hele tijd mee gewerkt, maar we kregen het niet beter toepasbaar voor bijv. de Nederlandse situatie, India of Afrika, waar je weer hele andere uitdagingen hebt qua hydrologie.

[Q]: Is wflow ook specifiek ontwikkeld voor het modelleren in gebieden waar data schaars is?

[A]: Dat is wel een kracht van wflow inderdaad. Een voordeel van wflow is dat het aansluit bij bestaande gegridde datasets. Daarom was het ook wel een bewuste keuze om voor een gedistribueerd hydrologisch model te kiezen in plaats van een semi-gedistribueerd of gelumpt concept. Daarvan zijn er natuurlijk ook heel veel in de wereld.

[Q]: Waarom zijn er niet veel wetenschappelijke artikelen beschikbaar die modelleerstudies in wflow adressen?

[A]: Het feit dat het vooral gebruikt wordt binnen Deltares speelt zeker een rol. Uiteindelijk is wflow ook nog groeiende. We hebben wel steeds meer dat we wflow gebruiken in onderzoek dat wordt gepubliceerd, maar bijvoorbeeld echt publicaties over wflow zelf zijn er inderdaad nog niet. Er is momenteel wel een in pre-print. De lijst van publicaties waarbij wflow is gebruikt is wel groeiende. Die kan je hier vinden: https://deltares.github.io/Wflow.jl/dev/publications/ . Kijk daar eens in rond. Er zitten een aantal publicaties in die hoge impact hebben. We zien ook wel dat het nodig is om meer te publiceren over wflow om het verder te verankeren bij gebruikers.

[Q]: Dus eigenlijk is het vooral omdat wflow nu nog heel erg in ontwikkeling is?

[A]: ja en uiteindelijk ook een kwestie van bugetering en prioritering. De ontwikkelgelden en tijd is ook beperkt en we hebben maar een klein team. We kunnen er slechts een bepaalde hoeveelheid tijd aan besteden. Het is wel groeiende, want het pakket wordt volwassenere. Dit genereert ook wel weer inkomsten waardoor je ook weer meer aan ontwikkeling kan doen.

<u>Hydrologische cyclus en aannames:</u>

[Q]: Wat is de 'canopy gap fraction'? En hoe heeft dit invloed op interceptie, grond verdamping en transpiratie?

[A]: Dit is een parameter die wat zegt over de dichtheid van de canopy, van het bladerdek of je vegetatie zou je kunnen zeggen. Dit zegt iets over dat als het regent, wat is de kans dat het in het bladerdek terecht komt of dat het direct op de ondergrond terecht komt. Hoe groter die canopy gap fraction is, hoe meer gaten je hebt en hoe meer water er direct op de bodem terecht komt. En hoe minder er op de canopy wordt opgevangen. De canopy gap fraction is gekoppeld aan de LAI:

$$CanopyGapFraction = exp(-k * LAI)$$

De LAI verschilt per maand. In Nederland heb je heel duidelijk verschillende seizoenen en verschilt de canopy gap fraction door het jaar heen. In de zomer en lente heb je veel meer interceptie dan in de winter.

[Q]: Ik had inderdaad gezien dat de LAI verschillende input bestanden heeft. Er zijn er 12 en ik vroeg me al af waarom dat was, maar dat zou dan voor elke maand een zijn. Correct?

[A]: ja, precies. Dus dat is het idee. Dat is ook hoe het in de werkelijkheid is. Wanneer de bomen in blad zijn, is er meer interceptie. Dit hangt natuurlijk wel weer af van het type boom dat er is, want met name loofbomen verliezen hun blad, maar naaldbomen behouden hun blad. Dat zijn allemaal dingen die je mee kan nemen in het model.

[Q]: op dit moment is Kigali een event-based model die simuleert voor 10 dagen. Daarin kan je een start- en einddatum opgeven. Stel je zegt dat het model moet simuleren in januari, dan wordt alleen de LAI van januari meegenomen denk ik? In hoeverre zorgt dit voor onzekerheid in de modelresultaten?

[A]: Op de eerste vraag, ja, dat is wel de bedoeling. Ik hoop dat ze dat daadwerkelijk zo geïmplementeerd hebben. Je kan je wel afvragen hoe groot het verschil in LAI zal zijn gedurende het jaar, want hoe dichterbij je bij de tropen komt, hoe kleiner de variatie. De tropen staan altijd in blad, dus dan maakt dat ook iets minder af. De klimatologie van je LAI is vooral van belang voor gebieden waar er ook een groot verschil is tussen de verschillende maanden.

[Q]: Oke, dus je zal niet adviseren om het model te runnen voor verschillende maanden omdat het verschil waarschijnlijk erg klein is?

[A]: Je zou even kunnen kijken hoe die LAI's eruitzien, maar mijn vermoeden is dat het verschil heel klein is.

[Q]: In hoeverre wordt afwatering van de vegetatie na interceptie meegenomen in het wflow sbm concept?

[A]: Zover ik weet is het vereenvoudigd. In feite heb je een soort bakje dat de interceptie van de canopy simuleert. Dat loopt vol wanneer het regent en loop leeg door verdamping. Als dat bakje vol is, elke druppel regen komt gewoon op de grond. Er zitten ook wel parameters in over stem-flow, dus hoe water langs de boom dan weer terug loopt. Ik zal even kijken of ik dat snel kan vinden. Het staat allemaal wel redelijk beschreven op de website.

[Q]: op read the docs neem ik aan?

[A]: Nee, dat is ook wel goed om te weten. Er is een nieuwe versie van wflow, de Julia versie. Dat is de versie waarin we nu verder door ontwikkelen. Er zijn verschillende redenen waarom hiervoor is gekozen, maar met name omdat de Python PCRaster versie niet meer sneller kregen, want het was gebaseerd op een andere code. Julia is een andere taal. Het volgende linkje gaat over de Julia versie:

https://deltares.github.io/Wflow.jl/dev/vertical/process/#Rainfall-interception

[Q]: Hoe wordt de hoeveelheid transpiratie bepaald? En is dit evenredig aan de hoeveelheid vegetatie?

[A]: Het wordt berekend aan de hand van het type vegetatie. Uit de landgebruikskaart, kan je verschillende vegetatietypes halen. Voor de vegetatietypes kan je verschillende parameters afleiden, waaronder de rooting depth. Dit is de parameter die het meest te linken is aan transpiratie. Die bepaalt namelijk hoe de toegang tot water is in de bodem. Dus uiteindelijk zitten de verschillen in vegetatie zit 'm aan de voorkant, hoe je je parameters afleidt, per klasse van je landgebruik.

[Q]: Is het dan ook evenredig aan de hoeveel vegetatie? Of is het meer afhankelijk van de hoeveelheid water in de saturated en unsaturated store?

[A]: Dat laatste is wel hoe het werkt. De dichtheid van de vegetatie zit in de landgebruik classificatie.

[Q]: Kan je dit aantonen met behulp van de landgebruik tabel in Table B- 2?

Table B- 2 - land use classes and corresponding parameters

Land use description	Class	Kext	N	PathFrac	RootingDepth	Sl	Swood	WaterFrac
Forest	1	0.8	0.6	0	429.8	0.036	0.5	0
Open Areas or grass	2	0.07	0.5	0	410	0.07	0.1	0
Agriculture(Seasonal)	3	0.6	0.2	0	390.4	0.1272	0	0
Bare Soil	4	0.6	0.02	0	10.7	0.04	0.04	0
Settlements and Buildings	5	0.7	0.011	0.45	257.4	0.04	0.01	0
Water bodies	6	0.7	0.01	0	0	0	0	1
Wetlands	7	0.6	0.15	0	106.8	0.1272	0	0
Mines	8	0.6	0.02	0	10.7	0.04	0.04	0
Sparse Forest	10	0.8	0.55	0	419.9	0.053	0.5	0
Agriculture(perennial)	11	0.6	0.2	0	390.4	0.1272	0	0

[A]: Dit is waarschijnlijk een zelf geclassificeerde landgebruikskaart. Wat je ziet is dat er verschil is tussen de rooting depths. Dat zijn typisch hoe de parameters samenhangen met het landgebruik. De classificatie van 1 t/m 11 geeft aan dat het een zelfgemaakte classificatie is waarschijnlijk op basis van Vito of GlobCover.

[Q]: Welke parameters hebben invloed op de hoeveelheid infiltratie in de 'saturated' en 'unsaturated store'?

[A]: Nee, dat is wel iets anders. Eigenlijk moet je het ook zien als dat de U en de S store gezamenlijk een bak met water en grond is. De scheidslijn tussen die twee kan variëren. Dat is dan het freatisch grondwaterpeil, simpel gezegd. Hoe die scheidslijn zich verplaatst hangt af van de hydraulische conductiviteit van de grond. Als je een hele doorlatende ondergrond hebt, dan zal je zien dat je heel veel sub-surface flow hebt, dus dat lateraal/horizontaal, die S store heel snel leegloopt. Water kan dan ook makkelijker naar beneden stromen en de S store aanvullen. Hoe water echt van het oppervlak in de store terecht komt, dan heb je het inderdaad over de infiltratie capaciteit. Dan heb je het vooral over deze twee parameters: InfiltCapPath (infiltratie capaciteit van verharde ondergronden) en InfilCapSoil (infiltratie capaciteit van de grond).

[Q]: Wat betekenen de getallen die in de .tbl bestandjes van deze twee parameters staan? (Zie onderstaand)

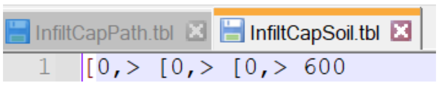


Figure B- 9 - screenshot of .tbl file

[A]: Dit is het typische PCRaster formaat. Moet ik even goed over nadenken. Deze tabel is gelinkt aan een landgebruikskaart, een bodemkaart en een sub-catchment kaart. In dit geval is je eerste kolom volgens mij je landgebruik, de tweede de sub-catchment en de derde de bodemkaart, bijvoorbeeld. [0,> is een cryptische manier om te zeggen dat alle waardes tussen 0 en oneindig uiteindelijk de waarde krijgen die in de vierde kolom staat. In dit geval 600. Wat hier dus eigenlijk staat is dat alles dezelfde infiltratie capaciteit van de soil.

[Q]: stel ik zou nog een extra infiltratiecapaciteit willen toevoegen, dan moet ik nog een extra regel toevoegen?

[A]: Als jij onderscheid wil maken tussen twee landgebruik types bijvoorbeeld, dan moet je aangeven voor welke landgebruik types waarde A geldt en voor welke waarde B geldt. Dat moet ik ook even nazoeken hoe dat je precies doet in zo'n tabel. Stel er zijn 10 bodemtypes, dan kan je ook gewoon 10 regels maken met alle bodemtypes en die allemaal een aparte waarde toekennen.

[Q]: Hoe wordt open water verdamping meegenomen?

[A]: Het open water zit in je Kinematic Wave. Je hebt je Kinematic Wave voor je stroompjes. Daarvoor kan je een oppervlakte van bepalen, dus wat is het oppervlaktewater in de Kinematic Wave. En daarop kan je de verdamping uitrekenen. Dat is de referentieverdamping. Ik denk zelfs je potentiële verdamping. Dus voor open water, dat je actuele verdamping gewoon gelijk is aan je potentiële verdamping. Dat weet ik niet uit mijn hoofd, dat zou ik even moeten uitzoeken. Dan heb je ook nog je reservoirs en je meren. Dat is natuurlijk ook open water. Daar wordt een soort waterbalans van het reservoir gemaakt, waarbij je dan ook weer zegt dat de verdamping gelijk is aan de potentiële verdamping, omdat je altijd voldoende water hebt om te kunnen verdampen.

[Q]: Hoe kan ik de evapotranspiratie verhogen in het systeem? Moet dan de 'forcing' van de potentiële evapotranspiratie worden aangepast worden aangepast of zit dit al verwerkt in de model parameters?

[A]: De input die wflow krijgt is potentiële verdamping. Potentieel is puur afhankelijk van meteorologische condities: temperatuur, straling en als je Penman-Monteith pakt dan heb je ook nog iets met windsnelheid. Dat zegt iets over, als ik oneindig veel water tot mijn beschikking heb, dan is dit wat er verdampt. Het hydrologisch model is vervolgens aan zet en die zorgt ervoor dat er waarschijnlijk niet voldoende water beschikbaar is om potentieel te kunnen verdampen. Dat verschil tussen wat er potentieel mogelijk is en wat er uiteindelijk echt verdampt (actuele verdamping), dat wordt bepaald door het hydrologische model, door dingen zoals bodemgebruik. Het kijkt naar hoe de waterbalans in het model in elkaar zit. Als we even een bakje pakken, als die bodem heel ondoorlatend is, dan zal die grondwaterstand altijd vrij hoog blijven, want het sijpelt niet zo snel door naar de ondergrond. Het water blijft dan in je root zone en de wortels kunnen dan blijven verdampen. Terwijl als je een hele doorlatende bodem hebt, dan zakt elke druppel regen direct door tot onder de wortels en blijft het dus eigenlijk niet beschikbaar voor verdamping. Dan zal je dus zien dat de actuele verdamping heel laag is in de vergelijking met potentiële verdamping. Dat zijn ook typische kalibratie parameters. Dus even helemaal uitzoomend, hoe kalibreer je een wflow model? Stap 1 is dat je probeert de waterbalans goed te krijgen, dus de verdeling van de neerslag tussen verdamping en afvoer. Over een jaar gezien wil je dat je afvoer en de verdampingscomponent overeenkomen met wat er in werkelijkheid gebeurt, voor zover we dat kunnen meten.

[Q]: Goed om te weten dat ik dan in ieder geval niet de forcing moet gaan aanpassen.

[A]: Ja, is er wel een uitzondering en daar zijn wel eens vragen over gekomen. Er wordt heel veel gesproken over herbebossing en de invloed van verdamping van bos op de circulatie. Dat je een soort van micro-klimaat krijgt. Dus het bos verdampt en dat vocht komt elders in het stroomgebied weer terug. Dat kan niet met wflow. Die terugkoppeling zit er nog niet in. Dan zou je het ook moeten gaan koppelen met een weer of klimaatmodel. Dat is een lange termijn onderzoek.

[Q]: In hoeverre zijn de effecten van bepaalde hydrologische processen op de afvoer verwaarloosbaar in wflow?

[A]: Dat is vrij lastig te zeggen, omdat het vaak vrij catchment specifiek is welke processen dominant zijn. Dat heeft alles te maken met factoren als helling, typische klimaat, etc. Kigali kan je vrij zeker van zijn dat je sneeuw en gletsjers kan negeren. De andere processen zijn echt catchment specifiek, dus dat ik vind ik lastiger te zeggen.

[Q]: Oke, maar het is dus niet zo dat als je een hele extreme bui hebt die maar kort duurt, dat processen als infiltratie verwaarloosbaar kunnen worden omdat het grootste deel van het water toch gewoon over land wordt afgevoerd?

[A]: Ja dat kan, maar ook dat is ook weer afhankelijk van wat is je infiltratiecapaciteit. Dit kan vrij snel afschatten door je infiltratiecapaciteit te vergelijken met je neerslag. Daarvoor hoef je nog geen eens echt sommetjes voor te doen. Daarnaast hangt het ook nog van veel andere processen af, bijv. hoe hoog is je grondwaterstand. Kan het überhaupt je grond in? Daarvoor is je laterale runoff weer belangrijk, hoe snel loopt het celletje leeg? Dat is best wat uitzoekwerk.

[Q]: In hoeverre is er onderzoek gedaan naar de effecten op de afvoer door gebruik te maken van de 'kinematic wave approach' voor een relatief vlak terrein?

[A]: We hebben daar wel eens naar gekeken. Bijvoorbeeld in de Amazone, daar was het effect echt enorm, maar goed dan heb je het ook over een enorme catchment, met aan het einde een hele lange vlakke rivier. Het hangt hier ook weer af van je catchment. We doen momenteel testen voor de Maas in België. In de Julia versie hebben we nu twee versies: de Kinematic Wave en de Diffusive wave. De diffusive wave zou dat al veel beter moeten doen. Het verschil is daar echter heel klein. Dit komt omdat de rivieren hier al iets minder steil zijn. Oftewel, het moet wel heel vlak worden om echt een effect te hebben.

[Q]: Kigali is niet heel vlak, dus ik denk dat de onzekerheid die hiermee gepaard gaat dus relatief klein is.

[A]: Ja, mijn inschatting is dat zeker de toestroom dat dat redelijk goed moet gaan met de Kinematic wave.

[Q]: Hoe zorgt de optie 'waterdem = 1' voor minder onzekerheid in het model voor een vlak terrein? In hoeverre in het aan te raden om dit mee te nemen voor Kigali?

[Q]: Dit zou in dit geval dus niet meer nodig zijn in het geval van Kigali?

[A]: Nee, ik denk het niet. Daarnaast is het een vrij rekenintensieve optie om dat aan te zetten. Hoe ik het altijd heb begrepen is dat het model voor elke tijdsstap o.b.v. de berekende head een nieuwe local drainage direction kaart gaat afleiden en o.b.v. daarvan het water routen. Dus dat is bestwel rekenintensief. Als jij echt nog gaat modelleren en rekenen aan het model, dan is het wellicht nog wel de moeite waard om eerst nog de overstap te maken naar de Julia versie van wflow, want dan krijg je zulk soort dingen er allemaal bij. Bijv. de diffusive wave en een verbeterde grondwater module. Dat is misschien wel veel interessanter voor het beoordelen van die NBSs.

[Q]: ik ga het model uiteindelijk gebruiken om eenheidseffecten van NBSs te bepalen, dus ik zal er wel flink mee gaan rekenen, dus het zou misschien wel interessant kunnen zijn.

[A]: We zouden je daarbij ook zeker flink kunnen helpen, want uiteindelijk zal de Python PCRaster versie ook uit gefaseerd worden. Hij wordt nog wel ondersteund, maar niet meer onderhouden. Iets om over na te denken zou ik zeggen.

<u>Implementatie van NBSs</u>

[Q]: Hoe kunnen kleinschalige maatragelen (kleiner dan de grid size) worden geïmplementeerd in wflow?

[A]: Dat is zeker lastig. Op een gegeven moment loop je wel tegen de grenzen aan van wat je wel of niet kan. Er zijn natuurlijk van die NBSs zoals het aanleggen van een overloopgebied langs een drain en daar een mooie vijver van willen maken. Dat is denk ik niet het type maatregel dat je met een wflow model moet willen doorreken. Ik zou het meer richten op de systematiek van bijv. wat nou als we in dit deel van het stroomgebied het landgebruik aanpassen? Wat als we rivieren meer laten meanderen? Dus meer kijken naar generieke maatregelen en de effecten daarvan, want uiteindelijk doet 1 NBS in het geheel ook niet zo heel veel. Uiteindelijk wil je gewoon gaan kijken of een NBS, gemiddeld genomen, optie is. Dan zou ik dus toch meer naar de opgeschaalde effecten van een combinatie van NBS kijken. Dus herbebossing bijv. of het toevoegen van heggen op de helling enz. Zo'n heg is slechts 5 meter breed dus dat zie je niet op de grid van wflow, maar je kan wel zeggen, in dit gebied kan ik zoveel heggen kwijt. Dus op 10% van het areaal kan ik die heggen kwijt. En daar ga je dan een parameterschatting voor maken. Iets wat onlangs nog in Duitsland hebben gedaan samen met HydroLogic is over in welk deel van je catchment die maatregel gaat implementeren. Bijvoorbeeld over wat je net zei, over maatregelen die in de rivier zijn, dat doe je typisch op cellen die ook rivier zijn in je model. Dus streamorder boven de 3 typisch. En andere zijn die je vooral op de helling zijn, dus dan gebruik je streamorder 1 om maatregelen te implementeren.

[Q]: Is het mogelijk om het model lokaal te verfijnen? En als dat het geval is, hoe?

[A]: Die optie bestaat niet. We hebben wel eens studies gedaan waar we kleine detailmodelletjes hebben gemaakt van delen van een stroomgebied met een hogere resolutie. Dat kan natuurlijk altijd. Dat is misschien ook wel een leuke aanpak. Dat kan je misschien nog wel testen. Hoe kan ik het aanpakken in zo'n kleinschalig model en hoe kan ik dit opschalen naar het grootschalige model waar je niet op die hogere resolutie kan rekenen?

[Q]: Waarom is het lastig om 'storage' maatregelen te implementeren in wflow door enkel gebruik te maken van model parameters?

[A]: het gaat erom, wat is een storage maatregel en hoe wil je het implementeren? Wat is het proces dat je simuleren en daar pas je een parameter bij dat het dichtst bij dat proces komt. Storage zit natuurlijk voor een deel in je interceptie, maar dat is maar een deel denk ik. Storage zit ook vaak in ponding, dus water langer vasthouden op het maaiveld. Dan zou je het ook weer kunnen koppelen aan de ruwheid dus water gewoon langzamer later afstromen. Er zit niet echt een storage knoop in het wflow sbm concept. Als we zeggen, daar willen we iets mee, dan zouden we daar ook wel eens over na kunnen denken.

[Q]: Wat zijn jouw gedachtes bij de haalbaarheid van de onderstaande wflow verbetering om 'storage' maatregelen te implementeren? (additionele 'storage store' boven de 'unsaturated store')

[A]: Ik denk dat dat wel heel leuk is. Misschien is het ook wel simpel te implementeren in de zin dat je soort van threshold waarde hebt, van als het over deze drempelwaarde heen komt, dan loopt het naar mijn volgende cel toe. Dan krijg je soort van weir formulering van het ene naar het andere celletje. Van pas als die over de drempel komt, dan stroomt het naar de volgende cel toe. Dit zouden we wel eens kunnen bespreken met de ontwikkelaar. Dit zou je dan ook weer kunnen koppelen aan een kaart die specifieert waar je die drempel omhoog wil zetten.

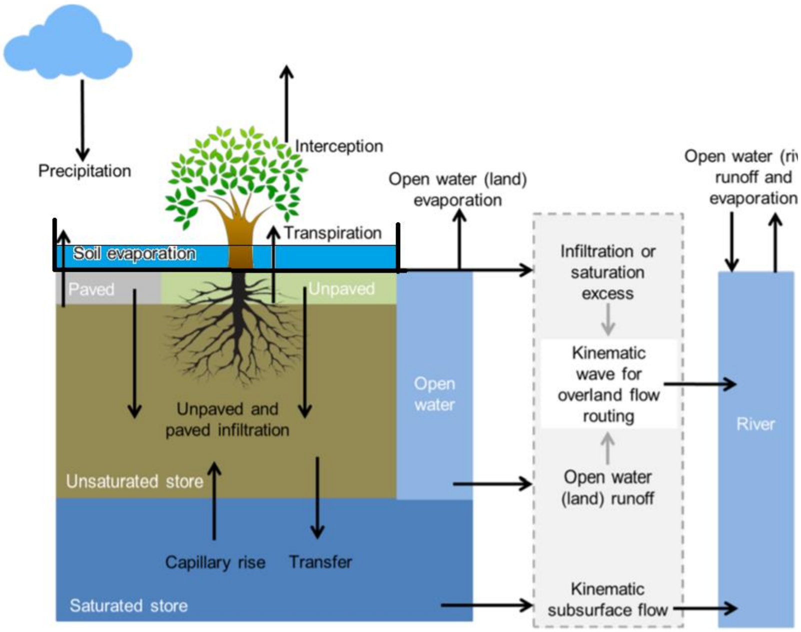


Figure B- 10 - SBM concept including the additional storage bucket

[Q]: Wat zijn de nadelen van het gebruiken van de Swood parameter voor 'storage' maatregelen?

[A]: ik moet daarvoor even de documentatie erbij pakken. Het is een trucje om het te doen denk ik. Het heeft niks met het echte proces te maken is mijn gevoel. Het is puur een parameter waarin je storage kwijt kan. Je werkt er omheen, maar misschien dat het tot goede resultaten leidt. Ik denk inderdaad dat het beter zou zijn als we daar een betere implementatie voor krijgen.

[Q]: ik zat vooral na te denken over het feit dat als je interceptie hebt en het vervolgens weer verdampt het weer vanuit daar. Er zitten hele andere hydrologische processen aan, dan dat je eigenlijk beoogd met je NBS.

[A]: Ja, klopt. Ik kan me bijvoorbeeld voorstellen dat je bijvoorbeeld met surface storage ook je infiltratie naar het grondwater wil vergroten. Ik vraag me af of je dat meeneemt als je het in de Swood stopt. Uiteindelijk heeft dat ook wel weer effect op de surface runoff als je je grondwater op een andere manier aanvult. Dus vandaar ik dat ik denk dat het een trucje is, waarschijnlijk bij gebrek aan beter. Dus ik denk dat we echt opzoek moeten naar een betere manier om dit te implementeren. Ik zal dit ook aangeven bij de ontwikkelaars en kijken wat zij hiervan denken. Wij zijn zelf ook bezig met NBS-gerelateerde zaken in wflow. Dit is dus denk ik wel iets waar je iets mee zou willen.

[Q]: stel je hebt dus een vijver of een reservoir, dan infiltreert er standaard meer water naar de grond toe neem ik aan?

[A] Ja klopt. Dat is wel iets wat je wil meenemen in je NBS. Jij kijkt nu voornamelijk naar overstromingen, maar NBSs kunnen ook relevant zijn in het geval van droogte. Dan kunnen zulk soort processen extra relevant worden.

B.5. Bobby Russell – Deltares – 26-11-2021

Basic questions:

[Q]: What is your role within Deltares?

[A]: At Deltares, I work within the hydrology department as a project manager. I am also the product manager of Wflow. So, I manage the development process. Then we also have a product owner, Willem van Verseveld. He is the lead programmer, not only for the software, but also for the hydrological processes. So, there is a distinction between what we talk about in terms of software functionality and in terms of the actual physics and mathematics behind it.

[Q]: In which ways were you involved in the wflow project for Kigali?

[A]: I am also on the marketing team for Africa. So, I work in a lot of projects in Africa as the team leader and that was how I was involved in the wflow project in Kigali. So, the project in Kigali was an urban flood project and we were to simply build an urban flood model. The core part of that was a 1D-2D Sobek hydraulic model. The upstream boundary conditions that drive the Sobek model was a distributed wflow model for the upstream areas.

[A]: You were the manager, so you did not do any programming?

[Q]: We did not do any programming. We just used the software as it is. There are no adjustments. We just used it off-the-shelf. The wflow modeller was Pieter Hazenberg, who since left Deltares, but is still contactable I presume. The Sobek modeller is Eskedar Gebremedhin.

Development goals wflow:

[Q]: Why did Deltares decide to develop wflow? [mention: extracting soil data from global SoilGrid database from ISRIC]

[A]: We mentioned it at our user day last week. We were told to. So, prior to Deltares forming, there was a strategic review. So Deltares was formed from a series of different organisations. One of the main ones was Delft Hydraulics. This strategic review looked at the coverage of our knowledge and our software. One of the things they noticed is that we have a lot of hydraulic software, but no hydrological modelling software of our own. Basically, they formed the open streams project. It was an initiative, which is long stopped. It was a collaborative open-source development with different institutions. Most of those institutions stopped a long time ago, but Deltares continued with wflow. The concept of wflow was always that it would be a framework within which you would have other concepts. By the time I came on board with wflow as a manager, we had 8 different model concepts. They were all grid distributed and mass balance hydrological models. So conceptually, they were not hugely different, but they all required different inputs and used different parameters. Many of the concepts were still being developed. So, they were added into wflow for a specific project and then we had to keep maintaining them. Then we just said, it makes no sense to keep maintaining 8 model concepts, so we made the decision to switch from the PCRaster python language, which is from Utrecht University (number of models have been built in that language, such as ListFlood and PCRGlobWB) to Julia. We had been more and more using the SBM concept. The reason why we did that is because it physically based, so we were able to model far more things than in a conceptual model, that is empirically based. And another thing, which you correctly pointed out, is that we can actually set-up the model in data scarce areas.

[Q]: Do you have any idea why there are few scientific articles available which address modelling studies using wflow?

[A]: I am wondering, what is only a few? How many did you find?

[Q]: Good question, I am not sure, but I have looked at approximately 10 articles, which I thought were relevant for my research. None of them were related to NBSs though.

[A]: if you go on our docs, so onto the wflow documentation. I think maybe if you look into the Julia documentation, it should be more complete and there should be a list of all the publications. There are lot of papers out there that do not really talk about wflow, but about HBV-96. They are actually wflow models. A lot of applied research and forecasting was using HBV not SBM. So, it will talk about applying HBV-96 and applying its concept, but they are actually using the wflow software. However, I would be careful about that, because if you are using SBM, do not confuse that and talk about other concepts within wflow. The other thing is that a lot of our projects, although they are not necessarily confidential, the client won't let us publish. So, we have to get written permission. They do not say no, they just do not respond to the emails. So, we try and get permission at the beginning of the project, get it written into the contract, but they just refuse. They say it is their product, it is for them to publish, we are not allowed. There are many HBV and SBM models out there that we have done and that are written about, but we do not scientifically publish them. That is why we encourage MSc and PhD thesis.

Model validation:

[Q]: For the Kigali model, the discharge was only validated using discharge data at Nemba (downstream of Kigali). What can be said about the resulting validity of the model?

[A]: Hang on, we could only validate at Nemba. I would not call it a validated model.

[Q]: So you could only validate at Nemba, but you decided not to, because it does not make sense?

[A]: It is not validated. If you look at our second report... We plotted rainfall and the actual gauge and the model, because the client was saying, you have got these huge differences between modelled discharge and the actual discharge. We were saying that the quality of the discharge data is pretty poor as we only have water level data at Nemba. The government of Rwanda does not publish discharge data and I know this for a fact, because I wrote that policy for the government of Rwanda. The government will be giving us a level of assurance that that discharge data is accurate, whereas they do not have enough discharge points. You understand how rating curves work?

[Q]: Yes

[A]: All of the rating curves are scattered from all over time. They do not collect enough rating curves within a single year to create annual rating curves could be used to generate discharges. The other problem at Nemba is that the gaging station is in a very small deep channel. Nemba is a tiny stream, so at bankful discharge it carries 30 m^3/s, maybe less. And in front of it a huge road embankment crossing the valley and then it goes under a narrow bridge. So, when you got 60-100 m^3/s going down the valley, it basically forms a lake at the gaging station, so your rating curve is not very valuable at Nemba. It works for low flows, but it does not really work for high flows. We were trying to discuss that with the client. If you line up major rain events, then you line them up with the gage, sometimes there was no corresponding increase in discharge. So, something was not quite right. Either the rainfall data was junk, or the water level data is junk, or our model is junk. Now what we did, we looked at the sub-catchment discharges and they all looked fairly reasonable. Nemba is very far downstream of Kigali. The area of interest is inside the city itself. So, is the model accurate inside the city? So even if we managed to say, at Nemba, it is validated, it does not necessarily say that it is validated for the interior of the sub-catchments. So, we looked at the sub-catchment discharge which go into the hydraulic model, and they all looked fairly reasonable, where you had the right kind of very steep hydrographs, the volumes looked fairly reasonable for the catchment sizes. The other thing was that the government of Rwanda had some flood marks from a known flood event. Although we had no rainfall data for that flood event, we had some water depths, which were very strangely measured. They said they saw something hanging in a tree and gave us that location and the distance to the ground. However, the depth was actually estimated to the bottom of the river, which might be 20 meters away. It was a bit strange. We also knew that the Digital Terrain Model had a +- 7 m vertical accuracy problem. So, the depth validation on the 2D domain only works if your digital terrain model is very accurate. And it wasn't. So hence, we basically talked about using the model in terms of the change in flood depth and the change in discharge. Relative changes, rather than absolute changes. So, if the client is saying, we want to know if this bridge floods or not. That's not something we can give a very strong assurance on. If they ask, what happens when the rainfall increases by 50%. Any hydrological model depends on how much water you put into it. So, when your rainfall data is not accurate, then your model is never going to be accurate.

[Q]: For the purpose that I am going to be using it, computing the effects of NBSs, I noticed that the differences between the NBSs can be very small. To what extent do you think we can have certain certainty that this model is accurate for computing the effects of NBSs?

[A]: That's a good question. Validation all the way downstream is irrelevant anyway. What I am interested in the micro-level rainfall mass balance and runoff. You want to know if I plant a garden right here, what is going to be the effect on infiltration, interception, maybe evapotranspiration, soil moisture balance and then runoff finally. The only way to do that, is to set up a physical experiment. Sorry. I am a physical hydrologist. I love going into the field and measuring stuff and this is how it used to be. So, they used to talk about the effect of forestry and land change on discharge. So, in the past, they have set up physical experimentation in catchments and said, let's cut all the trees down and see what happens to the discharge. Then they set up flume gages everywhere and this data is all available. They would compare it to different types of forested catchments and would measure how the discharge changes as the plants grow again. People did their PhDs on it and published this data and people calibrated models using it. I am not sure whether that is being done for micro-level Nature Based Solutions. I think you have to recognise the limitations of what you can do in a MSc.

[Q]: for some NBSs I indeed found some quantitative data, but for others I guess I will have to make some rough estimates.

[A]: There was a paper where somebody used MIKE SHE, which is not so dissimilar to the SBM concept and they had a 10cm resolution. They were modelling a green swale at the micro-scale. You would be looking at the micro-catchment level I would say. It depends on what you want to achieve. If you want to model something at the micro-scale, then you need some kind of validation, with a real structure, in which case the Kigali model is useless. You'd need to build something completely new. If you say that the Kigali model is reasonable, as the discharge we were putting into it were not extravagant and you are never going to get it more reasonable without spending millions on data collection. What you are actually doing is checking the sensitivity of the parameters and trying to make an evaluation of whether that represents reality. So, we only changed 3 parameters, the surface, channels and Swood for storage. Swood was a proxy for any kind of storage interception at that pixel scale. Swood is connected to land cover, so you have to be very careful to what you are changing in there. If you start fiddling with that and you change the land use as well, you might be making non-sense.

[Q]: That is actually something that I wanted to show you during this interview.

Implementation of NBSs:

[Q]: What are your thoughts on the following wflow improvement to represent storage measures? [*Show* Figure B- 10*]*

[A]: What I would be interested in, is whether you want to go in code and add an additional rainfall storage parameter. I think that would be a very nice addition for us. You are doing an MSc-thesis. We know how all these parameters kind of work, we are interested in something a bit new.

[Q]: How did Deltares conclude that 90x90m was a suitable grid size for the wflow model of Kigali?

[A]: well, no we didn't, we didn't know. We just had to make a choice.

[Q]: And you made that choice based on the available data?

[A]: Well, no. We have never gone lower than 90x90 m. We have just found out that somebody has gone down to 50x50 m, but that was a very flat terrain. 90x90m (it is not really 90x90, but whatever) is Merit Digital Elevation model. We use Global Datasets to build the models and typically we substitute out a couple of things. So, for Kigali, we substituted out the ERA5 dataset and put in the local dataset. And then we substituted out the GlobCover global dataset and substituted in the National Land Use Land Cover dataset. That one was a 10 m resolution, so we had to oppress it to 90x90 m. The global DEM, the Merit, is 90x90 it is basically a smoothed out SRTM. It is biased corrected for all the speckling, and it is hydrologically correct. So basically, you will know when you have got water on it, it will flow off. The local government in Kigali has a 10x10 m DEM. That is what we used for the flood modelling. It has got everything in it, such as road embankments. It is not being hydrologically corrected, so it is going to stick being all kind of weird features. The other problem was 90x90 m, for the size of the catchment, it ran very slow. We had four return periods and then so many climate change scenarios. It was very slow, partly because it was the PCRaster version. You attended the workshop last week. We get this question all the time: what is the optimal resolution? It is impossible to know without running so many different model scenarios. And then the client says, well we don't care how long it takes you, just run it with the highest resolution possible. Well actually, especially for bigger catchments, the accuracy is irrelevant. Now, with NBSs on a micro-urban catchment scale, if you got a 10x10 resolution model, you are actually able to have 10x10m intervention. Whereas what Job and his team had to do was say: we have 10x10m interventions, now we have to scale up those values to 90x90m. So, they had to average out the values. That is kind of a sh*tty thing to do. But we would have never gone to 10x10m resolution, because it would have been too slow, but if you are working on a micro-catchment, you could also consider doing 90x90, 30x30, and 10x10. And then show both how discharge changes, how is the model sensitive to spatial resolution and does that actually affect the change in discharge when you apply NBSs.

[Q]: That is similar to the presentation given by Jerom Aerts right?

[A]: Yes, but he did a bit of a higher scale.

[Q]: I am also going to talk to him and that is one of the questions that I wanted to ask him. I also talked to Geerten who implemented the NBSs in wflow. From that interview, I discovered that for example increasing the roughness of the surface for small-scale NBSs, the roughness was multiplied by a factor representing the area which it was implemented on in the 90x90 m grid cell.

[Q]: Why is difficult to implement storage measures into wflow using only its model parameters?

[A]: We don't use wflow that way. We have RiverSim. So, if you have to implement storage and control features on a large catchment, we use RiverSim, which is also a mass balance model, but it has a functionality to take out water and store water and put water in. For many reasons, it was never really put into wflow, because there is that division in Deltares software. RiverSim does that, RiverSim does storage and control and wflow does runoff and physical catchment modelling. The other argumentation is that actually such features should be done in a kind of hydraulic model in the urban environment. Obviously if you try to do it with a Sobek model, it will not work, because for such a huge city, you also go on to do it in a 1D or 2D model, because it would be too slow. At a micro-catchment scale, things like storage and water depths, are much more accurately represented in a hydraulic model than in a hydrological model. That said, this capture of rainfall would not work in a RiverSim model. RiverSim model do not work like that. I would be best implemented in a wflow model. Because mostly when people say, we want to do NBSs, this is where we get into these conceptual issues. NBSs are about nature, NBSs are not rainwater storage in cities. Let's be really clear of the science. NBSs are about restoring nature. If you are restoring nature, you can just use your land cover and Swood parameters, because they are physical and at the grid scale. What Job's team wants to represent; you could call it sustainable drainage systems. So basically, they were saying, you need to store rainwater where it lands, locally, and therefore, you need to represent that storage capacity in the grid framework, which makes sense. However, that's not part of a NBS that I would see it. It is a debate we had with the world bank. So, it is kind of like we need a parameter to make that storage and that's why they came up with the use of the Swood parameter.

[Q]: So Swood is the parameter that would normally be used for interception, right?

[A]: You have canopy interception and tree trunk interception. Swood, I think, is just the trunk and tree. Actually, it stores very little water, as does the canopy actually. Once it becomes saturated, it runs off. What we were actually doing with using this parameter, because you do not have many trees in the city anyway, we use this Swood as a storage parameter, while normally, it is linked to the LAI. So, to what the vegetation is. Which is why I am saying, it would be much more interesting for us, if we had a single S parameter. Normally it would be set at 0 or you could give it a raster file and the raster file would have a value. You would basically subtract that from the precipitation.

[Q]: That would work in the case of rainwater tank, but maybe it can also be used for ponds for examples. In ponds there are different processes involved than in a rainwater tank, because when water is in a pond, it doesn't leave the rainwater tank unless it is being used or full.

[A]: Yes, usually they are in the rainy season. They are full. They are empty in the dry season. This is something that is very interesting about NBSs. If you increase infiltration, you get less runoff. In the dry season, you might take all the rainfall and get 0 runoff, which is not necessarily good. People get used to a certain volume of water coming out of a catchment. So, if you think about things like dilution and pollution. If there is no water going water going into your drains, they get blocked. That's just to complicate things a little bit for you. Rainwater tanks, people need them full at the end of the rainy season, because they use them in the dry season. So, they typically flood fill-up. My parents have rainwater tanks. They are always full, because it always rains. So, you could create a single artificial storage and then you have a single parameter which represent all different rainwater capture methods. Or you could discretise it and say you have rainwater tanks, rainwater squares, etc. They are a very Dutch kind of solution by the way. These place, you have to imagine, what is it going to look like in an African city? They are either going to fill it with garbage or plastic or it is going to become a breeding ground for Malaria. Same with rainwater tanks. They have them everywhere, but they are a pain in the neck for Malaria. Anyway, that is not your problem. What I would suggest, is, you have the rainfall data, the gridded data. I would not necessarily apply the return periods. You might want to consider applying an adjusted dataset, so it is 10 mm of rainfall, 20 mm, 30 mm, 40 mm, 50 mm, etc. Then, basically, you have a little bit more discretisation of what happens to the rainfall. So, you are not only looking at flood flows, but actually look at all different quantities of water. So, what happens when you just put 5 mm on it? Does it capture everything, or do you still get a little bit of runoff? That's always the thing with these flood models. We put 65 mm in an hour on it and you get loads of runoff. We never really look at what happens when you only put 5 mm of rainfall on it. Do you get any runoff at all? What happens with 10 mm? That's more the common rainfall effect actually.

[Q]: That is a really good suggestion. The goal of my thesis is to compare the two approaches, so I think I will still have to compare the return period data that comes from the model, because that is also what HKV has done. However, this is quite a good thing to discuss. I think it is very relevant to discuss.

[Q]: Let's go back to the storage measures. We have talked about this before, but what do you think about the idea of implementing a threshold value to implement storage measures? When this threshold value is reached, water will overflow to the next grid cell. The water on the grid cell will evaporate into the ground and evaporate, such that it works like an additional storage bucket on top of the saturated store.

[A]: Yes, that is what I am also mentioning. You would have a gridded dataset. What you see in Figure B- 10, you have your little bucket on top. It would have value of so many millimetres of rainfall. So, it would basically extract that. So, you have the rainfall coming down. So, as long as that rainfall is not exceeding that value, it keeps filling up, until it reaches that value, because you cannot add any more to it.

[Q]: Let's say this is something that I would like to implement into wflow. Is this something I can do myself?

[A]: You do not need any permission. It is open source; you can do what you like. The question for you is, do you want to do it in PCRaster Python or in Julia.

[Q]: In PCRaster Python, because that is the model I am currently using. For you, I know it would be more useful to do it in Julia though.

[A]: The reason is that we are not going to change the PCRaster code as it is, unless there is a serious error in it. But we haven't found any in it for two years; it is stable. Any additional features and functionalities, we would like to have in the Julia. If you want to do it in the SBM concept and in PCRaster, you can do what you want.

[Q]: I do not really know where to start. For example, how can I look into the code for the SBM concept? What are things that I certainly need to look at before changing the code.

[A]: I haven't looked at this for a long time. Let me share the link: https://github.com/openstreams/wflow . So, this was our github under the openstreams project. We now have github under Deltares for the Julia version. This is the code. Anybody can go in here. I cannot remember the last time we did anything here. There is a lot of documentation in here. That is your starting point. The docs are here as well. They are not fantastic, because we are focussing more on the Julia version. If you are familiar with coding, they are okay, but otherwise, it might be a bit challenging.

Limitations and improvements:

[Q]: What are the other limitations of the Kigali wflow model?

[A]: I am not sure. I think it is a very suitable model for NBSs, like land cover changes and vegetation change. You have everything in there that you need, you have canopy interception, tree trunk interception, soil infiltration, surface runoff based on what the vegetation looks like.

[Q]: By the way, what about transpiration? How is that included?

[A]: You have to give it to the model, but if you change the input data, yes, you can change it as well. The thing that is very hard with any model, is, how representative are your changes on reality, if your parameter changes. So, you see that when people calibrate models, they crank up soil infiltration to something that is impossible; it is not physically representative anymore. The other thing is about surface roughness. There is a lot of misunderstanding about surface roughness. People presume that trees have a very rough surface. That only works for flooding in valley. So, if you are in the flood plain and you have small trees and the flood water is 2 m, it will slow the water down by a lot. If you got surface runoff from rainfall on a steep slope, trees do absolutely nothing. Their sole purpose is canopy interception. Then it goes down onto short grass on an urban park land and it just flies off. There is a big difference between a forest that is an urban park land and a forest that is a multiple storage tropical canopy. You have to kind of think about what changes you are making in the parameters and whether it is representing reality that you are envisioning. So, it is not a limitation of the model, but of the modeller, of the changes they make. Once you realise that you are in the world of doing parameter sensitivity analysis. Actually, if you are only turning one or two parameters, you find that with vegetation, a lot of them are interacting. So, your canopy, your water storing vegetation, you have higher soil infiltration in forests. So, if you are changing it to a forest, you are not only changing the canopy interception, but you also have to change the soil interception. All those working together complicate it a little bit.

[Q]: In that case, can I just change the land use class, or do I also need to look into the parameters?

[A]: A lot of them are connected to the LAI. Once you change them manually, then not. I think the parameters are kind of standard based on GlobCover land use map. Once you change it, you have to be a bit careful that you are changing thing consequently. The second this is of course on an urban scale is the spatial resolution. I would be very interested to know, if you go down all the way to 10 m resolution, does it dramatically change the kind of runoff result? I can't image what the hypothesis on that would be. The problem there is it when you go down to 10 m resolution, if you run it for the city, it is just going to take ages to run the model. So don't do too many scenarios. Don't do lots of climate scenarios. Keep it relatively focussed on what your research question is.

[Q]: I am also going to focus on just three sub-catchments. So, I will be taking out some parts of the model and will just look at the downstream discharges of three sub-catchments to speed up the simulations.

[A]: So next year, you are going to be giving a presentation at the software user day, I guess?

[Q]: It could be interesting, but obviously depends on what comes out of this research.

[A]: Yes, we are interested to know. Even if the results say, there is no difference, that is very good. Any result is important, because it tells you something.

[Q]: Okay, give me a heads-up next year!

[A]: Let us know how it is going. Once you have come up with an idea, share it with me and Mark.

[Q]: I will keep you up to date. Thank you so much. Bye!

B.6. Jerom Aerts – PhD candidate TU Delft – 29-11-2021

[Note, the interview was set-up in Dutch, because the interviewee and I both speak Dutch]

Inleiding:

[Q]: Wat is het onderwerp van je PhD?

[A]: Even heel kort. Ik heb eigenlijk twee onderwerpen. Het project waar ik in werk, e-water cycle. Daar is het doel om open source platform voor modelleren te ontwikkelen. Dat is al gelukt. Waar je daarbij aan moet denken is dat je met hydrologische modellen kan spelen en coderen met alleen de Python programmeertaal. Dus het maakt niet meer uit of iets geschreven is in Fortran of C++. We gebruiken een soort code laagje ervoor. En met die code kan je ook heel makkelijk modelkoppelingen doen. Je kan het model starten en stoppen. Je zou heel makkelijk bijvoorbeeld aanpassingen aan parametervelden kunnen doen tijdens run-time. Dus je hebt heel makkelijk interactie. Het mooie daarbij is dat het ook het omzetten van je meterologische input naar je hydrologische model doet, dus dat het meteen in je model kan. Wat ook wel tof is, is dat, we hebben nu iets van 6 modellen en die werken nu allemaal hetzelfde ongeveer. Je hoeft dus niet telkens je code aan te passen. Mijn onderwerp is kijken naar ruimtelijke schalen. We hebben namelijk gezien dat veel modellen alleen maar naar hogere resolutie gaan. Dat is ook wel logisch, want we hebben namelijk betere data qualiteit. Maar de vraag is, als je een modelconcept ooit hebt afgeleid, op een schaal x dat bijvoorbeeld heel grof is, of heel fijn, of er dan wel zomaar ingezoomd of uitgezoomd kan worden en dat die processen dan hetzelfde werken. Eigenlijk weten we dat dat niet het geval is. Je hebt namelijk non-lineaire processen in ruimte en tijd en daar ben ik eigenlijk naar aan het kijken.

[Q]: Oke, wat zijn dan voorbeelden van die non-lineaire processen?

[A]: Je kan bijvoorbeeld denken aan de Richards vergelijking. Die is op een bepaald medium afgeleid, op eigenlijk een best wel kleine schaal. Of dat nou toepasbaar is op een kleine schaal en op een 3x3 km grid, dat is de vraag. We weten eigenlijk dat dat niet zo is. Andersom heb je ook redelijk wat dingen die wel redelijk lineair werken. Bijvoorbeeld grondwaterprocessen, die schalen best wel goed lineair over ruimte en tijd. Dan is het effect weer minder. Je kan verder ook nog denken aan processen zelf. Dus stel we hebben een sneeuwgebiedje en we kijken er heel grof naar, dan is een Degree-D misschien wel voldoende. Dus dat het smelt als het boven de 0 graden is en het vriest als het eronder is. Maar als je dan eenmaal ingezoomd bent, dan zie je dat windrichting een rol speelt. Ook hoe verzamelt die sneeuw? Sneeuw is niet een uniform iets, dus het smelt niet overal even snel. Er komen zoveel meer processen bij kijken op een fijne schaal dan op een groffe schaal. Daar is dan de vraag of je dan die simpele parameter kan gebruiken, dus een waarde voor iets, een constante. Of dat je echt het proces in stukjes moet gaan opdelen en het echt moet gaan uitrekenen. Het gaat dus een beetje twee kanten op. Het is zowel voor de parameters als voor de hydrologische processen.

[Q]: Op welke manieren heb je wflow gebruikt?

[A]: Welke processen zitten erin en hoe schalen die in de ruimte. Er is nu een vervolgonderzoek dat veel meer in detail daarnaar gaat kijken. Daar wordt goed ingezoomd en gekeken naar hoe bijvoorbeeld de sneeuwprocessen erin zitten. Kijken hoe die veranderen a.h.v. schaling in ruimte en dan meteen ook heel goed bekijken wat het effect is van je meterologische input kwaliteit en resolutie.

Ruimtelijke schaal:

[Q]: Waarom wordt het model niet altijd beter bij een hogere resolutie?

[A]: Wat het complex maakt, is wanneer je een proces hebt dat op een kleine schaal is afgeleid, bijna labmetingen zijn. Dan zou je juist verwachten dat het beter wordt als je verder inzoomd, omdat het dichterbij die puntschaal komt, waarvoor het is afgeleid. Eigenlijk is de vraag zelfs, waarom wordt het ook slechter in sommige gevallen? We zien dat dat bij het wflow model ook echt wel in de laterale componenten zit. Willem zei het in zijn presentatie al een beetje, dat die Kinematic Wave het gewoon niet heel goed gaat doen in die hele vlakke gebieden en dat ze daarom willen overstappen naar Intertia Method van ListFlood, een hydrodynamisch model. Die kan het dan beter, want die heeft die slope gedrevenheid niet zo erg nodig als dat die Kinematic Wave dat heeft. Dus als ik die vraag helemaal kan beantwoorden heb ik denk ik een hele goede PhD gehad. Ik moet dan wel een stukje verder in mijn carière zijn. Het is heel lastig om alles te isoleren, maar er gebeurt wel wat meer. De aanwijzingen liggen daar wel, dus echt in die laterale component. Daar zal ik naar kijken.

[Q]: Kleinere gridcellen zorgen voor een minder steile helling in relatief vlakke gebieden. Kan je dit toelichten met het oog op de Kinematic Wave approach?

[A]: Tuurlijk. Als je eenmaal kleinere gridcelletjes hebt, dan heb je er gewoon meer. Stel we bekijken het even 1D, even rijtje van gridcelletjes, dan wordt die gradient tussen die gridcelletjes die wordt vlakker, dus het verschil van cel tot cel neemt af. Uiteindelijk gaat alles in een Kinematic Wave reservoir in wflow. Daarom vermoeden wij eigenlijk dat het water niet snel genoeg weggaat, omdat de gradient is afgenomen. Dat is eigenlijk de reden waarom we dat als probleem zien. Ook daar moet wel echt meer naar gekeken worden. Daarvoor zal ik wat meer in de formules moeten gaan duiken om dat analytisch te laten zien.

[Q]: Dus het wordt niet genoeg afgevoerd door wflow?

[A]: Ja, er komt eigenlijk een soort delay in. Je zou dan wel grotere verschillen in de timing verwachten. We zien echter vooral effecten in volumes. In vervolgenstudies wil daarom gaan kijken of het water wel echt snel genoeg afgevoerd kan worden van cel tot cel. Het is dus niet alleen de snelheid, maar ook het volume meteen.

[Q]: Wat ik nu wel interessant vind is dat ik bij een ander interview ontdekte dat er in het wflow model van Kigali hele hoge ruwheidswaardes gebruikt worden. In de kalibratie is er waarschijnlijk gecompenseerd, maar dat is dus niet de kinematic wave approach in vlakkere gebieden. Dat zorgt dan dus blijkbaar dat het nog minder snel wordt afgevoerd en het volume heeft het dan ook weer effect op. Dan is er dus waarschijnlijk nog iets anders waarvoor nog extra wordt gecompenseerd?

[A]: Ik denk dat als die Manning waardes zo hoog zijn, dan zou ik daar ook als eerste naar kijken. Dat is wel een duidelijke indicatie dat als de ruwheid gewoon heel hoog is, dan ga je dat effect ook zien. Ik heb er wel naar gekeken in de modellen die ik ook heb afgeleid en daar viel het wel mee, omdat ik er een limiet aan had gezet van wat mocht qua waardes. Als je ziet dat die waardes super hoog zijn, dan is het daarop gekalibreerd. Ik snap wel waarom je dat zou doen, maar het is wel zo dat je dan je onzekerheid maar in je Manning waardes stopt. Er gaat wel echt iets mis als die waardes veel te hoog worden. Ik zou daar dus zeker naar kijken. En ook gewoon even een keer een run doen en het aanpassen naar realistische waardes en kijken wat het verschil is.

[Q]: In hoeverre is er onderzoek gedaan naar de relevante ruimtelijke schalen van hydrologische processen? (interceptie, infiltratie, transpiratie, etc.)

[A]: Ik ben er mee bezig, maar heb nog niet echt een relevante ruimtelijke schaal gevonden. Aan de ene kant kan je altijd zeggen, hoe meer je inzoomt, hoe dichter je bij de waarheid komt als je iets numeriek oplost. Net zoals met integreren, hoe kleiner hoe beter. Wat ik wel heb bekeken is hoe die fluxen van die processen, of die een beetje goed schalen. Dat doet het wflow model echt wel heel goed. Als je het op een hele kleine schaal uitrekent en je pakt dan het aantal celletjes, bijv. 6, dat overeenkomt met een groffe cel. Dan schaalt dat wel heel netjes voor de evaporatie fluxes en de transpiratie. Interceptie en infiltratie dat is wel lokaler natuurlijk, maar dat schaalt allemaal ook gewoon goed. Maar dan kijk je vanuit de modelschaling en niet vanuit de werkelijkheid. Dat is wel altijd iets anders. Ik heb wel vergeleken met wat data producten, evaporatie producten waarmee je het kan vergelijken. Dat ging opzich wel aardig. Dus dat is op een groffe schaal allemaal oke. Dat is eigenlijk mijn onderzoek nog waar ik nog verder in ga duiken.

[Q]: Hoe heb jij veranderingen in verschillende fluxes in wflow onderzocht?

[A]: Op een catchment-scale ernaar kijken heb ik sowieso gedaan, dat ik de makkelijkste manier. Dan kijk je puur naar de verandering in uitstroom als bepaalde processen veranderen. Ik heb wel voor een catchment, een beetje een grotere catchment, eerst geprobeerd de fluxen te valideren met satelietproducten, zover dat kan. Dan moet je aan de sneeuwproducten denken bijvoorbeeld of de staat van soil moisture (is dan geen flux, maar goed), bodemvocht en evaporatie. En dan vervolgens ga je dan wel naar de relatieve verschillen kijken, want ik had 3 modellen opgesteld. Je hebt een referentie tot de waardheid, maar bent vooral geïnteresseerd in wat er nummeriek gebeurd als je relatief tussen die modellen er tegenaan kijkt. Ik zou als je daarin geïntereseerd bent, beginnen met valideren aan de hand van data producten. Dan kan je denken aan soil moisture producten als map denken, dan heb je nog meer sneeuwproducten, modus aquas en terra kan je bij elkaar nemen. Ik heb niet naar Grace gekeken, dan zou ook nog kunnen eventueel, dan kijk je meer naar de totale state van je catchment. Even kijken, Grace, Gravitational annomaly, dus je kijkt eigenlijk naar het relatieve verschil van water in je catchment. Ik heb FluxCom gebruikt om naar evaporatie te kijken. Het blijft gewoon heel lastig, want je zit gewoon tussen modelwerkelijkheid en de echte werkelijkheid in. Het valt zelfs te beargumenteren dat sattelieten niet eens de echte werkelijkheid zijn. Dus je komt snel in een soort welles niettes situatie terecht en dan nemen we maar aan dat de sattelietproducten dichterbij de werkelijheid zijn dan wflow, mag ik hopen. Zo heb ik het aangepakt. Gewoon eerst valideren.

<u>Implementatie NBSs:</u>

[Q]: Is het mogelijk om de ruimtelijke schaal van het wflow model lokaal te verfijnen? En zo ja, hoe?

[A]: Dat kan, e-water cycle is daar handig voor, maar dan ga je heel veel model instanties starten en stoppen en ga je de fluxen doorgeven tussen de modelletjes. De boundary conditions worden gevormd door het ene model dat in het ander model nested is. Dat kan wel. De vraag is wel of het niet veel meer werk is dan om gewoon heel fijn te gaan runnen en dan niet naar je laptop te kijken. Ik weet niet of HKV iets van een cluster heeft. Het is altijd een beetje een afweging qua tijd, want dit kan heel intensief zijn om al die modellen in serie te draaien. En dat hoef niet persé sneller te zijn dan gewoon een heel fijn grid pakken.

[Q]: Hoe zouden kleinschalige maatregelen (kleiner dan de gridcellen) geïmplementeerd kunnen worden?

[A]: Goeie vraag. Dat is heel lastig. Als we gewoon kijken naar het model, wat je kan aanpassen zijn de parameters en wat je erin stopt. Dat is de meterologisch input. Je zou in het geval van regentonnen, (je zou moeten quantificeren natuurlijk, omdat het proces niet in het model zit natuurlijk)) een schatting kunnen maken van wat het verschil in neerslag wordt dat uiteindelijk op de grond terecht komt. Misschien dat je je neerslag kan aanpassen. Maar dan zit je er weer mee dat het water in de regentonnen uiteindelijk ook wel weer in het systeem terecht komen als je een soort buffer gebruikt neem ik aan?

[Q]: Nou, waarschijnlijk wordt het water daarvan gebruikt voor tuinen en huishoudens. In tuinen komt het dan uiteindelijk wel weer in het model terecht. Ik denk dat het best een goede optie zou zijn om het af te trekken van de neerslag, omdat het echt buien zijn die gesimuleerd worden. Als het dus toch later nog in het model terecht zou komen, dan heeft dan een heel klein effect.

[A]: Ja en ze zou in dat geval ook moeten bedenken, wat is de regen intensiteit waarbij opslag in de regentonnen niet meer werkt? Op een gegeven moment zitten ze vol. Of ik weet niet hoe het daar werkt, als het via een buis gaat en daar komt teveel doorheen, dan schiet het ook niet op. Het zal gewoon gekwantificeerd moeten worden. Dat is prima in dit geval, maar dan ga je denk ik naar heel wat regentonnen kijken en bedenken hoe dat proces in directe verhouding staat tot neerslag en hoe het met de interceptie zit. En anders zou je misschien toch iets van een interceptie parameter kunnen aanpassen in het Gash model?

[Q]: Swood zou je daarvoor kunnen gebruiken.

[A]: Wat je ook altijd nog kan doen, is de code induiken en een extra constante toevoegen in een formule. Dan noem je dat de waterton roughness constante ofzoiets, die dan effect heeft op je interceptie. Dan ga je wel echt de code in.

[Q]: Storage maatregelen zijn lastig te implementeren in wflow. Nu gebruiken ze inderdaad een interceptie parameter, maar ik zit eraan te denken om een extra storage laag bovenop het huidige model te maken. Dit zou nuttig kunnen zijn voor bijvoorbeeld een vijver of retentie gebied. Dit bakje zou dan kunnen vollopen totdat het overstroomt naar de volgende grid cel. Dat zou misschien voor regentonnen ook wel haalbaar kunnen zijn.

[A]: Dat zou een mooie oplossing zijn denk ik, dat je een mini reservoirtje hebt. Ik zou het met je begeleiders bespreken. Dit soort dingen kunnen namelijk heel lang duren en heel frusterend zijn als het allemaal niet meteen werkt in de code. Je kan altijd zeggen van kwantificeer eerst en probeer dan gegeven de tijd die je nog in je master thesis hebt, het nog te implementeren. Dat je er stapsgewijs induikt.

[Q]: Dat is een goede tip.

[A]: Het kan allemaal heel tijdsintensief en frusterend zijn. Wat wel altijd de vraag is met schaal, is, stel je hebt die hele kleinschalige NBSs, waar wil je het in terugzien? Wil je het gaan terugzien in het debiet van een riviertje? Hoe wil je die effecten gaan beoordelen uiteindelijk?

[Q]: Uiteindelijk wil ik zowel gaan kijken naar het volume als naar de piekafvoer vooral bij de uitstroom van een stroomgebied.

[A]: Dan is het ook altijd fijn om een soort van ruwe berekening zelf te maken. Dus gegeven de water balans, ga je deze effecten terugzien? Zodat je een beetje een verwachting hebt.

[Q]: Op die manier kan je waarschijnlijk ook zeggen welke maatregelen verwaarloosbare impact hebben op de afvoer?

[A]: Als de ordegroottes niet kloppen tussen de debietafvoer en de mogelijke verandering door de NBS, dan is de afvoer misschien niet de beste manier om het te beoordelen. Dat is altijd wel handig om dat van tevoren een beetje te bepalen. Een voorbeeld is dat ik een review heb gedaan van een studie, waar ze gekeken hadden naar het effect van een stad is op een hele grote catchment met een hele grote rivier. Die stad werd geïmplementeerd als een soort ruwheid in de catchment. Echter, alleen al een simpele berekning van de water balans, met het totale oppervlakte van de catchment vs het totale oppervlakte van de stad, kon je al weten dat die fluctuaties die zij in de afvoer zagen, dat die zo klein waren. Daardoor vielen ze binnen de onzekerheid van het model. Het betekent niet dat het dan niet van waarde is om het te doen, maar dan kan je ook bedenken of er wellicht een andere manier zou zijn om het te evaluaren.

[Q]: En wat zou een andere manier dan kunnen zijn?

[A]: Dat is een goeie vraag. Ik zit ook even te denken hoe het gebied in Kigali eruit ziet.

[Q]: Het is best wel heuvelachtig. De stad ligt nog in de bergen. Er komt heel veel afvoer van de bergen. Dat stroomt allemaal de stad in. Vanaf de stad wordt het weer afgevoerd naar wetlands in de buurt.

[A]: Dan is het misschien handig, dat als je de metingen hebt, om ook gewoon te kijken naar de kleinere zijstromen. Dan ga het verschil gewoon eerder merken, dan wanneer je het op de grotere afvoer van de hoofdstroom gaat beoordelen. Wel altijd leuk om over na te denken. Je kan meerdere kanten op. Je kan het gaan kwantificeren, iets gaan spelen met de input of echt het modelleren en dan met een reservoir aan de slag gaan. Je hebt wel opties.

<u>Verbeterpunten:</u>

[Q]: Wat zijn in jouw ogen de tekortkomingen van het wflow model? En wat zouden mogelijke verbeterpunten kunnen zijn?

[A]: Dat is dan misschien iets technischer, dat je niet heel gemakkelijk zo'n reservoirlaag kan toevoegen or andere aanpassingen in de code kan doen. Het is niet erg modulair. Dat is dan een beetje code technisch. Daarnaast ben ik benieuwd of het model presteert in het gebied. Als je bijvoorbeeld naar een hydrograph kijkt, maar het klinkt of in jouw geval een tekortkoming wel die Manning coefficient zou kunnen zijn. Daar zou ik als eerste naar gaan kijken. Wat gebeurt er nou als je dat naar iets normalere waardes zet. Dat is ook meteen wel een verbeterpunt als ik jou zo hoor. Voor mij is het heel moeilijk om te beoordelen. Mensen bij Deltares zijn erg kundig, dus die weten vast wel hoe ze het model hebben gekalibreerd.

Ik denk dat het modelconcept misschien wat simplistisch is als je het op 90x90 m resolutie gaat bekijken. Als je het vergelijk met andere modellen, dan zijn er modellen die hele energiebalans meenemen bijvoorbeeld. Dat is dan relevant voor mij, voor bijvoorbeeld sneeuw. Dus dat je niet alleen Degree-D doet. Wat ook een tekortkoming van het model is, is dat het Pedo-transfer functies gebruikt. De een is fan, de ander niet. Het is een methode om van een paar sampels die ze in het lab hebben bepaald voor o.a. de doorlatendheid van de bodem, data voor een hele gridcel te extrapoleren. Dat zijn allemaal puntmetingen geweest. Als je kijkt naar hoeveel sampels er in totaal zijn geweest, dan is dat best wel gelimiteerd. De vraag is, hoe dichtbij komt het bij de werkelijkheid als je zulk soort methodes gebruikt. Je zou daar dus even naar kunnen kijken. Je kan volgens mij ook de Pedo-transfer functie aanpassen die het model heeft gebruikt. Tegelijkertijd doe je dat omdat je het gewoon kan afleiden op die 90 m schaal, en dat is fantastisch aan het model. Anders had je het model niet gehad om 90x90 m. Elk voordeel heeft zijn nadeel, als je Johan Cruiff moet geloven. Dat zie ik hier ook wel terug. Voor jouw toepassing, ik denk dat het heel mooi is dat je op zo'n hoge resolutie kan modelleren en ik ben heel benieuwd of je die fijnmazige NBSs ook gaat terugzien in de fluxen. Ik zou daar gewoon mee beginnen, om gewoon naar die fluxen te kijken en te zien wat het effect is.

Appendix C – small-scale calculations

C.1. Manning equation

The Manning equation is shown in Equation 1 and is as follows:

$$Q = \frac{1}{n} A R^{\frac{2}{3}} \sqrt{S} \tag{2}$$

When the hydraulic radius and the area are assumed to be constant, the equation can be used to find relations for the runoff, Manning coefficient, and slope.

Relation between the slope and runoff

Assume that the slope is unchanged. The relative increase or decrease in runoff is given by:

$$\Delta Q_{relative} = 1 - \frac{Q_{new}}{Q_{old}} \tag{3}$$

Substituting the slope gives (other factors are constant):

$$\Delta Q_{relative} = 1 - \frac{\sqrt{S_{new}}}{\sqrt{S_{old}}} \tag{4}$$

Relation between the Manning coefficient and runoff

Assume that the Manning coefficient is unchanged. The relative increase or decrease in runoff in terms of the Manning coefficient is then given by:

$$\Delta Q_{relative} = 1 - \frac{n_{old}}{n_{new}} \tag{5}$$

Since only the Manning coefficient is changed when implementing NBSs into the model, a change in the slope, should be expressed in terms of a change in the Manning coefficient. Therefore, Equation 4 should first be used to determine the change in runoff due to the slope change. Then, Equation 5 is used to determine the representative change in the Manning coefficient because of this slope change.

C.2. Calculations using Sobek

A 1D hydraulic Sobek model is used to estimate the effect of gabions by implementing weirs in a straight channel. The channel's cross section is shown in Figure C- 1 and has a Manning roughness of 0.03. The simulation is like the Mpazi catchment as the elevation difference is 450 m over approximately 5 km (same slope). The upstream boundary condition is the flood wave shown in Figure C- 2 and the downstream boundary condition is the Q-h relation. This relation is estimated using the Chézy formula and displayed in Figure C- 2.

Five gabions are placed on the riverbed at equal spatial intervals on a stretch of 1km, as shown in Figure C- 3. At 1200m, the change in discharge is observed. The gabions are estimated to have a width of 2m and a height of 90 cm (Gabionsupply.com, 2012).

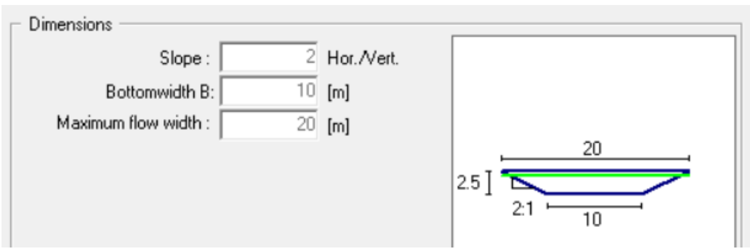


Figure C- 1 – estimated channel dimensions

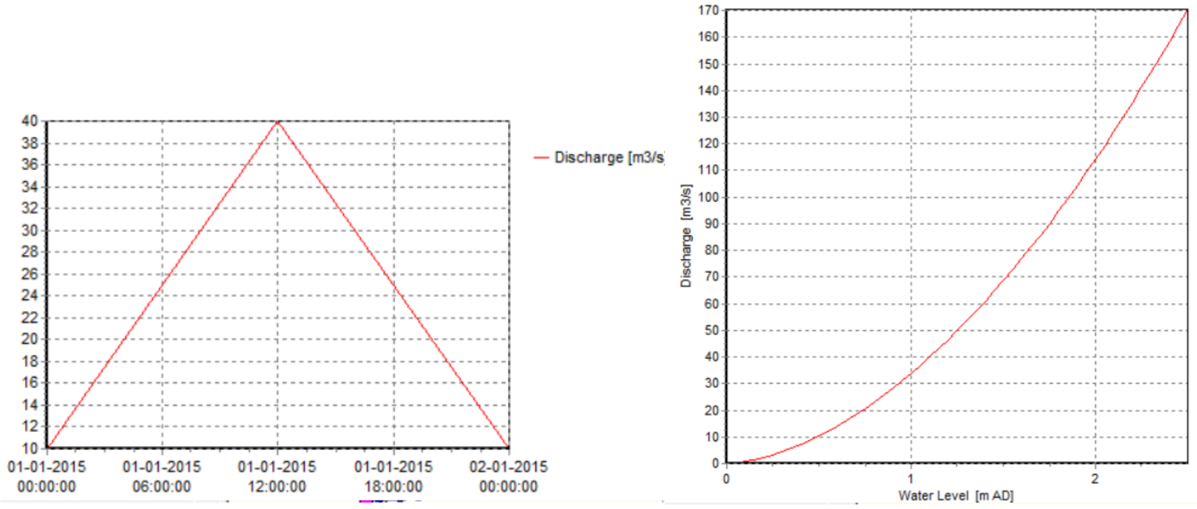


Figure C- 2 - left: incoming flood wave; right: Q-h relation

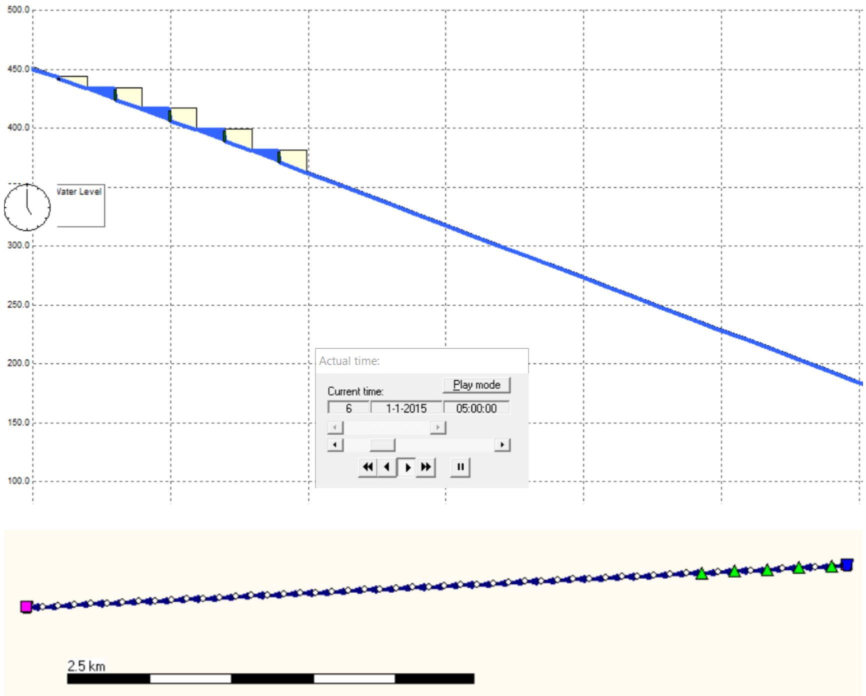


Figure C- 3 - placement of Gabions. Top: side view; bottom: top view

The resulting change in runoff due to the presence of gabions is shown in XX below. It is shown that the gabions are more effective at the beginning of the flood wave. However, since the flood wave in the model is expected to be short, but intense, the initial change in runoff is used to quantify the effect of gabions on the runoff (-0.7 m^3/s). The original discharge without the gabions was 12.43 m^3/s, so the relative change in discharge is 5.6%. Using Appendix C.1., the new Manning roughness accompanied by this change is then 0.032, which is an increase of 6%. The effect of different gabions widths (0.9m, 5m and 10m) and spacings (25m, 50m and 100m) have been investigated, but none of these variations resulted in a greater reduction of runoff. Since the relative increase in roughness is less than 10%, gabions are labelled as ineffective measures to reduce the delay the runoff.

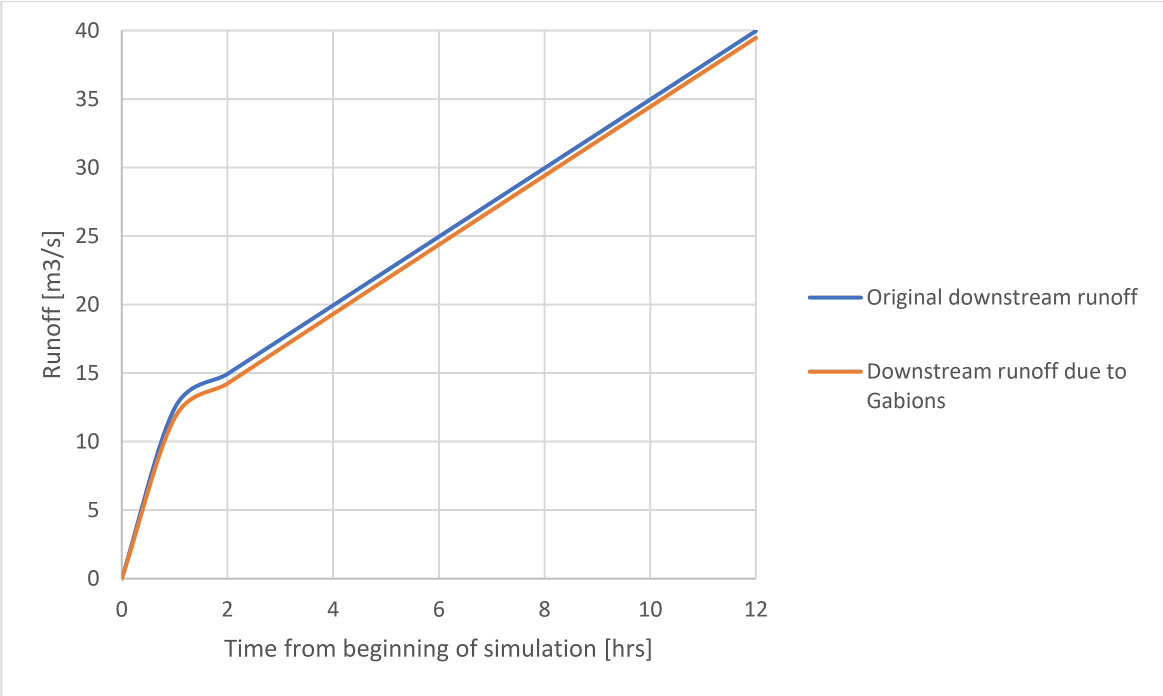


Figure C- 4 - change in runoff due to the gabions over time during the rising limb of the flood wave

C.3. Quantification of NBSs using the Adaptation Support Tool (AST)

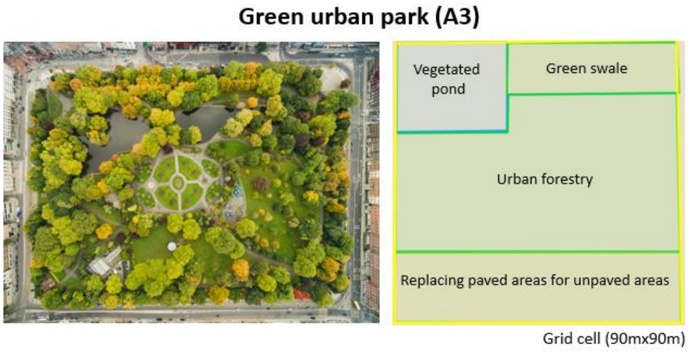


Figure C- 5 - schematisation of a green urban park in a grid cell in AST

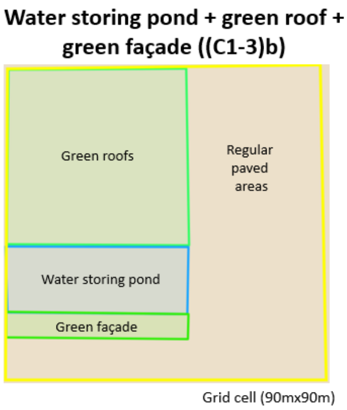


Figure C- 6 - schematisation of a water storing pond, green roofs and green facade in a grid cell in AST

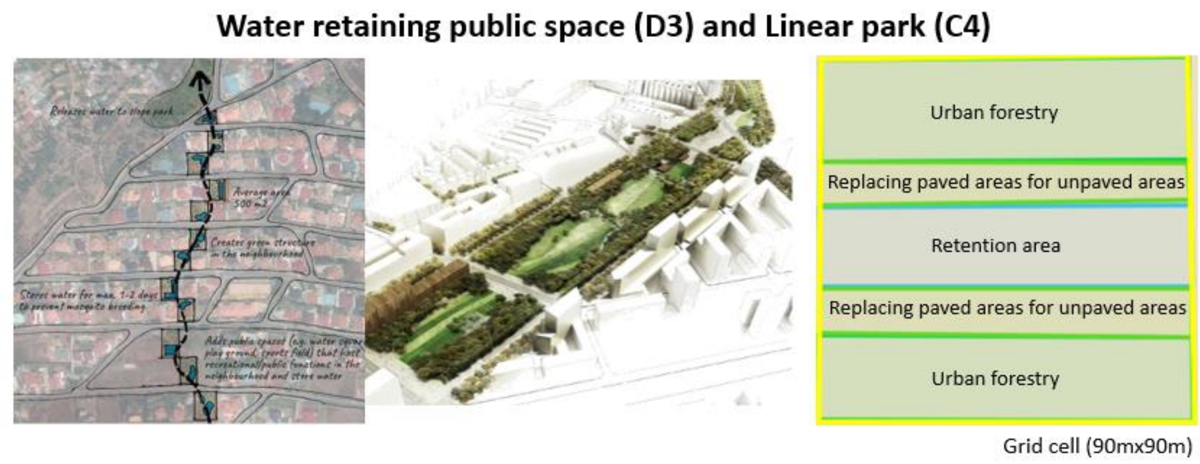


Figure C- 7 - schematisation of water retaining public space and a linear park in a grid cell in AST (World Bank, 2021)

Table C- 1 - quantification of storage volumes (R) in m^3 of NBSs using the AST and corresponding infiltration capacity (I) in mm/hr and Manning roughness on land (L) in $s/m^{1/3}$

NBS	**Sub-measures**	**Surface area [m²]**	**R**	**I**	**L**	**Source**
Green urban park (A3)	Green swale	850	311	80	0.15	I: (Litt et al., 2020); L: Table A- 3
	Vegetated pond	1050	601	40	0.03	I: (Negev et al., 2020); L: Table A- 3
	Urban forestry	4100	822	113	0.18	I: (Litt et al., 2020); L: Table A- 3
	Replacing paved for unpaved areas	2100	154	80	0.15	I: (Litt et al., 2020); L: Table A- 3
Green roofs + water storing pond + green façade (C1-3)b	Green roofs	2700	260	74	0.1	I: (Johnson, 2008); L: (Hamouz & Muthanna, 2019)
	Water storing pond	1000	585	40	0.03	I: (Negev et al., 2020); L: (Hamouz & Muthanna, 2019)
	Green façade	380	4	74	0.1	I: (Johnson, 2008); L: (Hamouz & Muthanna, 2019)
	Remaining area (urban)	4020	0	44	0.09	I: (Litt et al., 2020); L: Table A- 3
Linear park (C4) and water retaining public space (D3)	Urban forestry	3900	767	113	0.18	I: (Litt et al., 2020); L: Table A- 3
	Replacing paved for unpaved areas	2300	167	80	0.15	I: (Litt et al., 2020); L: Table A- 3
	Retention area	1900	1103	40	0.03	I: (Negev et al., 2020); L: Table A- 3

C.4. Quantification of other NBSs consisting of multiple small-scale interventions

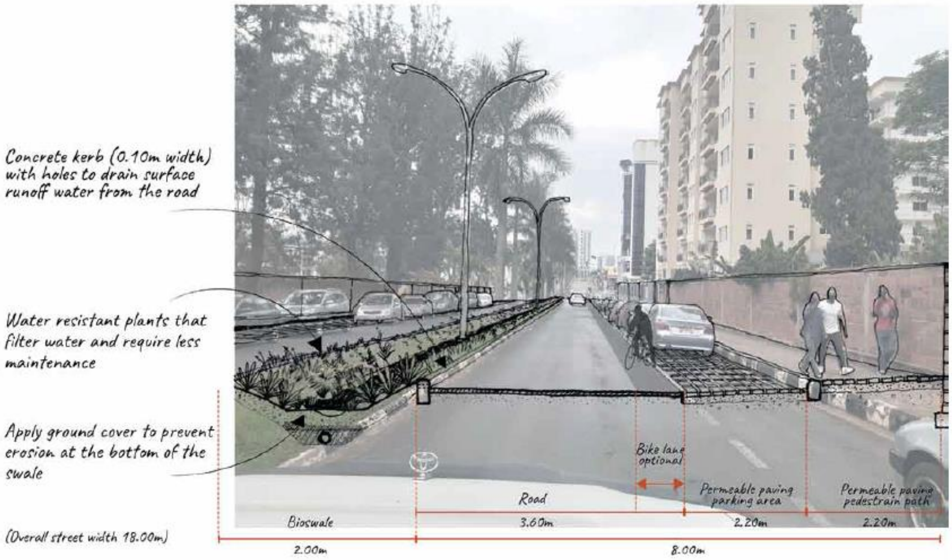


Figure C- 8 - integrated road profile / green blue spine (B1 & C5) (World Bank, 2021)

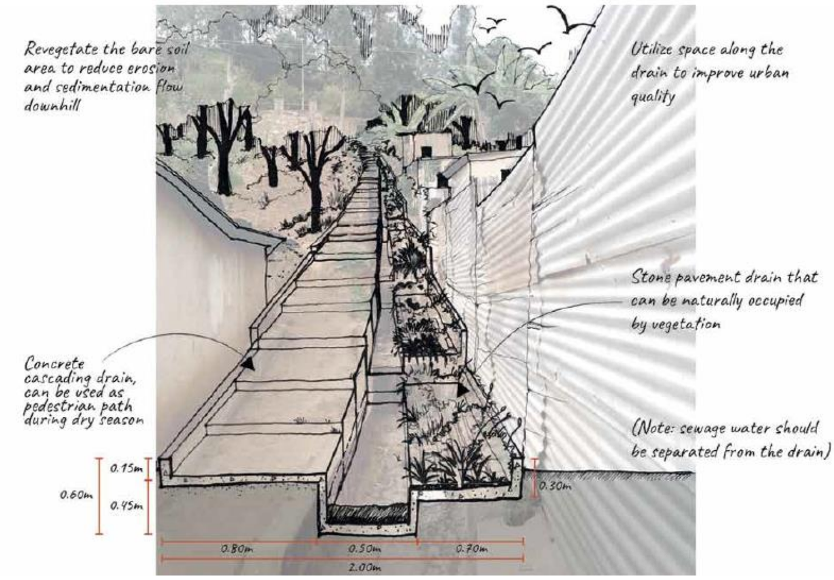


Figure C- 9 - integrated neighbourhood drain (B2) (World Bank, 2021)

Table C- 2 - street profile regulations/zoning (B4) (World Bank, 2021)

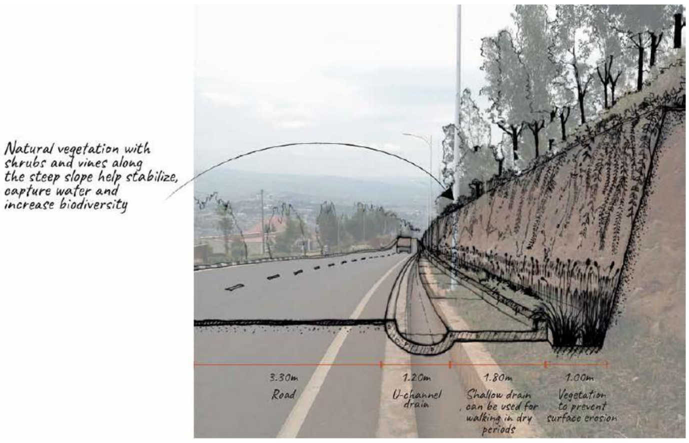


Figure C- 10 - green integrated drain (D5) (World Bank, 2021)

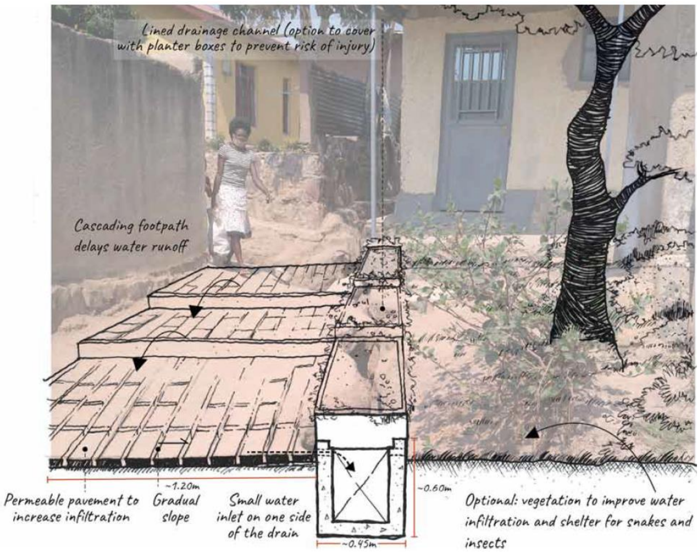


Figure C- 11 - Stepped footpath with planters (F3a) (World Bank, 2021)

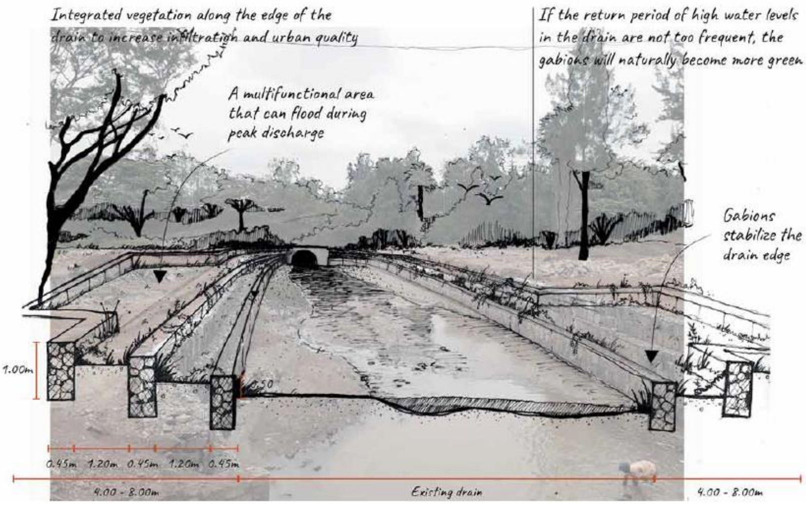


Figure C- 12 - stepped drain (F4) (World Bank, 2021)

Table C- 3 - quantification of NBSs consisting of multiple small-scale measures in terms of infiltration capacity (I) in mm/hr and Manning roughness in the drains (D) in s/m$^{1/3}$.

NBS	Sub-measures	Relative contribution to total surface area [%]	I	D	Source
Integrated neighbourhood drain (B2)	Paved cascading drain	65%	0	0.09	D: Appendix C.1.[15]
	Vegetated cascading drain	35%	75	0.11	I: (Bean et al., 2004); D: Appendix C.1.[16]
Stepped drain (F4)	Regular channel	50%	40	0.03	I: (Negev et al., 2020); D: Table A- 2
	Vegetated stepped edge	50%	80	0.035	I: (Litt et al., 2020); D: Table A- 2

Table C- 4 - quantification of NBSs consisting of multiple small-scale measures in terms of infiltration capacity (I) in mm/hr and Manning roughness over land (L) in s/m1/3.

NBS	Sub-measures	Relative contribution to total surface area [%]	I	L	Source
Integrated road profile / Green blue spine (B1 & C5)[17]	Bioswale	8%	80	0.15	I: (Litt et al., 2020); L: Table A- 3
	Road	14%	80	0.15	I & L: Figure C- 8[18]
	Permeable parking & pedestrian path	18%	75	0.1	I: (Bean et al., 2004); L: (Cui et al., 2019)
	Remaining area (urban)	60%	44	0.09	I: (Litt et al., 2020); L: Table A- 3
Street profile regulations/ zoning (B4)[20]	Roadside vegetation	40%	63	0.1	L: Table A- 3[19]; I: scaled using A1 and effect for L of B4.
	Remaining area (urban)	60%	44	0.09	I: (Litt et al., 2020); L: Table A- 3
Green roofs (C2a)[20]	Green roofs	40%	74	0.1	I: (Johnson, 2008); L: (Hamouz & Muthanna, 2019)
	Remaining area (urban)	60%	44	0.09	I: (Litt et al., 2020); L: Table A- 3
Green integrated drain (D5)[17]	Vegetated strip	6%	80	0.15	I: (Litt et al., 2020); L: Table A- 3
	Road	18%	0	0.02	L: Table A- 3
	U-channel drain	10%	0	0.02	L: Table A- 3
	Pavement	6%	0	0.02	L: Table A- 3

[15] Assumptions: initial roughness is 0.03 (Table A- 2), initial slope is 10%, new slope on steps is 1%
[16] Assumptions: initial roughness is 0.035 (Table A- 2), initial slope is 10%, new slope on steps is 1%.
[17] Assumption: there are 4 roads each with a length of 90m per grid cell. Therefore, this NBS makes up approximately 40% of a grid cell. The remaining area of the grid cell is paved.
[18] Assumption: due to the holes in the kerbs, all the water from the road will drain to the green swale and therefore, the roughness and infiltration capacity of the green swale are normative.
[19] Assumption: trees on the side of the road cause delay and cause the roughness to be similar to that of a sparse forest.
[20] Assumption: NBS applied for 40% of the grid cell

	Remaining area (urban)	60%	44	0.09	I: (Litt et al., 2020); L: Table A- 3
Stepped footpath with planters (F3a)[21]	Planter boxes	2.5%	80	0.15	I: (Litt et al., 2020); L: Table A- 3
	Permeable cascading footpath	6.67%	75	0.06	I: (Bean et al., 2004); L: Appendix C.1.[22]
	Vegetation[23]	8.33%	80	0.15	I: (Litt et al., 2020); L: Table A- 3
	Remaining area (urban)	82.5%	44	0.09	L: Table A- 3

[21] Assumption: in each grid cell, there are 5 footpaths of 90m.
[22] Assumptions: initial slope is 10%, Manning roughness is 0.02, slope of steps is 1%.
[23] Assumption: width is 1.5m and is present along all footpaths in the grid cell.

Appendix D – additional storage bucket (Paddy areas function)

A threshold value for surface runoff is added to implement surface runoff storage NBSs. This addition to the wflow-SBM concept is schematised in Figure D- 1 below.

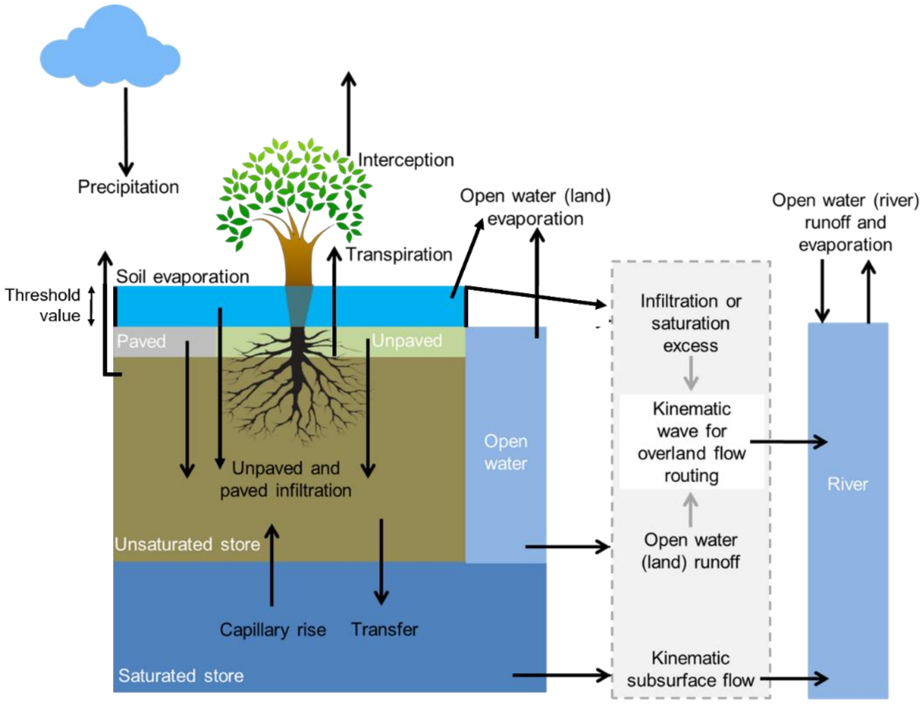


Figure D- 1 – wflow-SBM concept including additional storage layer

The Paddy areas function of wflow is used to implement the additional storage bucket. Paddy areas are irrigated rice fields. Using this function, the model calculates a ponding depth for each grid cell and timestep, using the water supply (rainfall), water demand for irrigation and the optimal water level of the paddy area (Schellekens & van Verseveld, 2019). Paddy areas can be defined by including the following static maps:

- wflow_irrigationpaddyareas.map: map of areas where the paddy areas are located.
- wflow_irrisurfaceintake.map: map of downstream intake points, where the id of an area matches with the id of an area in the wflow_irrigationpaddyareas.map. In this case, the intake points are at the locations of the downstream gauges of each catchment.
- wflow_hp.map: map of the water height [mm] when rice fields start spilling over. This is used to mimic the storage capacity of the surface runoff storage NBSs.
- wflow_hmax.map: map with the optimal water height [mm] in the irrigated rice fields. In this case, wflow_max = wflow_hp.
- wflow_hmin.map: map with the minimum required water height [mm] in the irrigated rice fields. In the reference model of Kigali, wflow_hmin is always equal to 0 mm.

Furthermore, the CRPST parameter is defined in the model's configuration file such that no rice crop growth occurs. Also, the initial ponding depth is defined to be 0 mm in all grid cells and the irrigation demand is set to 0 mm for each timestep.

Appendix E – data used for old implementation of NBSs

In Table E- 1, the following abbreviations are used:

- A = Agriculture & rural housing
- O = Parks & open spaces
- F = Forest area
- C = Commercial & mixed use area
- P = Public facilities & administration
- LM = Low & medium density
- H = High density
- D = Densification area
- N = New development

Table E- 1 - urban typologies of NBSs as approximated by Defacto and used by HKV to determine suitable locations of NBSs

	Urban typolgoies					Residential area				Urban upgrading
NBS-ID	A	O	F	C	P	LM	H	D	N	
A1			x							
A2a		x	x							
A2b	x					x				
A3								x	x	x
B1										x
B2	x					x				x
B3a					x	x		x	x	
B3b										x
B4				x		x	x	x	x	x
B5	x					x				x
C1a				x	x		x		x	
C2a				x	x		x		x	
C3a				x	x		x		x	
(C1-3)b										x
C4				x	x		x		x	
C5				x	x		x	x	x	
C6				x	x		x			
D1a				x	x	x	x	x	x	
D1b										x
D3						x		x	x	x
D5						x		x	x	
F1						x				x
F2a		x								
F3a						x				x
F4						x				x
G1a					x	x	x	x	x	
G1b										x
H1	x									
H2			x							
H3	x					x				
H4	x					x				x

Table E- 2 - changes of parameter values to implement NBSs using the old approach

NBSs-ID	Parameter	Value
A1	N	*1.5
A2b	N	=0.6
A3	N	*1.01
A3	Swood	+2
B1	N_River	*1.5
B2	N_River	*1.5
B3a	Swood	+3.5
B3b	Swood	+3.5
B4	N	*1.03
C1	Swood	+25
C4	Swood	+14
C4	N	*1.02
C5	N	*1.08
C6	N	*1.25
D1	Swood	+15
D3	Swood	+2
D3	N	*1.01
D5	N_River	*1.5
D6	N	*1.01
E1	N	*1.5
F1	Swood	+9
F3a	N	*1.013
F4	N_River	*1.5
G1a	Swood	+1.5
G1b	Swood	+1.5
H1	N	*1.014
H2	N	*1.75
H3	Swood	+2.2

Appendix F – individual effects of NBSs

In this Appendix, cluster numbers of NBSs are indicated using the following colours:

- Cluster InfSur
- Cluster InfSurSSt
- Cluster InfSSt
- Cluster InfRiv
- Other: Rainwater tank (H4)

Also, the following abbreviations are used in the tables:

- M = reduction in maximum runoff [$m^3/s/km^2$]
- V = reduction in runoff volume [mm/km^2]
- D = peak runoff delay [min/km^2]
- A = Area on which a NBS is implemented [km^2]
- MP = relative reduction of maximum runoff [%]
- VP = relative reduction of runoff volume [%]

F.1. Individual unit effects of NBSs for new approach

Table F- 1 – individual unit effects of NBSs when implemented using the new innovative physically-based approach

			Return period = two years			Return period = 100 years		
NBS-ID	**Subcatch**	**A**	**M**	**V**	**D**	**M**	**V**	**D**
A1	Rufigiza	4.10	0.13	0.11	2.44	0.66	0.22	0.00
	Kavure	0.38	0.33	19.36	26.27	1.36	0.53	0.00
	Mpazi	1.34	0.35	0.31	0.00	1.63	0.58	0.00
A2a	Rufigiza	4.43	0.08	0.07	0.00	0.48	0.21	0.00
	Kavure	0.50	0.24	14.66	19.91	1.17	0.55	0.00
	Mpazi	1.47	0.68	0.33	0.00	2.54	0.63	0.00
A2b	Rufigiza	9.30	-0.11	-0.03	0.00	-0.70	-0.38	-1.08
	Kavure	0.57	-1.07	11.83	0.00	-6.30	-3.79	-17.64
	Mpazi	2.89	2.29	1.20	6.92	5.02	1.30	3.46
B1	Rufigiza	3.52	-0.21	-0.33	0.00	-0.57	-0.51	0.00
	Kavure	0.57	-0.54	12.19	0.00	-1.39	-0.88	0.00
	Mpazi	2.85	0.61	0.08	3.51	2.08	0.10	3.51
B4	Rufigiza	4.85	-0.73	-0.92	-4.12	-3.03	-2.00	-2.06
	Kavure	2.49	-0.36	2.49	0.00	-1.40	-0.88	-4.01
	Mpazi	4.72	0.70	0.10	2.12	1.70	0.02	2.12
C2a	Rufigiza	0.59	-1.33	-1.88	0.00	-3.89	-2.96	0.00
	Kavure	1.24	0.05	5.84	0.00	0.42	0.17	0.00
	Mpazi	1.39	0.98	0.22	0.00	3.49	0.37	7.18
C5	Rufigiza	0.59	-1.28	-1.73	0.00	-6.67	-5.31	-16.91
	Kavure	1.24	0.10	5.89	8.07	0.11	-0.10	0.00
	Mpazi	1.39	1.71	0.43	0.00	4.89	0.23	7.18
C6	Rufigiza	0.48	-1.35	-1.62	0.00	-4.02	-2.54	0.00
	Kavure	1.03	0.51	7.63	0.00	2.03	1.55	0.00
	Mpazi	1.39	2.36	1.18	7.18	6.59	1.99	7.18
D5	Rufigiza	4.38	-0.65	-0.95	-2.28	-2.28	-1.81	-2.28
	Kavure	1.66	-0.59	3.67	0.00	-1.81	-1.32	-6.02
	Mpazi	3.47	0.00	-0.29	2.88	0.36	-0.60	2.88
F2a	Rufigiza	0.33	0.32	0.58	0.00	2.26	1.88	0.00
	Kavure	0.12	0.72	60.46	0.00	4.38	1.91	0.00
	Mpazi	0.13	7.75	2.21	0.00	27.47	3.67	0.00
F3a	Rufigiza	3.52	-1.02	-1.33	-5.68	-4.30	-2.91	-2.84

	Kavure	0.57	-2.32	10.32	-17.64	-9.38	-5.25	-17.64
	Mpazi	2.85	1.25	0.05	7.01	4.09	-0.38	3.51
H1	Rufigiza	5.78	0.14	0.16	1.73	0.75	0.34	0.00
	Kavure	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Mpazi	0.04	0.26	0.27	0.00	1.47	0.50	0.00
H2	Rufigiza	1.26	0.17	0.14	0.00	0.91	0.31	0.00
	Kavure	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Mpazi	0.02	0.59	0.46	0.00	3.02	0.61	0.00
A3	Rufigiza	0.86	-4.00	-6.27	-23.29	6.48	10.10	0.00
	Kavure	1.09	0.17	7.13	-9.14	7.31	8.11	0.00
	Mpazi	0.62	29.00	21.66	81.22	135.73	78.53	64.98
(C1-3)b	Rufigiza	0.11	9.30	11.85	88.18	74.48	65.87	0.00
	Kavure	0.21	-0.09	34.50	0.00	2.89	3.20	0.00
	Mpazi	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C4	Rufigiza	0.59	-0.45	0.08	0.00	1.45	5.21	0.00
	Kavure	1.24	1.29	7.78	0.00	8.02	8.43	0.00
	Mpazi	1.39	5.20	3.54	7.18	23.12	11.84	7.18
D3	Rufigiza	4.38	-0.15	0.63	0.00	2.05	5.93	0.00
	Kavure	1.66	0.61	5.42	0.00	5.47	6.25	0.00
	Mpazi	3.47	5.19	3.96	14.42	23.51	13.73	11.54
F1	Rufigiza	3.52	-2.14	-2.97	-8.51	-6.17	-4.71	-2.84
	Kavure	0.57	-4.68	7.46	-17.64	-13.39	-8.44	-17.64
	Mpazi	2.85	0.47	-0.61	3.51	2.78	-0.76	3.51
B3a	Rufigiza	4.39	0.21	0.98	2.28	3.38	6.55	2.28
	Kavure	1.85	1.10	5.47	5.39	7.40	7.48	5.39
	Mpazi	3.60	3.92	2.94	5.55	17.95	10.38	5.55
B3b	Rufigiza	0.11	2.27	3.07	0.00	14.49	13.97	0.00
	Kavure	0.21	1.24	35.97	0.00	6.87	5.78	0.00
	Mpazi	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C1a	Rufigiza	0.59	0.81	1.89	0.00	4.27	6.88	0.00
	Kavure	1.24	1.41	7.92	0.00	7.05	6.83	0.00
	Mpazi	1.39	5.03	3.52	7.18	15.30	7.64	7.18
G1a	Rufigiza	4.81	0.23	1.03	2.08	3.16	6.29	2.08
	Kavure	1.93	1.09	5.34	5.19	7.26	7.35	0.00
	Mpazi	4.25	4.11	3.07	9.41	18.41	10.59	7.05
G1b	Rufigiza	4.39	-0.11	-0.26	0.00	0.47	0.20	0.00
	Kavure	1.85	-0.31	3.57	0.00	-0.85	-0.54	-5.39
	Mpazi	3.60	4.78	3.70	13.87	19.77	11.37	8.32
H3	Rufigiza	9.30	0.52	0.98	4.30	1.10	1.26	0.00
	Kavure	0.57	0.22	13.24	17.64	1.14	1.20	0.00
	Mpazi	2.89	1.65	1.23	3.46	2.12	1.19	3.46
B2	Rufigiza	9.30	0.15	0.09	4.30	0.85	0.09	2.15
	Kavure	0.57	-0.11	12.65	0.00	-0.21	-0.26	0.00
	Mpazi	2.89	2.07	0.52	13.83	7.75	0.21	6.92
F4	Rufigiza	3.52	0.02	0.06	0.00	0.08	0.16	0.00
	Kavure	0.57	0.02	12.85	0.00	0.08	0.12	0.00
	Mpazi	2.85	0.22	0.12	0.00	0.64	0.22	0.00
H4	Rufigiza	9.30	0.44	0.85	3.23	0.37	0.53	0.00
	Kavure	0.57	0.53	13.60	17.64	1.00	1.03	0.00
	Mpazi	2.89	0.55	0.42	0.00	0.83	0.41	0.00

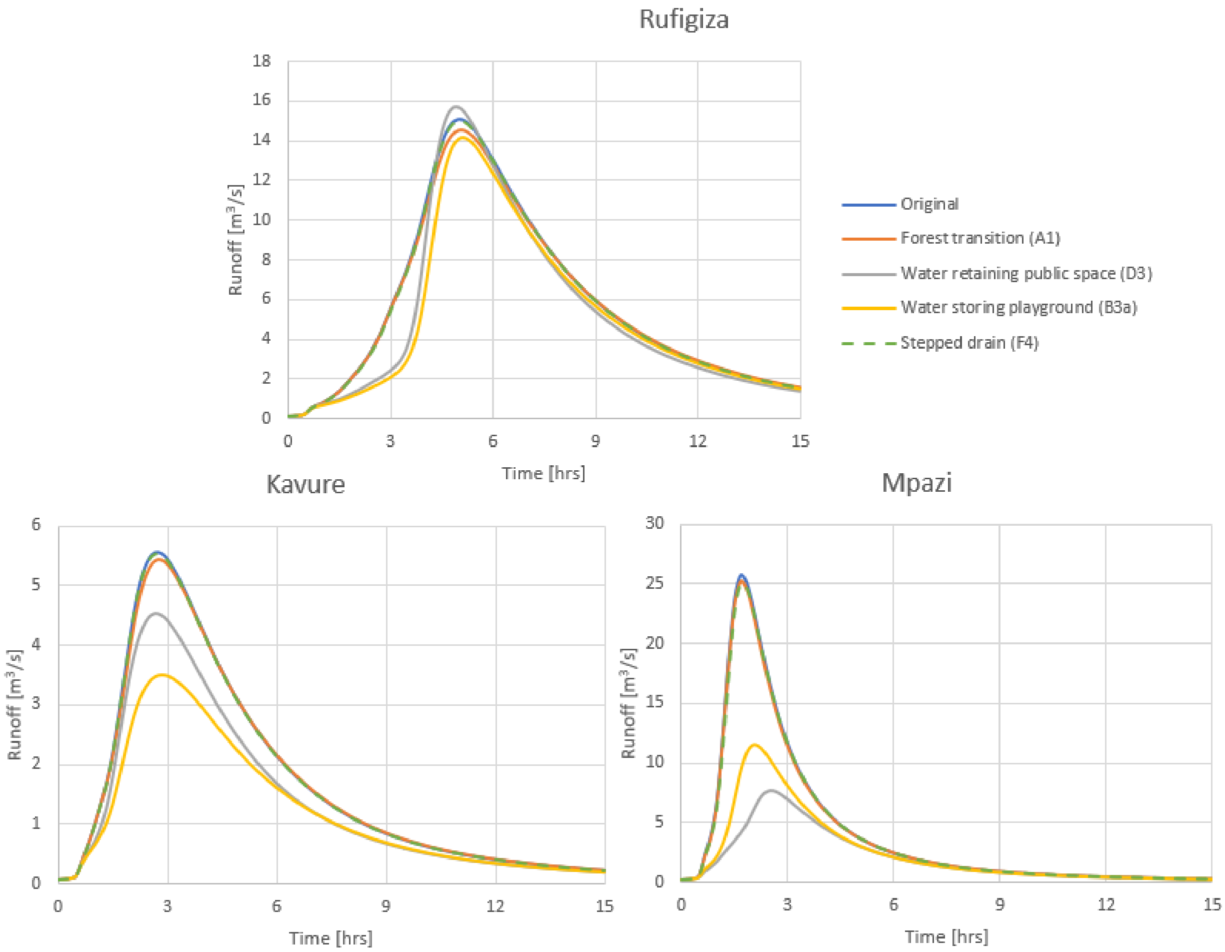


Figure 24 – hydrographs after implementing individual NBSs in all sub-catchments. One NBS is selected from each sub-catchment.

F.2. Effects of NBSs for long and short rainfall events for new and old approach

Table F- 2 - individual NBSs for long and short rainfall events (relative reduction of maximum runoff (MP) [%] and unit delay (D) in minutes/km²) for the new and old approach for two years return period

		New approach				Old approach			
		Long rain event		Short rain event		Long rain event		Short rain event	
NBS-ID	Subcatch	MP	D	MP	D	MP	D	MP	D
A1	Rufigiza	0.0	0.0	3.5	2.4	0.0	0.0	9.1	2.4
	Kavure	2.0	26.3	2.3	26.3	2.8	26.3	3.8	26.3
	Mpazi	0.4	0.0	1.8	0.0	0.0	0.0	1.7	0.0
D3	Rufigiza	3.1	0.0	-4.3	0.0	0.2	0.0	0.7	0.0
	Kavure	6.3	0.0	18.4	0.0	0.3	0.0	1.1	0.0
	Mpazi	40.4	8.7	70.2	14.4	0.1	0.0	0.5	0.0
B3a	Rufigiza	2.9	0.0	6.0	2.3	0.4	0.0	0.5	0.0
	Kavure	7.6	0.0	36.7	5.4	0.8	0.0	1.9	0.0
	Mpazi	39.1	5.5	55.1	5.5	0.1	0.0	0.5	0.0
B2	Rufigiza	3.4	2.2	9.1	4.3	1.3	1.1	4.2	2.2
	Kavure	-0.4	0.0	-1.1	0.0	-0.4	0.0	-0.9	0.0
	Mpazi	5.9	24.2	23.3	13.8	3.9	17.3	12.3	6.9
H4	Rufigiza	14.8	4.3	27.0	3.2				
	Kavure	0.9	0.0	5.5	17.6				
	Mpazi	3.4	0.0	6.1	0.0				

F.3. Combined effects of NBSs for new and old approach

Table F- 3 - combined absolute effects of NBSs for the new and the old approach for the different catchments

	New approach						Old approach					
	RP = two years			RP = 100 years			RP = two years			RP = 100 years		
Subcatch	M	V	D	M	V	D	M	V	D	M	V	D
Rufigiza	6.58	13.58	80	34.39	46.92	40	4.74	7.33	70	19.81	5.73	30
Kavure	2.66	11.42	-10	18.36	20.61	0	0.58	8.20	10	0.28	-0.2	0
Mpazi	23.16	18.15	160	104.40	63.65	120	14.92	7.30	120	55.23	6.16	70

Table F- 4 - combined effects of NBSs expressed as percentages decrease in maximum runoff and runoff volume for the new and old approach for different catchments

	New approach				Old approach			
	RP = two years		RP = 100 years		RP = two years		RP = 100 years	
Subcatch	MP	VP	MP	VP	MP	VP	MP	VP
Rufigiza	43.7	4.8	36.6	2.7	31.5	2.6	21.1	0.3
Kavure	48.0	6.5	57.5	4.4	10.5	4.7	0.9	0.0
Mpazi	90.3	7.4	90.5	6.1	58.1	3.0	47.9	0.6

F.4. Effects for upstream and downstream roughness increases and decreases

Table F- 5 - reduction in maximum runoff in m³/s (M), reduction in runoff volume in mm (V) and delay of maximum runoff in minutes (D) when the upstream roughness is increased and is decreased downstream

		Return period = two years			Return period = 100 years		
Parameter	Subcatch	M	V	D	M	V	D
N	Rufigiza	4.47	4.75	-200	38.94	9.08	20
	Kavure	-2.64	7.81	-100	-3.99	2.03	-60
	Mpazi	12.59	7.04	-40	56.18	12.45	-20
N_River	Rufigiza	2.75	1.21	50	13.62	0.99	20
	Kavure	0.74	7.47	10	3.68	0.14	10
	Mpazi	3.59	0.49	10	11.51	0.26	10

Table F- 6 - reduction in maximum runoff in m³/s (M), reduction in runoff volume in mm (V) and delay of maximum runoff in minutes (D) when only the upstream roughness is increased

		Return period = two years			Return period = 100 years		
Parameter	Subcatch	M	V	D	M	V	D
N	Rufigiza	8.52	15.89	110	37.66	36.96	50
	Kavure	2.71	11.58	-20	16.37	18.76	-10
	Mpazi	23.65	18.15	160	105.27	62.75	140
N_River	Rufigiza	2.69	1.07	50	13.54	0.99	20
	Kavure	0.72	7.45	10	3.63	0.14	10
	Mpazi	3.40	0.34	10	11.45	0.26	10

Table F- 7 - reduction in maximum runoff in m³/s (M), reduction in runoff vulume in mm (V) and delay of maximum runoff in minutes (D) when the roughness is increased in the entire sub-catchment

		Return period = two years			Return period = 100 years		
Parameter	Subcatch	M	V	D	M	V	D
N	Rufigiza	0.39	-0.56	10	-4.01	-18.93	0
	Kavure	0.88	7.64	20	3.09	-4.16	10
	Mpazi	13.66	4.83	50	49.28	-2.34	30
N_River	Rufigiza	5.44	7.34	220	32.48	13.09	120
	Kavure	1.36	8.34	80	7.38	1.46	40
	Mpazi	8.19	2.29	60	31.66	1.54	40

F.5. Comparison of relative individual effects of NBSs for both approaches

Table F- 8 - percentages decrease in maximum runoff and runoff volume of individual NBSs for the new and old approach for different return periods

		New approach				Old approach			
		RP = two years		RP = 100 years		RP = two years		RP = 100 years	
NBS-ID	Subcatch	MP	VP	MP	VP	MP	VP	MP	VP
A1	Rufigiza	3.5	0.2	2.9	0.1	9.1	0.4	8.5	0.1
	Kavure	2.3	4.2	1.6	0.0	3.8	4.2	3.1	0.1
	Mpazi	1.8	0.2	1.9	0.1	1.7	0.2	2.0	0.1
A2b	Rufigiza	-7.1	-0.1	-6.9	-0.2	1.1	0.1	3.1	-0.1
	Kavure	-11.0	3.8	-11.2	-0.5	-13.5	3.7	-10.4	-0.5
	Mpazi	25.8	1.4	12.6	0.4	32.1	1.0	25.7	0.1
B1	Rufigiza	-5.0	-0.4	-2.1	-0.1	3.1	0.1	2.5	0.0
	Kavure	-5.5	3.9	-2.5	-0.1	-0.1	4.1	0.0	0.0
	Mpazi	6.8	0.1	5.1	0.0	4.3	0.1	3.3	0.0
B4	Rufigiza	-23.7	-1.6	-15.7	-0.6	0.3	0.0	0.2	0.0
	Kavure	-16.2	3.5	-10.9	-0.5	0.9	4.2	0.8	0.0
	Mpazi	13.0	0.2	6.9	0.0	1.0	0.0	1.0	0.0
C5	Rufigiza	-5.0	-0.4	-4.2	-0.2	0.2	0.0	0.3	0.0
	Kavure	2.3	4.2	0.4	0.0	1.9	4.2	2.0	0.0
	Mpazi	9.3	0.2	5.9	0.0	0.8	0.0	1.1	0.0
C6	Rufigiza	-4.3	-0.3	-2.0	-0.1	0.0	0.0	0.2	0.0
	Kavure	9.4	4.5	6.5	0.3	2.4	4.2	2.4	0.1
	Mpazi	12.8	0.7	8.0	0.3	2.2	0.1	2.4	0.0
D5	Rufigiza	-19.0	-1.5	-10.6	-0.5	0.5	0.0	0.3	0.0
	Kavure	-17.7	3.5	-9.4	-0.5	-0.5	4.1	-0.3	0.0
	Mpazi	0.0	-0.4	1.1	-0.2	10.4	0.2	6.9	0.0
F3a	Rufigiza	-23.9	-1.7	-16.1	-0.6	0.1	0.0	0.1	0.0
	Kavure	-23.7	3.3	-16.7	-0.6	0.0	4.1	0.1	0.0
	Mpazi	13.9	0.1	10.1	-0.1	0.5	0.0	0.6	0.0
H1	Rufigiza	5.3	0.3	4.6	0.1	0.4	0.0	0.3	0.0
	Kavure	0.0	4.1	0.0	0.0	0.0	4.1	0.0	0.0
	Mpazi	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
H2	Rufigiza	1.4	0.1	1.2	0.0	4.4	0.2	4.0	0.1
	Kavure	0.0	4.1	0.0	0.0	0.0	4.1	0.0	0.0
	Mpazi	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0
A3	Rufigiza	-22.8	-1.9	5.9	0.5	8.1	0.8	3.6	0.2
	Kavure	3.3	4.4	25.0	1.9	0.4	0.0	0.2	0.0
	Mpazi	69.6	5.4	72.4	4.7	0.6	4.2	0.2	0.0
C4	Rufigiza	-1.8	0.0	0.9	0.2	1.2	0.1	0.1	0.0
	Kavure	28.9	5.5	31.1	2.2	5.2	4.3	1.4	0.1
	Mpazi	28.3	2.0	27.9	1.6	0.4	0.0	0.3	0.0
D3	Rufigiza	-4.3	1.0	9.6	1.5	0.4	0.8	0.1	19.37
	Kavure	18.4	5.1	28.5	2.2	0.7	0.1	0.2	0.0
	Mpazi	70.2	5.6	70.6	4.6	1.1	4.2	0.3	0.0
F1	Rufigiza	-50.1	-3.7	-23.1	-0.9	3.5	0.4	0.5	0.0
	Kavure	-47.8	2.4	-23.8	-1.0	2.9	4.3	0.4	0.0
	Mpazi	5.2	-0.7	6.9	-0.2	2.6	0.2	0.4	0.0
B3a	Rufigiza	6.0	1.5	15.8	1.6	0.5	0.1	0.1	0.0

	Kavure	36.7	5.8	43.0	3.0	1.9	4.2	0.2	0.0
	Mpazi	55.1	4.3	56.1	3.6	0.5	0.0	0.1	0.0
B3b	Rufigiza	1.7	0.1	1.7	0.1	0.1	0.0	0.0	0.0
	Kavure	4.7	4.3	4.5	0.3	0.0	4.1	0.0	0.0
	Mpazi	11.2	0.7	10.7	0.5	0.0	0.0	0.0	0.0
G1a	Rufigiza	7.5	1.7	16.2	1.7	0.2	0.0	0.0	0.0
	Kavure	37.8	5.9	43.9	3.1	0.5	4.1	0.1	0.0
	Mpazi	68.0	5.3	67.8	4.3	0.1	0.0	0.0	0.0
G1b	Rufigiza	-3.2	-0.4	2.2	0.0	0.1	0.0	0.0	0.0
	Kavure	-10.5	3.8	-5.0	-0.2	0.0	4.1	0.0	0.0
	Mpazi	67.2	5.4	61.7	4.0	0.1	0.0	0.0	0.0
H3	Rufigiza	31.8	3.2	10.9	0.7	0.6	0.1	0.1	0.0
	Kavure	2.2	4.3	2.0	0.1	0.3	4.1	0.0	0.0
	Mpazi	18.6	1.4	5.3	0.3	0.2	0.0	0.0	0.0
B2	Rufigiza	9.1	0.3	8.5	0.0	4.2	0.1	4.2	0.0
	Kavure	-1.1	4.1	-0.4	0.0	-0.9	4.1	-0.2	0.0
	Mpazi	23.3	0.6	19.4	0.1	12.3	0.3	10.1	0.0
F4	Rufigiza	27.0	2.8	3.7	0.3	1.0	0.0	1.0	0.0
	Kavure	5.5	4.4	1.8	0.1	-0.8	4.1	-0.2	0.0
	Mpazi	6.1	0.5	2.1	0.1	12.1	0.2	10.0	0.0

Table F- 9 – average percentages decrease in maximum runoff and runoff volume of each NBS cluster for the new and old approach for different return periods

		New approach				Old approach			
		RP = two years		RP = 100 years		RP = two years		RP = 100 years	
Cluster	Subcatch	MP	VP	MP	VP	MP	VP	MP	VP
InfSur	Rufigiza	-7.8	-0.5	-4.9	-0.2	1.9	0.1	1.9	0.0
	Kavure	-6.0	3.9	-4.2	-0.2	-0.5	4.1	-0.2	0.0
	Mpazi	8.3	0.2	5.2	0.0	5.3	0.2	4.3	0.0
InfSurSSt	Rufigiza	-19.8	-1.1	-1.7	0.3	1.4	0.2	0.2	0.0
	Kavure	0.7	4.4	15.2	1.3	2.4	4.2	0.6	0.0
	Mpazi	43.3	3.1	44.4	2.7	1.0	0.1	0.3	0.0
InfSSt	Rufigiza	8.8	1.2	9.4	0.8	0.3	0.0	0.1	0.0
	Kavure	14.2	4.8	17.7	1.2	0.5	4.2	0.1	0.0
	Mpazi	44.0	3.4	40.3	2.6	0.2	0.0	0.0	0.0
InfRiv	Rufigiza	13.7	1.4	2.0	0.2	2.6	0.1	2.6	0.0
	Kavure	2.8	4.3	1.0	0.1	-0.8	4.1	-0.2	0.0
	Mpazi	4.3	0.3	1.8	0.1	12.2	0.2	10.0	0.0

Appendix G – relevant NBSs

In this study, a NBS is neglected when:

1) The NBS has a negligible effect on the simulated runoff.
2) The NBS is related to the wetlands of Kigali (E-NBSs in Table 7), since there are no wetlands within the three sub-catchments that were selected.
3) The NBS is a sub-NBS part of a parent NBS. These are also omitted by HKV, because they are usually too small to be significant.

In the study by HKV, some NBSs have also been neglected because they are assumed to have a negligible effect on runoff. The potential effectiveness of these NBSs is investigated using the NBS-clusters shown in Table 7 of Paragraph 4.2. Each cluster number is classified as a group of NBSs that either store or delay water. Based on this classification, the criteria for the significance of the NBSs are as follows:

- Clusters in which the main function of the NBSs is to (temporarily) store water – 2, 3, 5, 9 & 10. F1 does not belong to any cluster but is also classified into this group. An NBS is assumed to be negligible if storage capacity < 10% of peak rainfall volume.
- Clusters in which the main function of the NBSs is to (temporarily) delay water – 1, 4, 6, 7 & 8. C5 does not belong to any cluster but is also classified into this group. A NBS is assumed to be negligible if roughness increase < 10%.

The peak rainfall volume is calculated by summing up the simulated rainfall of the most intense rainfall event in Figure 7. To deal with the spatial variability in rainfall in the catchment, the minimum total volume of peak rainfall is calculated and used for the significance criterium. This is 262 m^3 per grid cell, which corresponds to 32.3 millimetres.

An overview of this methodology is shown in the flowchart below:

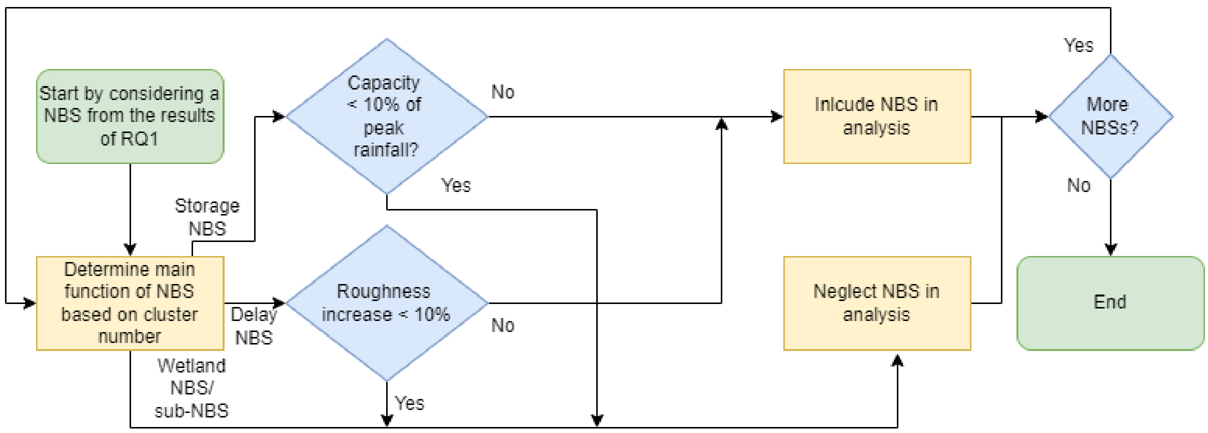


Figure G- 1 - overview of method to determine relevance of NBSs

Storage NBSs

Water storage tanks (B5) – significant

When the following assumptions are made:

- The volume of a water storage tank is assumed to be 2500 litres (NRGI, 2010).
- 80% of a grid cell consists of roofs that connected to water storage tanks.
- Each roof is connected a separate water storage tank.

- Each building's roof has an area of 100 m^2 (CAHF, 2016).

Then, approximately 65 water storage tanks can be placed within a grid cell. These water storage tanks can hold a total volume of up to 162.5 m^3 of rainwater (20 mm). Therefore, they may be considered effective in decreasing the maximum runoff and runoff volume.

Water storing walls (D2) – negligible

When the following assumptions are made:

- The thickness of a water storing wall is 30 cm and its height 3 m.
- 50% of the wall can be occupied by water.
- Water storage walls are only located along the outside boundaries of the grid cells and thus have a total length of 360 m. A plot bordered by water storing walls is assumed to be large, because smaller plots are less likely to be bordered by a wall.
- Only the outer 2 m on all sides of the grid cell are connect to the water storage walls (e.g. the roof). This is approximately 10% of the grid cell.

These water storing walls can hold a total volume of up to 16.2 m^3. This is less than 10% of the minimum rainfall in the catchment and therefore, it is assumed that water storing walls have a negligible effect.

Green blue development standard (H5) & guidelines private water storage (D1) – negligible

The effect on the peak runoff of standards and guidelines is highly uncertain because it is dependent on human actions. Therefore, these NBSs are not considered. Regulations (e.g. B4) are taken into account, because in this way, humans actions are more likely to occur and thus the effect is less uncertain.

Climbing plants with arches (F3b) – negligible

The main runoff-related function of the climbing plants is the (temporal) interception of rainfall. The Rutter method calculates the amount of interception using the LAI, Sl and $C_{max,wood}$ (Rutter et al., 1975; Schellekens, 2019). Representative values for these parameters are obtained from the look-up table in Table A- 1.

The maximum LAI value of the three isolated sub-catchments is obtained from the wflow input data and is approximately 1.9 m^2/m^2. The maximum increase in Sl due to the climbing plants is 0.09 mm and therefore, the maximum increase in $C_{max,leaves}$ 0.17 mm. The potential maximum increase in $C_{max,wood}$ is 0.5 mm. So, the total increase in interception capacity could be 0.67 mm. However, this is negligible compared to the peak rainfall volume (especially because climbing plants will only be implemented on a small scale) and therefore, climbing plants with arches are not implemented into wflow.

Wall with planter boxes (G2) - negligible

The maximum increase in interception of the plants in the planter boxes is like the value calculated for the climbing plants with arches. An additional value of water can be stored in the planter boxes (approximated at 100 mm). However, walls with planter boxes are also local NBSs which are implemented on a small scale. To have a significant effect on the peak runoff of a catchment, approximately 270 m^2 of planter boxes should be present in a grid cell. This is unrealistic and therefore, this NBS is also assumed to have a negligible effect.

Delaying NBSs

Contour planting (A2) - significant

Planting crops along the contours of the land can decrease the runoff by 32% (Farahani et al., 2016). The Manning equation in Equation 1 shows the runoff is proportional to 1/n. When the initial roughness is assumed to be 0.100 s/m$^{1/3}$ (agricultural land use from Table A- 3), the roughness because of contour planting (all other factors in Equation 1 remain unchanged) is approximately 0.15 s/m$^{1/3}$. This is an increase of 50% and therefore, contour planting is considered effective in decreasing the runoff.

Forest protection (A4) – negligible

Forest protection or demarcation is not expected to have any direct effect on the runoff. It is a measure to prevent tree removal which may have a negative effect on the urban runoff. However, if forest protection is successful, no changes in the urban runoff will be observed and therefore, this NBS is neglected.

Terraced Park (F2a) – significant

A terraced park can slow down runoff water since the slope of the surface decreases. The Manning equation in Equation 1 shows that runoff is proportional to the square root of the slope. A slope reduction of a factor of 4 results in a reduction of the runoff with a factor of 2. When the initial roughness is assumed to be 0.100 s/m$^{1/3}$ (agricultural land use from Table A- 3), the roughness should increase to 0.110 s/m$^{1/3}$ to be significant. This results in a decrease in runoff of approximately 9%. These calculations are shown in Appendix C.1.

It is assumed that the nearly horizontal terraces have gradient lower than 2% (Defacto, 2020). So, to decrease the runoff by at least 9%, the initial slope before contour planting should be at 2.5%. It is assumed that this is the case and therefore, a terraced may be considered effective in decreasing the runoff.

Green façades (C3a) – negligible

Green façades are walls covered with greenery. The greenery intercepts rainfall and its roots take up rainfall. Also, the rainfall is returned to the atmosphere by evapotranspiration. The interception of rainfall is most relevant to reduce the stormwater runoff. Research shows that green façades can reduce peak runoff volume by up to 6% (Roehr et al., 2009). Using the calculations shown in Appendix C.1., the roughness increases by approximately 6% as well. For that reason, this NBS is considered to be negligible.

Gabions (D6 and F2b) – negligible

The effectiveness of gabions is tested using a 1D hydraulic Sobek model. This is shown in Appendix C.2. The maximum increase in roughness due to the presence of gabions is only 6% and therefore, gabions are ineffective for delaying the runoff.

Appendix H – NBS locations to optimise runoff reduction

This study shows that the effects of NBSs depend on where the NBSs are implemented. Suitable locations of NBSs are currently determined using potential effectiveness and suitability. However, it is potentially more efficient and effective to apply certain types of NBSs in upstream and downstream areas only.

Therefore, the following questions are answered: is it possible to optimise the runoff reduction by delaying the runoff in upstream sections and accelerating it downstream? Or is only increasing the upstream roughness more effective? This is tested for both Manning roughness parameters in the model: N and N_River. For both parameters, the upstream roughness is set to the maximum roughness that could occur in the model (see Paragraph 3.4.3) and the downstream roughness to the minimum. The Manning roughness maps are shown below in Figure H- 1.

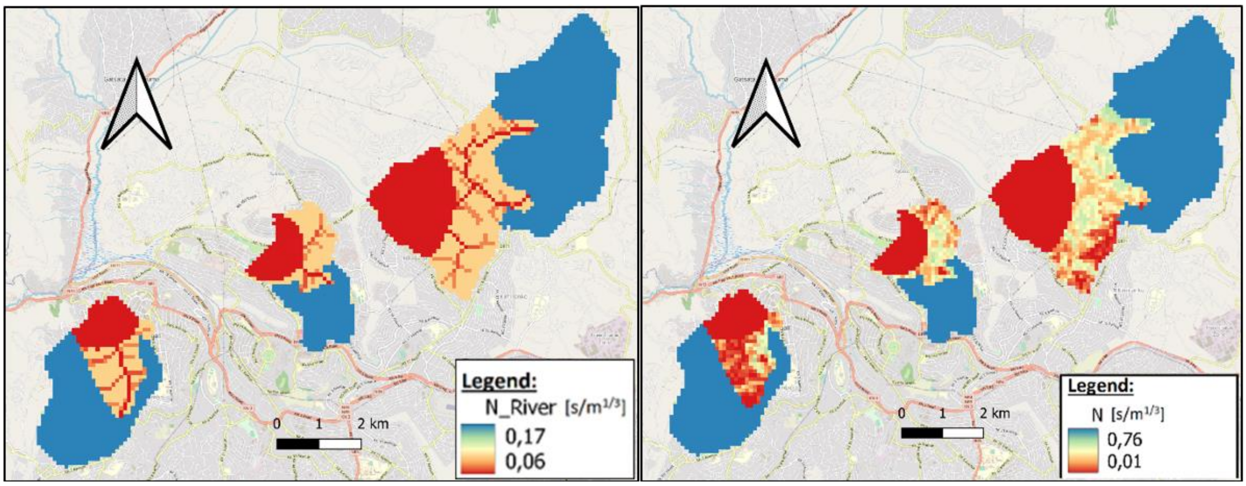


Figure H- 1 - static maps for N_River (left) and N (right) when upstream roughness is increased, and downstream roughness is decreased

Examples of the flood waves for a return period of two years are shown in Figure H- 2. The quantitative results for both return periods are shown in Table F- 5, F-6 and F-7. The effects of changing the upstream and/or downstream roughness should not be compared to the combined effects of NBSs in Paragraph 4.4.3, because surface water retention and infiltration are excluded from this analysis.

<u>Increasing upstream roughness and decreasing downstream roughness</u>

The results for the Manning surface roughness (N) show that the peak runoff occurs earlier, especially when the return period is two years. However, in most cases, the maximum runoff and runoff volume decrease. Decreasing the downstream roughness causes the initial response to be fast, but the increase in upstream roughness delays the flow which is far away from the downstream gauge. An increase of the maximum runoff is only observed in Kavure, suggesting that the size of the area with a decreased roughness is too large relative to the size of the catchment.

The flood wave due to the surface roughness changes observed in Rufigiza is also interesting. This wave has two peaks, instead of one. This is because Rufigiza consists of multiple rivers confluencing near the downstream boundary. The roughness changes have a larger effect on one of these rivers than on the others.

When N_River is used instead of N, both the maximum runoff and runoff volume decrease, and runoff delay occurs in all sub-catchments for both return periods. This is because the rainwater from upstream areas is slowed down by the increased roughness, which in turn causes the delay of the runoff peak in all sub-catchments. The flow accelerates once the runoff peak reaches the downstream area because the roughness decreases.

The different responses when using N and N_River are explained by the differences between upstream and downstream rivers. Downstream, rivers have confluenced and carry more water. Therefore, there are not only more upstream than downstream streams, but downstream rivers are also deeper and wider. The hydraulic radius increases with river depth and width and so, the effect of bottom roughness dampens. For overland flow, the upstream and downstream flow depth are more similar.

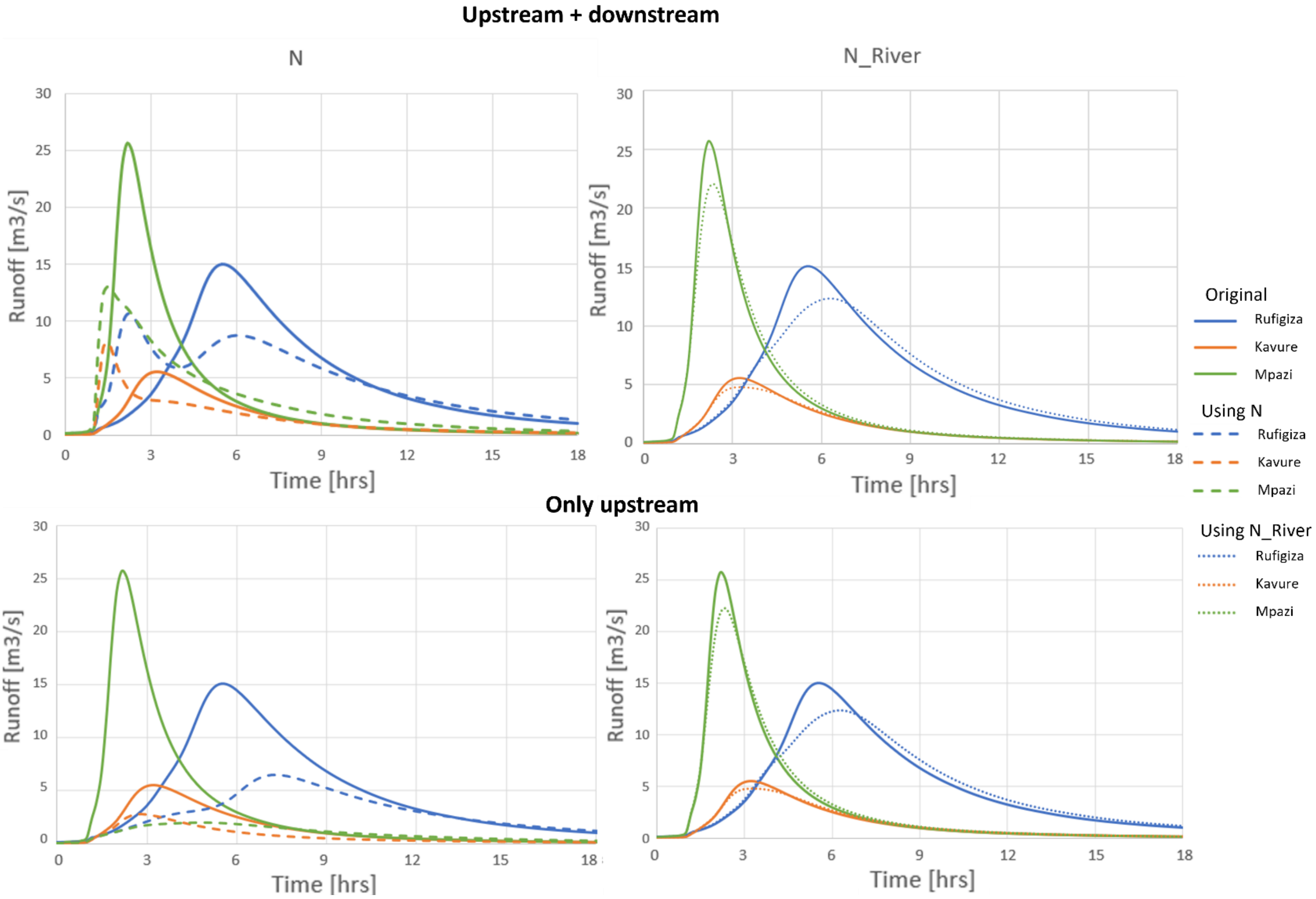


Figure H- 2 - changes in flood waves after increasing the roughness upstream and decreasing it downstream (top), and only increasing the upstream roughness (bottom) for a return period of two years

<u>Only increasing upstream roughness</u>

For N, the maximum runoff reduction is larger when only the upstream roughness is increased. For N_River, no significant differences are observed. This applies to all sub-catchments. Also, for the parameter N in Rufigiza, two peaks are no longer observed.

In conclusion, these results show that increasing the roughness upstream is an effective measure to decrease the downstream discharge. Decreasing the roughness downstream can have adverse effects, which include an increased maximum runoff and a steeper rising limb. Both effects are unfavourable as they can lead to increased extensive erosion, which increases the risk of landslides (World Bank, 2021).

<u>Increasing roughness in the entire sub-catchment</u>

Increasing the roughness in the entire sub-catchment is more effective in decreasing the maximum runoff than when only increasing it upstream when applied to drains and rivers, but not on the surface. This suggests that NBSs increasing the surface roughness are most effective in most upstream areas. Delaying NBSs in drains and rivers can be applied to the entire catchment.

Appendix I – pictures taken during field trip in Mpazi

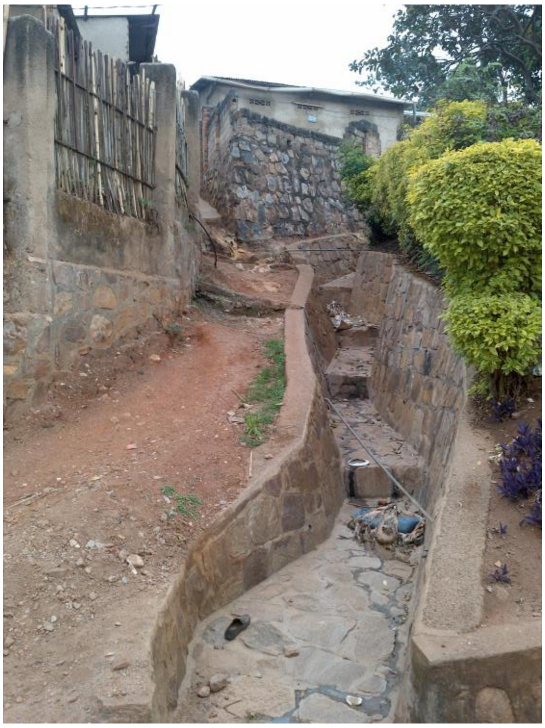


Figure I- 1 – stepped drain in Mpazi

Figure I- 2 - unplanned settlements on the hillslope and paved road with drains on either sides of the road

Figure I- 3 - paved areas, erosion and unplanned settlements on the hillslope

Figure I- 4 - satellite image of Kigali (Astrium Geo, 2009)