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Development of a Hydrodynamic Model for River Sosiani

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Abstract

River Sosiani's catchment is a sub-catchment of the larger river Nzoia sub-basin which drains into Lake Victoria. River Sosiani drains rich agricultural lands and is the source of water for Eldoret town. The river is also the receiving body of effluent discharges from Eldoret town. It, therefore, has a major economic and environmental value in the western region of Kenya. For effective and sustainable management of river Sosaini it is important, among other things, to understand the hydrology and hydraulics of the river. MIKE 11 HD software was applied to simulate river Sosiani's discharge. The river's catchment was delineated from topographical map sheets after digitization using ArcView 3.3 GIS software. Geometrical parameters of the river were obtained by physical survey. In total seventeen cross-sections were surveyed. The model was calibrated using measured streamflow at the catchment outlet for three years and then validated for additional three years. The reliability of the MIKE 11 HD module was evaluated based on the Efficiency Index (EI) and Root Mean Square Error (RMSE). The EI and RMSE obtained are 0.75 and 0.050 m^3s^{-1}, respectively. This model can be used for various watershed management purposes, including construction of the river's water quality model.

Keywords: River Sosiani; Hydrodynamic model; MIKE 11; model calibration, model validation

1. Introduction

River Sosiani's catchment (00°- 03'S and 00°-55'N; 34°-50'E and 35°-37'E) is a subcatchment of the larger river Nzoia sub-basin which drains into Lake Victoria, the largest fresh water lake in Africa (Figure 1). Rainfall regime is bimodal with annual average of 1000 mm. (KMD, 2010).

River Sosiani's catchment has witnessed rapid population growth rate in the last three decades. Eldoret, the major town in the catchment, for example, has experienced a threefold population increase up to 300,000 (KNBS, 2010). The unchecked population growth has impacted negatively on the catchment's water storage capacity both in terms of quantity and quality (Sewe, 1999). Besides increased water demand from the river by the riparian population for various socio-economic activities in the catchment, there has been unabated deforestation of forested land to give way to agriculture, and encroachment of Eldoret town into agricultural lands. Unchecked depletion of forest resources and poor planning in the catchment has both direct and indirect negative impact on the catchment's water storage capacity.

Mathematical model offers a quantitative framework that integrates diverse physical, chemical & biological information that constitute complex environmental systems. It is rational & economical tool for holistic river catchment management, since it can simulate the potential response of aquatic system to external stimuli at less than 5% of the total cost scaled physical model (Chapman, 1999). Cost-effective, model-based control strategies could, therefore, provide a tool for sustainable water quality and quantity management at the catchment scale by promoting integrated proactive management strategies that will improve riparian quality of life while maintaining economic growth.

Different model types exist to mould catchment surface water quantity and quality. They vary in details from physically based to simplified conceptual and empirical models. The most appropriate model type for a certain application depends on the project objectives and the data availability. The detailed models, for example, are useful for a short-term simulation of representative events, but for long-term statistical information and as a management tool, they are not feasible. For the latter purpose, more simplified models are more practical (Radwan, et al., 2000). In the case of river Sosiani, a working (calibrated and validated) one-dimensional model was desired to route the discharge in the study area. The results from such model were expected to be adequately accurate to estimate the flow at different locations along the river length.

MIKE 11 modeling system (DHI, 2004) was used in this study to develop a hydrodynamic model for River Sosiani. The river's catchment was delineated and subsequently subdivided according to land-use practice into Forested zone (Fz), Agricultural zone (Az), Urban zone and (Uz) (Figure 2). The rainfall runoff processes were simulated using the NAM module. The NAM output discharge was filtered in its subflows using WETSPRO, and the hydrodynamic model was developed using MIKE 11 HD module (Figure 3). Model calibration and validation was done on the basis of available observed river discharge data at Fz – Az; Az – Uz boundaries.

2. Catchment delineation and subdivision according to land-use

River Sosiani's catchment was delineated using 1:50,000 Topographic Map Sheets (TMS). River Sosiani catchment falls under the small or medium size watersheds. Following the guideline by Maidment (ESRI, 1999) 25 m grid cell were derived from 1:50,000 topographical maps. A Digital Elevation Model (DEM) was subsequently generated from TMS after scanning and digitization and catchment map finally delineated from DEM using Arc View GIS and subdivided according to land-use practice (Figure 2). Table 1 shows the pertinent catchment characteristics of River Sosiani. In total the river has 21 subcatchments, with two major tributaries: Elgarin and Endoroto, flowing northwestward and southwestward, respectively to confluence at the Two-river dam. The elevation between the upper (Fz0) and lower (Uz5) catchments (Figure 2) is approximately 300 meters.

3. Model Setup and Data Requirement

3.1 NAM module

MIKE 11 NAM model (NAM) is a professional engineering software package developed by Danish Hydraulic Institute (DHI), Denmark. NAM is a set of linked mathematical statements describing, in a simplified quantitative form, the behavior of the land phase of the hydrological cycle. It represents various components of the rainfall-runoff process by continuously accounting in four different and mutually interrelated storages (DHI, 2004). This study was limited to three catchment storages area: surface storage (U), root zone storage (L), and groundwater storages (G). Model parameters were CQOF and CQIF, for overland flow and interflow runoff coefficients, respectively (Table 3). Rainfall, evaporation and discharge data were simulated on daily basis for a period of 25 years. The model was the calibrated and validated using the observed discharge data at the catchment outlet (Figure 2). The reliability of the NAM was evaluated based on the Efficiency Index (EI) as described by Nash and Sutcliffe (1970). The fully description of River Sosiani's NAM model is available in "Rainfall Runoff Model for River Sosiani's Catchment", (Chibole, 2011).

3.1.1 Input requirement

The input data requirements for NAM module include catchment area, rainfall time series, evaporation time series, and discharge time series (Figure 3). Rainfall, evaporation and discharge time series were acquired from the meteorological department (Table 2) on daily basis for a period of twenty five years. Catchment area was calculated using Arc View GIS as indicated above. The meteorological variable time series were analyzed and evaluated using Water Engineering Time Series Processing tool (WETSPRO). WETSPRO is a multi-criteria model evaluation protocol (Willems, 2009). The protocol is based on the analysis of graphical time series displays. Among other things, it can be used to filter the time series of total rainfall-runoff discharges into its subflows using a numerical digital filter technique, base on the linear reservoir modeling concept. WETSPRO was employed to filter subflows in the river (Table 4, Figure 7).

3.2 HD module

The MIKE 11 hydrodynamic module (HD) uses an implicit, finite difference scheme for the computation of unsteady flows in rivers and estuaries. The module can describe sub-critical as well as supercritical flow conditions through a numerical scheme which adapts according to the local flow conditions in time and space.

The HD module simulates one-dimensional river flow by solving the fully dynamic de Saint-Venant equations, which combine the equations for conservations of mass and momentum for unsteady open channel flow. The computational grids are generated with alternating discharge (Q) and water level (h) points. The h points were created at the locations where cross sectional data was available, and Q points were generated automatically in between the h point. There were a total of 121 grid points and 17 cross-sections (Figure 4). The differential equations are solved using an implicit finite difference 6-point Abbot-scheme (DHI, 2004). MIKE 11 provides an option where bed resistance, Manning roughness coefficient (n), can be calculated as a function hydraulic parameters, radius or flow velocity. The latter was used in this study for model calibration purposes.

3.2.1 Input requirement

a. *Branch*

The model is a single-branch model, and only one of its tributary, Endoroto, is included in the model (Figure 4). MIKE 11 requires defining the beginning (Upstream) and ending (downstream) points of the branch modeled. In this study Eligerin was considered as part of the larger Sosiani. For this model, the upstream chainage, Fz0, is at 0 m, and downstream, Uz5, at 4390 m (Figure 2, Table 5). The discharge input for Fz0 was calculated from the weighted NAM output for subcatchment Fz.

b. *Cross-sections*

Cross-sections (x-s) are required at certain levels across the river. The interval between x-s has to be adequately small to the model to resolve the longitudinal variations in the x-s shape and elevation. Conversely, the distance may become too small from a practical point of view since the computational time required to run the model for a particular period of time is inversely proportional to the square of the distance between x-s. The following aspects were considered when we selected locations for extraction of x-s:

(i) Representation of the river morphology as much as possible, factoring in areas with energy loss, subject to the geometry of the river: size of the cross-section, shape of the river, the gradient of the river, etc.

(ii) Potential pollution sources and sites.

c. Boundary conditions

The model requires inflow boundary conditions at the upstream end of the branch as well as lateral inflows from the significant tributaries and direct rainfall-runoff. All these inflows are obtained from the NAM sub-model.

d. Resistance number

HD module requires resistance numbers in terms of Manning's number (*n*) to be specified for the model as a global value or as local values for sub-reaches. Additionally, Manning's *n* can be specified to change with water level. Manning's n, determined as part of the calibration process, is a valuation of bed roughness, losses associated with channel form (expansions and contractions), rapids, etc. River Sosiani's HD model was calibrated by adjusting *n*, to reduce the discrepancy between measured and simulated values.

4. Model Simulation and calibration

Model calibration is the tuning of model parameters within acceptable limits to ensure that simulated results compare favourably against observed data. Model calibration was performed for both NAM and HD modules.

4.1 NAM module

For NAM model calibration, observed discharge data at the catchment outlet Uz5 for 1965 – 1968 was used (Figure 5). Table 3 shows the NAM model parameters after calibration. The model efficiency was 0.75.

4.2 HD module

After creating the simulation file, period, time and type of initial conditions for simulation were set. The initial conditions were taken from the created HD parameters. Δt of 30 seconds and Δx of 100 m were found to be optimal time step and computational distance for the courant condition.

Measured discharge data for 1983 – 1984 and 1984 – 1985 were used for HD model calibration and validation, respectively (Figure 6). Manning roughness values used in the model calibration and the model efficiency at specific boundary sites are given in Table 5.

5. Conclusion and Recommendation

The objective of the research was to develop a hydrodynamic model for River Sosiani as water management tool. The developed model was able to simulate the flow in the catchment with mean model efficiency value of 0.75, and RMSE of 0.05 m^3s^{-1}. There is tendency, however, for the model to overestimate and underestimate very high & very low flows, respectively. Many factors can affect the results, especially if the data sources are inaccurate or incomplete. The amount of stream geometry data can become very substantial as the size of the stream network increases. WETSPRO analysis results indicate that most of the flow in the river during dry season is recharged by baseflow, while there is substantial amount quick flow during wet season, especially in the urban zone. It is recommended that monitoring stations be set up at the identified sites: Fz0 (775957, 49398); Az1.0el (766728, 50441); Uz1.1 (755087, 55495); Uz5 (746706, 60843) to collect more data for future model calibration and validation. This model can in future be used as a core module for River Sosiani's water quality model.

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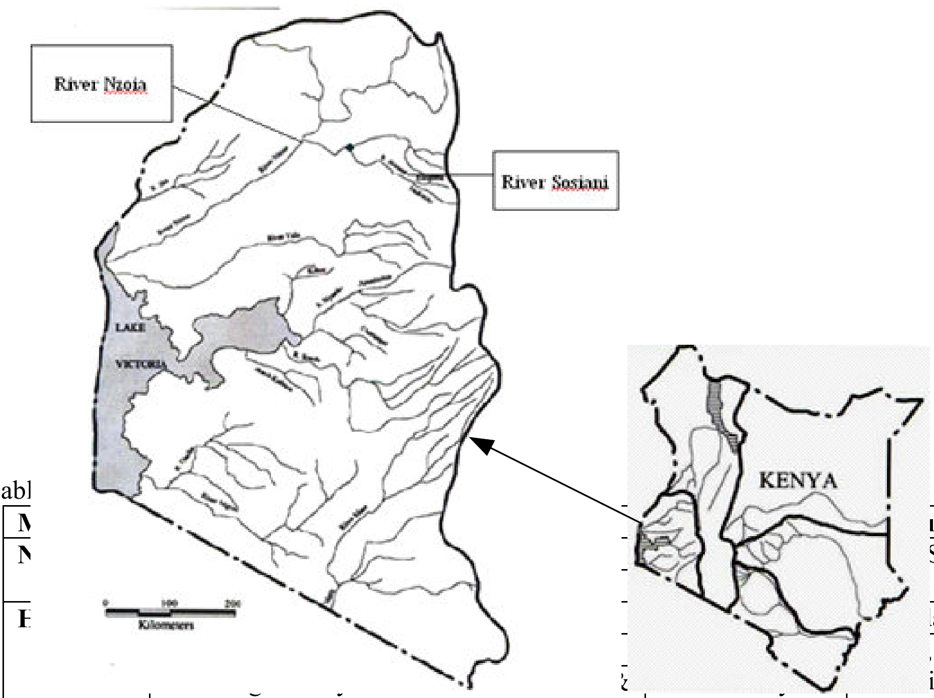
Table 1. River Sosiani's catchment characteristics

S. No	Parameters	Unit	Value
1	Basin length	km	34
2	Area	Sq km	225
3	Perimeter	km	88
4	River length	km	44
5	Fz	Sq km	33
6	Az	Sq km	110
7	Uz	Sq km	82



Tabl

M			ıt
N			Sosiani's discharge (*Q*)
F			ary conditions
	altitude (gradient) **a**	**b**	, used as boundary ion at Fz0, Az2en & Uz5

MD* Meteorological department, Kenya government

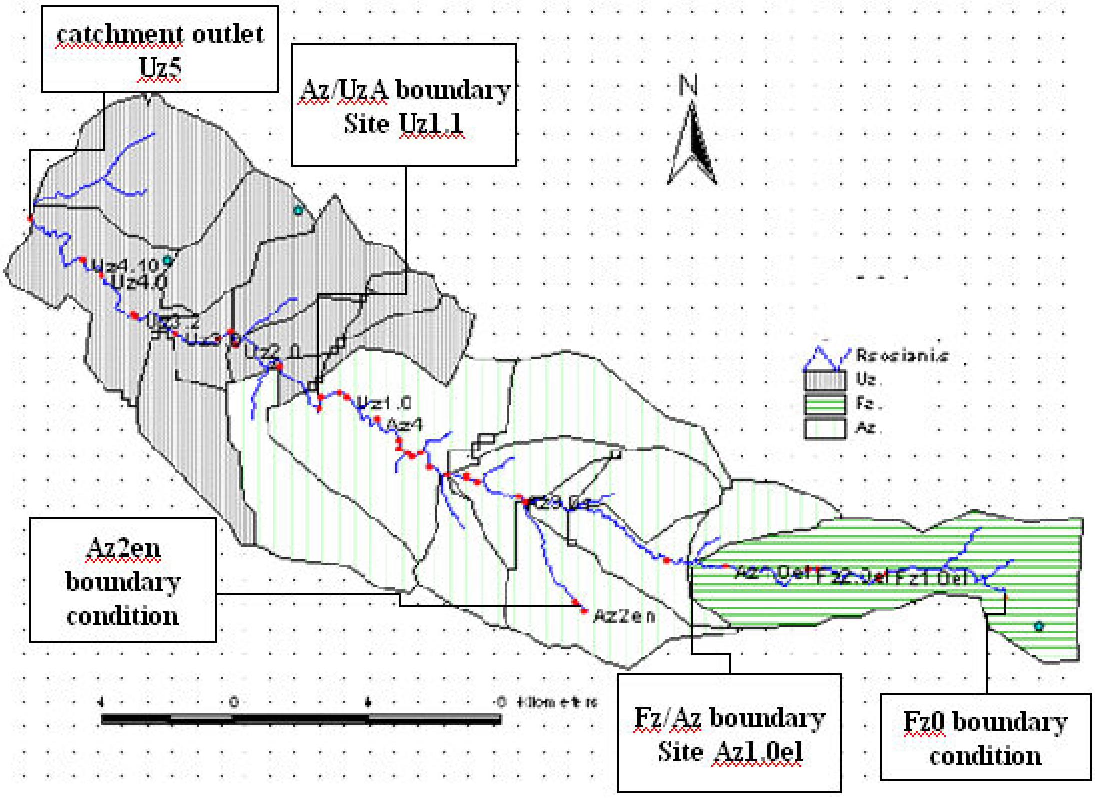


Figure 2. River Sosiani's catchment according to land-use with sampling calibration sites

Table 3. NAM model parameters after calibration

Parameter	**Unit**	**Value**
Area of catchment	km^2	225
Max. water content surface zone	mm	20
Max. water content root zone	mm	200
CQOF	dimensionless	0.3
Time constant routing QIF	hr	700
Time constant routing QOF	hr	20
Root zone threshold value for QIF	dimensionless	0.1

Table 4: Subflow Filtering Parameters

Filter Parameter	Baseflow	Interflow	Overland Flow
Constant term (m^3/s)	0	-	-
Initial flow value (m^3/s)	1.5	1	-
Number of filter steps	1	1	-
Recession constant, *k*, (days)	80	10	1
w-parameter filter [-]	0.5	0.4	-

Table 5. HD model parameters and efficiency after calibration

Site	**Coordinates (UTM)**	**Chainage (m)**	***n***	**RMSE m^{3}s^{-1}**	**EF**
Fz0	775957, 49398	0	0.035	0.048	0.670
Az1.0el	766728, 50441	12231	0.039	0.078	0.750
Uz1.1	755087, 55495	29570	0.043	0.083	0.813
Uz5	746706, 60843	43905	0.039	0.093	0.745

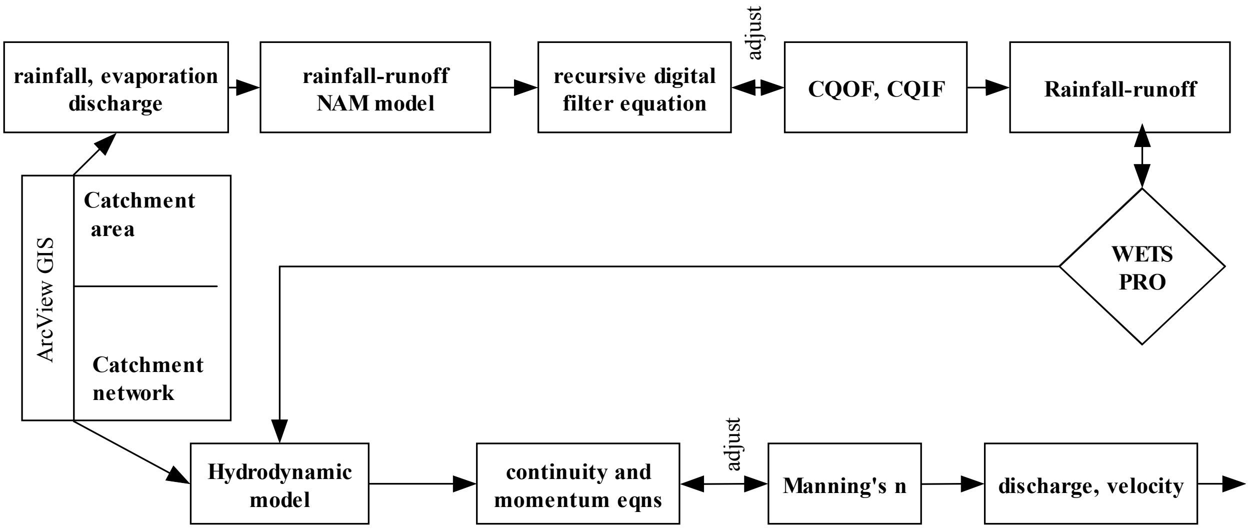


Figure 3. Study flow diagram

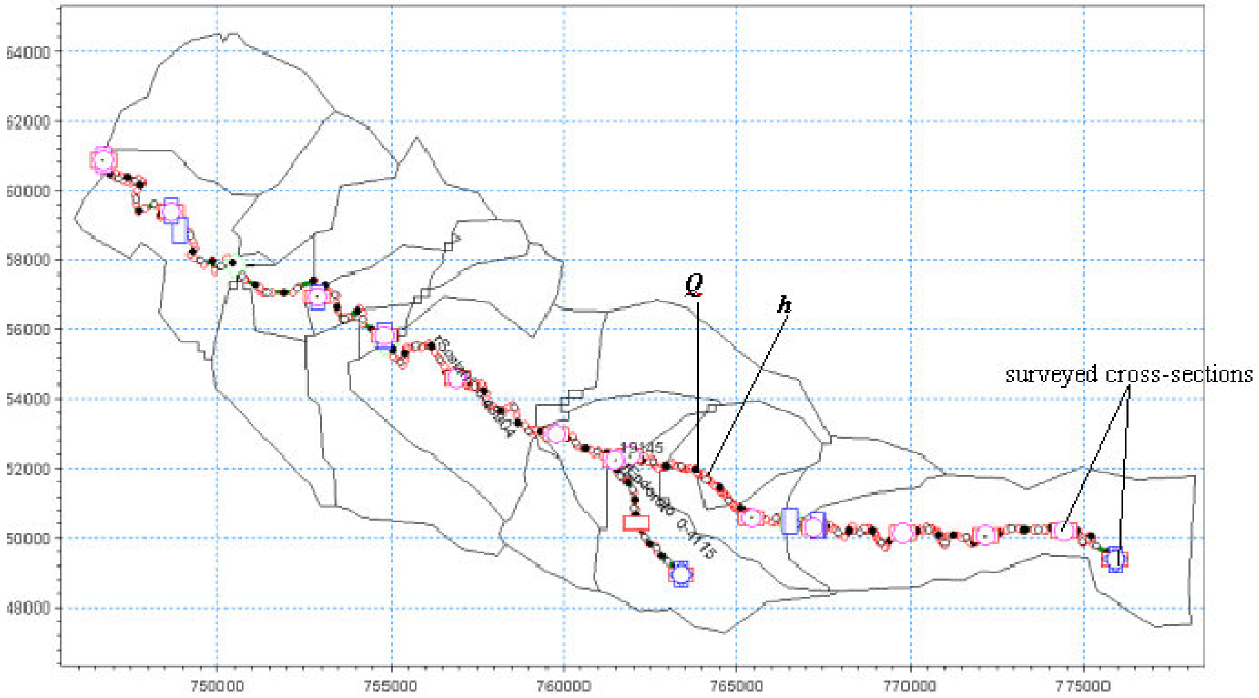


Figure 4. River Sosiani's cross-sections and calculation nodes

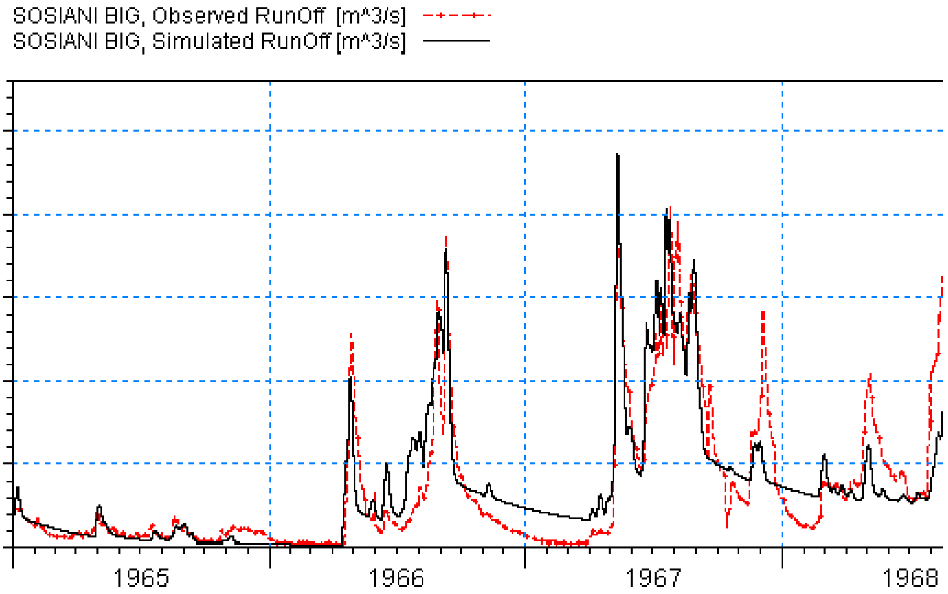


Figure 5. NAM simulated and observed rainfall runoff

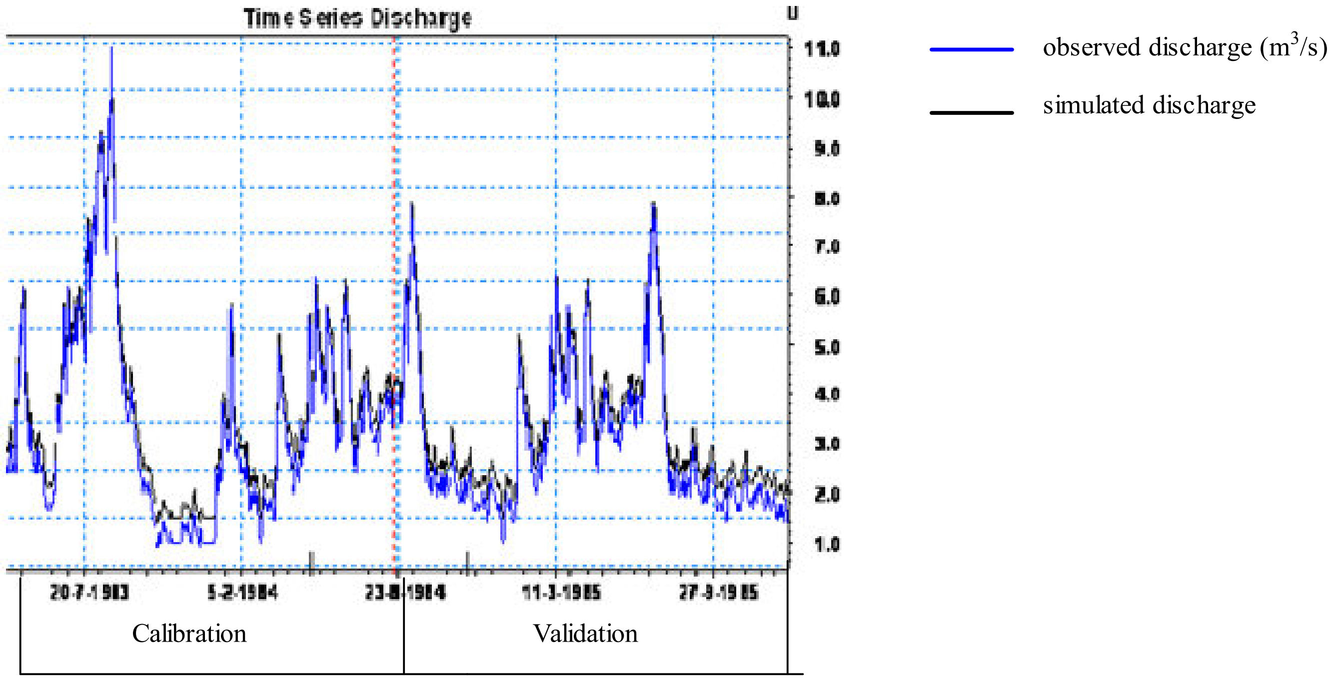


Figure 6. HD simulation for discharge after calibration and validation at Uz5

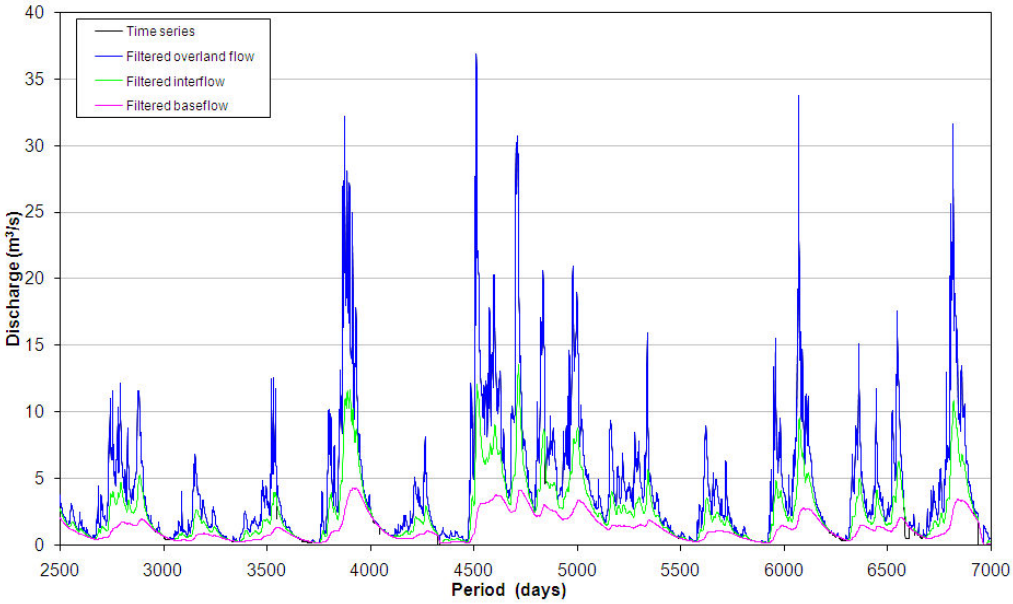


Figure 7: Filtered subflow at the catchment outlet

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