



The Influence of Dam Construction on the Catchment Hydrologic Behavior and its Effects on a Discharge Forecast in Hydrological Models

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Abstract

The hydrological properties of a river basin are extremely affected by the construction of a dam. The discharges and sediment flow distribution, in a modified river basin will not be the same as to a natural catchment. Hydrological models contextually focus on a natural river basin without any modification. Unfortunately, most of the river basins have been under such modification, which is not favorable for a model simulation at a normal condition. This research was done at the Awash River Basin, already modified because of dam construction. A systematic approach was applied to handle the modification in the basin, through an application of the Soil and Water Assessment Tool (SWAT) and Hydrologic Engineering center's River Analysis System (HEC-RAS) consecutively. SWAT model was implemented to simulate the upstream part of the basin. At the downstream parts of the basin, a simulation process was difficult on a SWAT model, due to the modified hydrologic parameters. Hence, the HEC-RAS model was applied because of its applicability under such circumstances. The model outputs indicate that the SWAT model can simulate the upstream part of the basin, in a good performance range that can be used for practical implementation. The downstream i.e., the modified catchment was simulated relatively better in the HEC-RAS model with good accuracy. Also, this research pointed out that a combined hydrologic and hydraulic model system development can be the best solution for modified catchments.

Keywords Hydrologic behavior · Modified basins · Flow discharge · Awash River · SWAT · HEC-RAS

1 Introduction and Rationale

Hydrologic studies via simulation models are common in recent days. Flow discharge in a river can be predicted through an application of a river basin or hydrodynamic model. A good understanding of a catchment property and the existence of hydraulic structures

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such as dams are the main requirements for a discharge prediction and forecast (Peel & Blöschl, 2011). The construction of a dam induces a certain modification (Thirel et al., 2015) on a flow discharge and sediment dynamics in the river basin. It significantly affects the base and peak flow component of the hydrograph, based on the purposes and operation of a dam. The flow characteristics downstream of a dam were no more governed by the rainfall pattern in a basin, but it will be regulated through the operation of a dam (Schaeffli et al., 2005).

River basin hydrologic characteristics downstream of the dam are significantly influenced by the construction of a hydraulic structure. The effect depends on the purposes and operation of a dam. The purposes in some cases may be, withdraw water from a system or store for a while, which all contribute to a change in a natural water flow pattern in rivers. A model such as SWAT needs a good understanding of a model background, before application on the river basins. The rainfall-runoff modeling in the SWAT model focus on rainfall and other hydrologic properties in the entire basin (Arnold et al., 2011; Neitsch et al., 2011). Currently, most of the river basins in the actual world, have a dam in one or more sites. Therefore, this circumstance will change the catchment hydrology, particularly, the base flow, peak flow, and the variation on a flow discharge upstream and downstream of a dam.

Currently, a hydrologic model such as SWAT does not have a direct application system to simulate a modified hydrologic characteristic in river basins. Practical these days, most of the river basins had some modifications to the natural basin due to the development works. The modifications may not affect the upstream part of the basin significantly, which may allow an application of a catchment-based model as per model background conventions (Neitsch et al., 2011). The simulation models need to be improved to consider modified catchment cases, as a result of hydraulic structures construction. The improvement requires categorizing a basin as upstream and downstream, because of a change in the hydrologic behaviors. Such an approach has the benefit to implement the usual rainfall-runoff processes at upstream basins and modified hydrologic behavior case at the downstream basin. The simulation models at the downstream basin need to have the capability, to consider the changes in the hydrologic property due to the effect of the dam and the component of the lateral flow from the rainfall.

The SWAT model is recognized to be functional in most parts of the world (Cao et al., 2006; Keshta et al., 2009). To increase its applicability and accuracy in the modified catchments as a result of the hydraulic structure such as a dam (Kirchner, 2006; Thirel et al., 2015), it needs additional system development in the simulation process. The simulation processes on a modified catchment have two components that must be addressed. Outflow from a dam is the first, which is a modified flow at a downstream section. The second is the lateral flow due to the direct rainfall on the downstream catchment. The SWAT model can consider the lateral flow from a catchment on usual modeling processes. Nonetheless, there was no system on the model to supply modified inflow discharges, for discharge estimation at downstream reaches. The usual model outputs need to be adjusted as per a change on an outflow of a dam if there is an interest to estimate model outputs, further downstream locations. Besides, during a calibration process, the parameters selection process needs to consider such changes, which are not endorsed under normal conditions. To handle such changes in a model simulation, an optional suggestion is the development of a system that performs simulation tasks, at a sub-basins level at an initial stage separately. Later, a linking system for a simulation output to the next sub-basin, both for the outflow of a dam and the usual rainfall-runoff processes at a downstream basin.

This research aims to model flow discharge changes due to the construction of hydraulic structures such as a dam. A separate simulation for a river basin model and hydrodynamic model was executed in the study basin. SWAT model was applied at the upstream catchment of the Koka Dam. The basin below the dam site was not good for the SWAT model exploitation, due to the modification of the flow properties. HEC-RAS model (Brunner, 2016), which can handle the modified flow discharge was used in the downstream section. The approach has a drawback in considering the lateral flows but still works with some limitations. The research is important in its application on river basins, which are already modified, due to the construction of the dam. The main focus of this research was to reflect, the weakness of river basin models for an application to a modified hydrologic property, and to demonstrate an approach that can handle such modification on the simulation processes. Most research works undermine this effect because of the complication which it will impose on the simulation process while considering it in practice.

2 Study Catchment

The Awash river basin is located in an indispensable part of Ethiopia. The sources of the river are the central highlands of Ethiopia and it drains to the valleys in the Afar region. The river remains in a part of Ethiopia in sands on a desert. Awash River basin is the most important and useful basin, which significantly contributes to the development of Ethiopia. Currently, the basin needs due consideration on the development works as it is being over-exploited. It can be a source of dispute among the peoples in the regions, due to a shortage of water in the basin. The basin is located at $8^{\circ}16'$ and $9^{\circ}18'$ N and $37^{\circ}57'$ and $39^{\circ}17'$ E, latitudes and longitudes, respectively (Fig. 1). The river basin population was more than 18.6 million.

3 Methodology and Materials

Hydrologic models do not consider the catchment properties alteration in the basins due to the construction of dams. The reason behind was the complexity and unavailability of the model which consider such condition in the simulation process directly. The hydrological properties of a river basin are complex even before a modification due to human interactions (Musy & Higy, 2011). It was one of the challenges on a current physical-based model, which mostly applied to simplified cases without considering such complications. However, for a river reach with dam construction, the flow discharge at the upstream and downstream of the dam shows a significant variation (Fig. 2). It is not possible to ignore such noticeable incidence on the modeling effort, for a better and accurate estimation of the flow discharges at the furthest downstream parts of a river basin.

The discharge variation in a hydrograph (Fig. 2), at an upstream and downstream station has a usual hydrologic property of a dam outflow. Peak discharges are lowered and the baseflows are higher for the downstream section of a dam. The reverse is sought at an upstream section of a dam unless some extreme rainfall events were observed. The discharge variation in hydrological modeling has to reflect a similar predisposition. It has not to be similar necessarily. However, a variation in peak and base flows has to show a similar trend on the hydrographs. In Fig. 2 the base flow component was changed to a higher level due to the effect of the dam operation downstream. Discharge hydrographs at an upstream

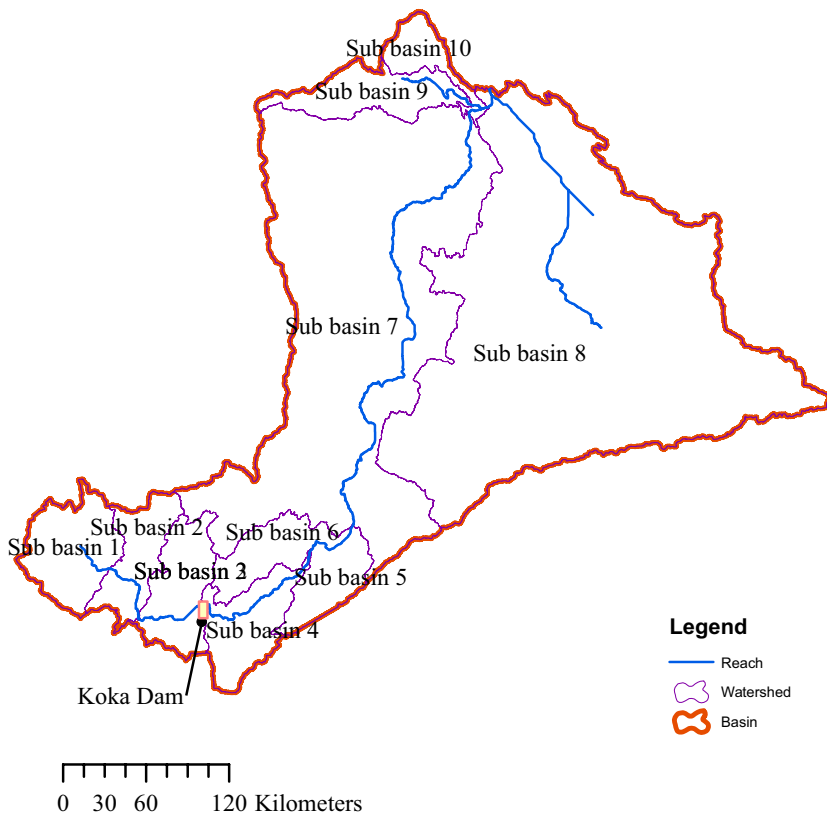
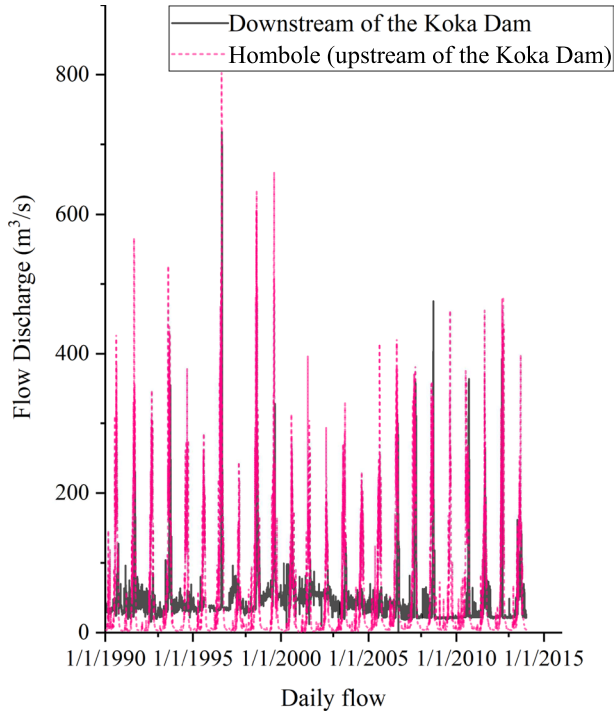


Fig. 1 Study area map, Awash River Basin

of a dam have to reflect the same variation as downstream for hydrologic model applications, such as SWAT. It is an important criterion that will support the parameter selection, calibration, and validation processes in a hydrologic model (Duan et al., 2003). Otherwise, if a model simulation was carried out on a river basin with such change, the calibration processes were difficult and a parameter was going to be selected wrongly, to fit the observed and simulated data forcibly.

An optional approach to simulate the change in a hydrologic behavior can be made through an application of a river basin and hydrodynamic models in common. The selection of such a model can be based on their capabilities to simulate such conditions in an integrated way (Fig. 3). A model background awareness is important for the systematic management of such problems. The SWAT model was applied at an entire basin to simulate the flow discharges. The model was working well at an upstream part of a catchment. However, a downstream part i.e., below a dam was challenging and not good during a calibration and validation process. Therefore, to handle such a problem, the HEC-RAS model was applied at a downstream part of a river basin. An isolated modeling approach

Fig. 2 Flow discharge comparison at the upstream and downstream stations of the Koka Dam



at an upstream and downstream part of a river basin was relatively good in considering the actual event and those variations.

3.1 River Basin Model and its Application on the Study

SWAT model can be used to study the water balance, flow discharge, and sediment yield from the river basins. The model uses DEM, land use/land cover, soil, and agricultural practice in the study areas, as an input to simulate the aforementioned processes. Discretization of a river basin area to an apt sub-basin and further to a hydrologically similar response unit (hru) (Gurtz et al., 1999) is an important procedure in a model setup procedure. A model uses rainfall, temperature, relative humidity, wind, and solar radiation as input to simulate the runoff. The model uses the rainfall-runoff relation as a base, to predict the sediment and pollutant transport in the simulation process.

Discharges and sediment flow studies can be made through an application of a SWAT model. The model uses the hydrologic routing method for the simulation of the hydrologic process. The water balance equation was as follows:

$$SW_t = SW_o + \sum_{i=1}^t (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \tag{1}$$

where SW_t = Water content on day t, (final) (mm), SW_0 = Water content on day I, (initial) (mm), R_{day} = precipitation on day i (mm), Q_{surf} = Surface runoff on day i (mm),

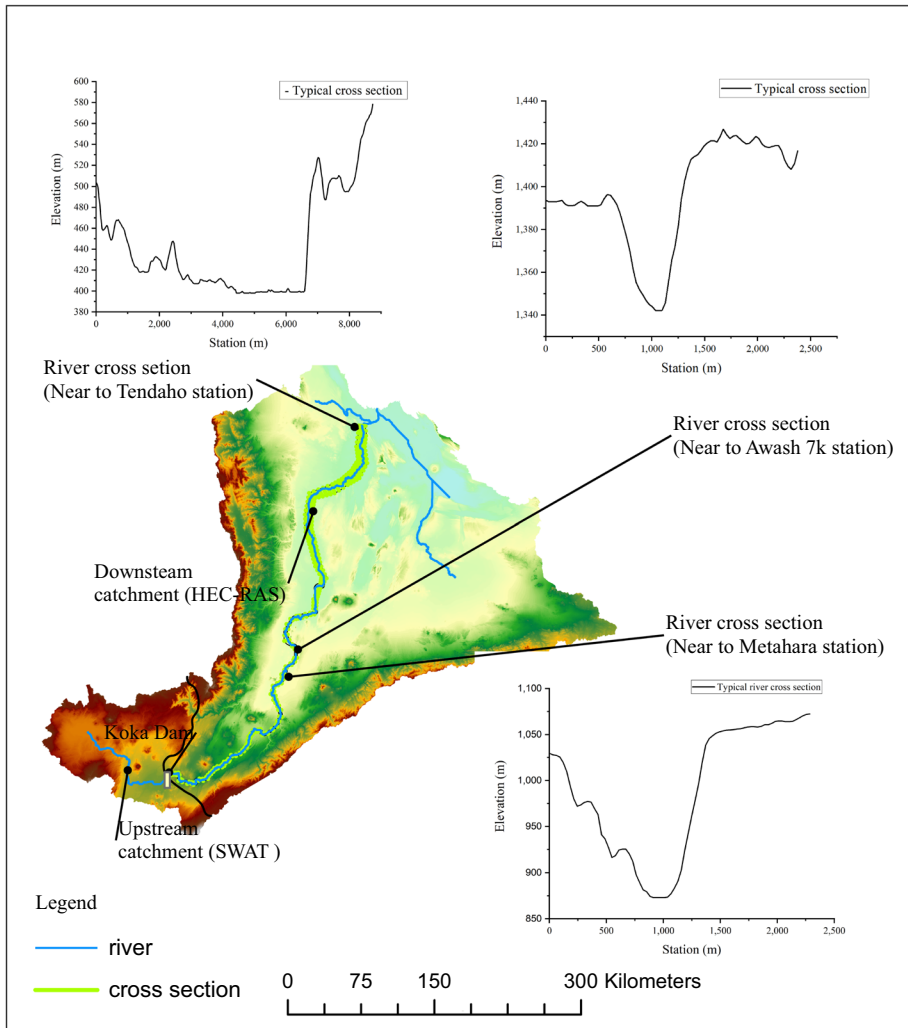


Fig. 3 A systematic application of simulation models under modified hydrologic properties

E_a = evapotranspiration on day i (mm), W_{seep} = water entering the vadose zone from the soil profile on day i (mm), and Q_{gw} = groundwater return flow on day i (mm).

Data for the simulation process was collected from different sources. The weather data were collected from the Ethiopian metrological Agency. The flow discharge data were collected from the Ethiopian Ministry of Water, Irrigation, and Energy. Discharge data are important for the calibration and validation of both, the hydrodynamic and river basin models. DEM data was collected from the SRTM database with the resolution of 30 m by 30 m. Land use and soil data were collected from the FAO database (Fig. 4a) (<http://maps.elie.ucl.ac.be/CCI/viewer/download.php>).

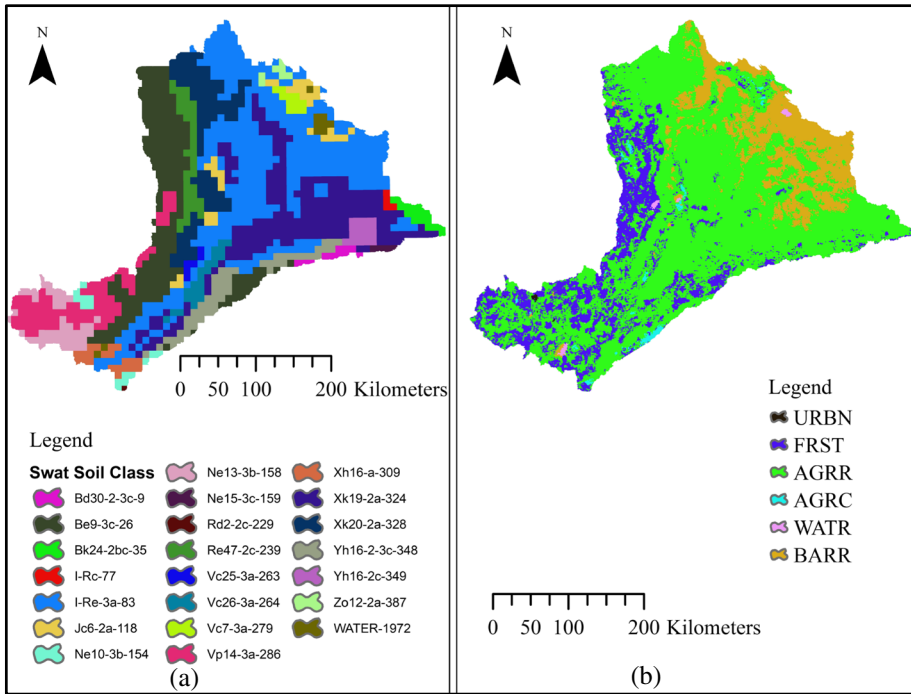


Fig. 4 a Soil data b Land use/Landcover for the SWAT model

3.2 Hydrodynamic Model and its Setup for the Current Study

HEC-RAS is a one and two-dimensional model which can solve steady and unsteady flows in natural and artificial constructed channels (Brunner, 2016). The code of the model was prepared by the U.S. Army. The layout of a river network, cross-sectional property, stream junction, and hydraulic structures data are the main inputs for a simulation process. Several model outputs can be extracted from the simulation processes. Some of the outputs are water level, discharge, velocity, flood area, etc. These outputs will be used for model effectiveness evaluation with comparison to a measured value at the location of interest. Therefore, a simulation output location is an important criterion at an initial model setup. Under normal conditions, cross-sectional information needs to be supplied at a 6 km range. However, if there are any cross-sectional property changes, such as shape, slope, or roughness a smaller distance is preferable for a good simulation.

Boundary conditions are a major requirement for any hydrodynamic model. In most hydrodynamic models a discharge, water levels or both can be supplied for an upstream boundary condition. The downstream boundary is the initial water level. The profiles of the water levels at each cross-section will be calculated from discharge data. The steady-state modeling can be applied to calculate the initial water surface profile in the HEC-RAS model. Energy equations for a one-dimensional model were solved using the backward standard method, for the water surface computation (USACE, 1990).

The governing equation in the HEC-RAS model is continuity and momentum equations as any of the 1-D models.

$$\frac{\partial A}{\partial t} + \frac{\partial S}{\partial t} + \frac{\partial Q}{\partial x} - q_1 = 0 \quad (2)$$

where x = distance along the channel, t = time, Q = flow, A = cross-sectional area, S = storage from non-conveying portions of cross-section, q_1 = lateral inflow per unit distance.

HEC-RAS was made easier for practical application through integration with GIS technology (Vieux, 2001), (Bedient & Huber, 2002), for extracting an important input variable for a simulation process. The alignment and cross-sectional properties are the main input for a simulation process. These input data were extracted from the 30 m resolution DEM through the application of a method specified in the HEC-GeoRAS manual (Cameron & Ackerman, 2012). River alignment and typical cross-sections that were extracted from DEM for a study basin were shown in Fig. 3.

4 Model Calibration and Performance Evaluation

Calibration is a process that requires a fine-tuning of influential model parameters, to find the best performance in a simulation process. It depends on the selection of the most relevant parameters of a model. Validation is a subsequent process which evaluates an agreement between an observed and simulated data sets, without any change in the model parameters, yet for different data period from a calibration process. The calibration and validation process can be made either automatic or manual. The manual process somewhat challenging due to an intensive trial requirement (Balascio et al., 1998, Fencia et al., 2007). SWAT-CUP was an automatic calibration and validation tool for the SWAT model. This tool can be used for uncertainty analysis and parameter selection (Abbaspour et al., 2007). There are different optional calibration and validation algorithms in SWAT-CUP tools. The SUFI-2 algorithm was applied for the calibration and validation process in this research (Abbaspour 2015).

Calibration of a hydrodynamic model can be done through an adjustment of a channel bed roughness values. The channel bed roughness can be calculated from a discharge measurement at different river reaches. However, such a method is not preferable due to difficulty in labor intensiveness and tedious work. The optional method is using similar researches and literature to fix the initial bed roughness values (USACE, 2001; Phillips & Tadayon, 2006), then further adjustment can be made based on the fitness of data between an observed and simulated dataset. The same approach was adopted in this research, an initial bed roughness was estimated from literature and further adjustment was performed based on the best calibration fit on simulated and observed data.

Model performance can be evaluated using well-recognized methods in hydrological simulation (Moriasi et al., 2007). The goodness to fit simulated and observed data in a modeling process was a major evaluation criterion. The coefficient of determination (R^2), Nash Sutcliffe efficiency (NSE) (Nash & Sutcliffe, 1970) and the percent bias (PBIAS) are the well-known indicators, for a model performance evaluation. The amount of discrepancy in observed data can be described through R^2 in model output. The PBIAS evaluates the tendency of variation in observed data, from an average, as a lower or higher value (Gupta et al., 1999). Table 1 shows NSE, PBIAS, and R^2 computation formulas and ranges for a model performance evaluation.

Where \bar{O}_m and \bar{S}_s are the mean of the observed and simulated time series, respectively, and $O_{i,m}$, $S_{i,s}$ are the observed and simulated variables, respectively.

Table 1 Model performance indicators and formulas

Performance indicator	Constituent	Performance status			
		unsatisfactory	satisfactory	Good	Very good
$NSE = 1 - \frac{\sum_{i=1}^N (O_{i,m} - S_{i,s})^2}{\sum_{i=1}^N (O_{i,m} - \bar{S}_m)^2} \quad (3)$	all	< 0.5	0.5-0.6	0.6-0.7	0.7-1.0
$\frac{\sum_{i=1}^N (O_{i,m} - \bar{O}_m) \cdot (S_{i,s} - \bar{S}_s)}{\sqrt{\sum_{i=1}^N (O_{i,m} - \bar{O}_m)^2 \cdot \sum_{i=1}^N (S_{i,s} - \bar{S}_s)^2}} \quad (4)$	all	< 0.5	0.5-0.65	0.65-0.75	0.75-1.0
$\pm PBIAS\% = \frac{\sum_{i=1}^N (O_{i,m} - S_{i,s})}{\sum_{i=1}^N O_{i,m}} * 100 \quad (5)$	Q ss	>25 >55	15-25 30-55	10-15 15-30	<10 <15

Q discharge, ss suspended sediment

5 Result and Discussion

The model outputs for the application of catchment modification, due to the hydraulic structure were discussed in the following sections. The approach tries to catch up on the real events in a simulation process. A separate section was arranged to discuss, the results of a river basin model (SWAT) and hydrodynamic model (HEC-RAS).

5.1 River Basin Model (SWAT)

SWAT model was used to simulate an entire basin, to test an application of a model with modified flow discharge due to dam construction. The model performance was good for an upstream part of the catchment.

Fig. 5 Flow discharge simulated vs observed (calibration at Melika Kunture station)

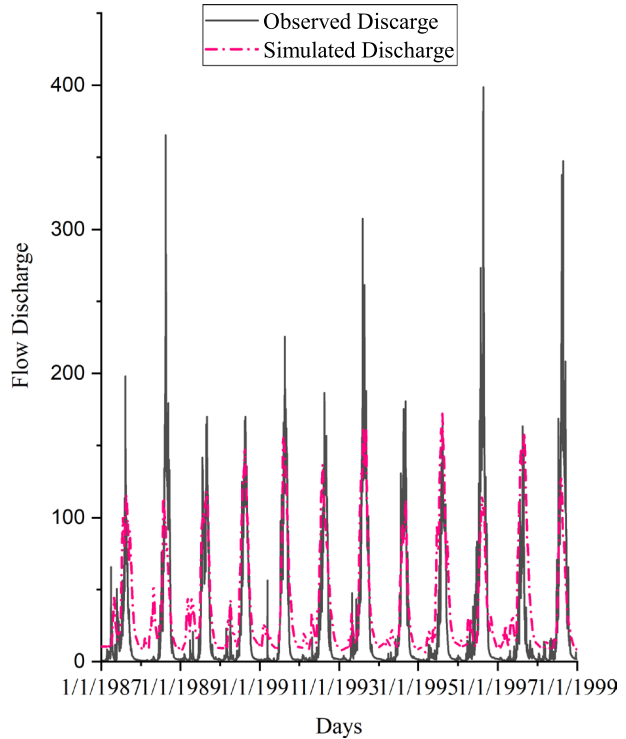
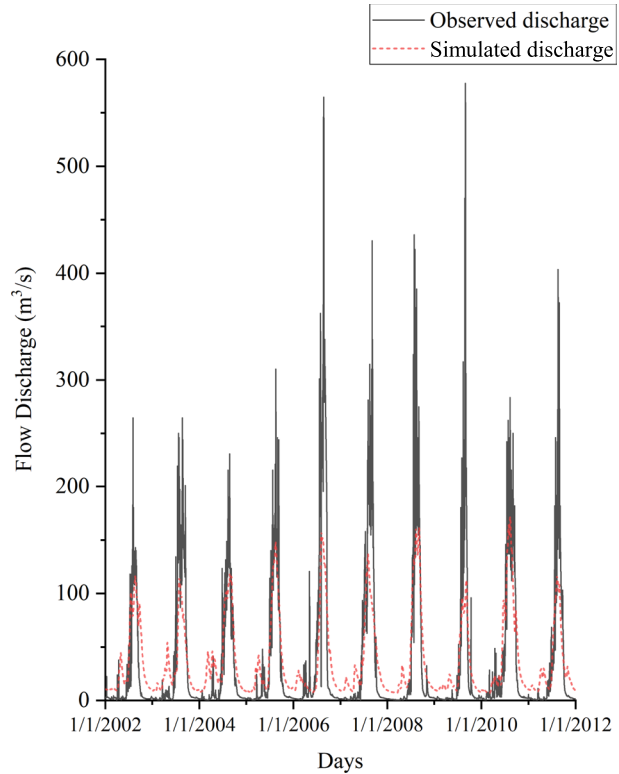


Fig. 6 Simulated vs observed flow discharge (Validation at Melika Kunture station)

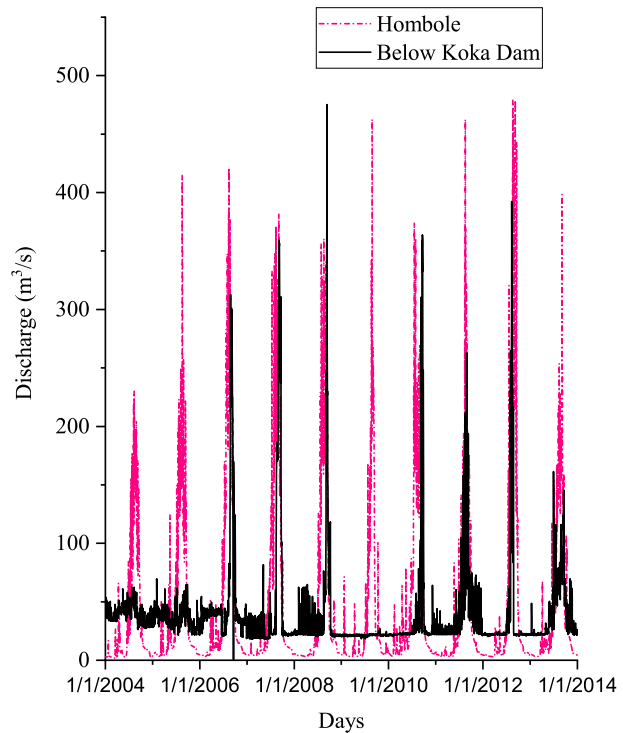


Discharge hydrographs comparison on Fig. 5 reflects that a performance of a model was good, for an overall condition, with R^2 and NSE values of 0.67 and 0.65, for a daily flow, respectively. Upon a careful evaluation of the hydrograph, peak simulated discharge results were not well fitted to an observed discharge. It is the model contextual background, which is stated in a manual (Neitsch et al., 2011), a model performs very well under long term hydrological studies (monthly or yearly) rather than a short term (daily).

Outputs from a validation process show a similar trend as a calibration, which was indicated with an R^2 value 0.63 and NSE values 0.62, for daily discharge, during a model performance evaluation. The model application is still valid for a long-term hydrologic study. The simulation results for a validation process were shown in Fig. 6.

Historical data at an upstream (Hombole) and downstream below a Koka dam station (Fig. 7) shows an obvious flow discharge variation due to dam existence. The peak flows are lowered and the base flows are inflated at a downstream section. Having such variation, it is not appropriate to evaluate a calibration and validation task in a model at a downstream catchment. It is an important indicator that provides valuable information to good simulations. Evaluation of the data sets for such changes before implementation of a SWAT model is an important precondition for good modeling. As it was thought, at a downstream part of a basin, the simulation result was not good because of a change in a hydrologic property. It is an important lesson that, sometimes it may be possible to calibrate such data sets forcibly, by choosing the wrong parameters (Klemes, 1986; Grayson et al., 1992). Therefore, calibration and validation have to be done with well understanding of

Fig. 7 Historical discharge data at an upstream (Hombole) and downstream station below a Koka Dam



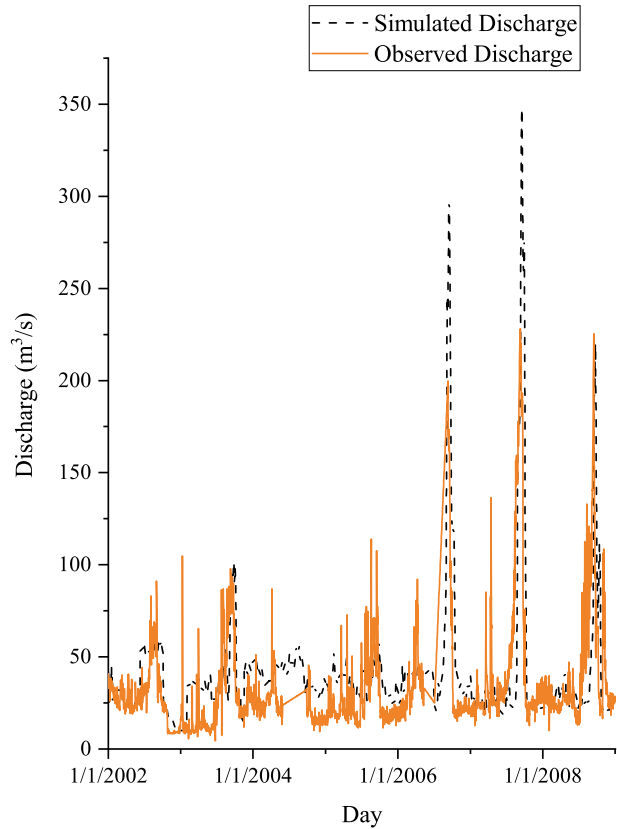
hydrologic processes and model background, for such events. Also, verification at another station beside a calibration and validation of the results is an important step, which grants an accuracy of simulation outputs, for practical works. Unfortunately, most of the time, because of the unavailability of data at most stations' verification was not performed on many hydrological studies.

5.2 Hydrodynamic Model (HEC-RAS)

The changes in the hydrologic properties such as peak flow, base flow, and flow pattern variation in the river basin, which results from human interaction on a natural basin, cannot be simulated on a model like SWAT under normal conditions. It needs a further systematic approach that can accommodate such changes. A one-dimensional model was applied to simulate a downstream part of a river basin with such changes. This is because of support from a background of a one-dimensional model, to handle such changes on the input and outputs data. Besides, the capability of a model to simulate a variability of flow discharges at a location of interest was a key consideration. The catchment below the dam needs to consider the outflow from the dam and the direct rainfall component which will contribute to the runoff at this part of the basin.

Results at Metahara station (Fig. 8), which is below a dam site, show a good relationship for an observed and simulated flow discharge. The R^2 and NSE value of 0.7 and 0.72 were a performance indicator for the model, for daily discharge, respectively. The performance evaluation of a model was in a good range, which can be used for a practical application in the study basin.

Fig. 8 Comparisons of an observed vs simulated discharge at Metahara station



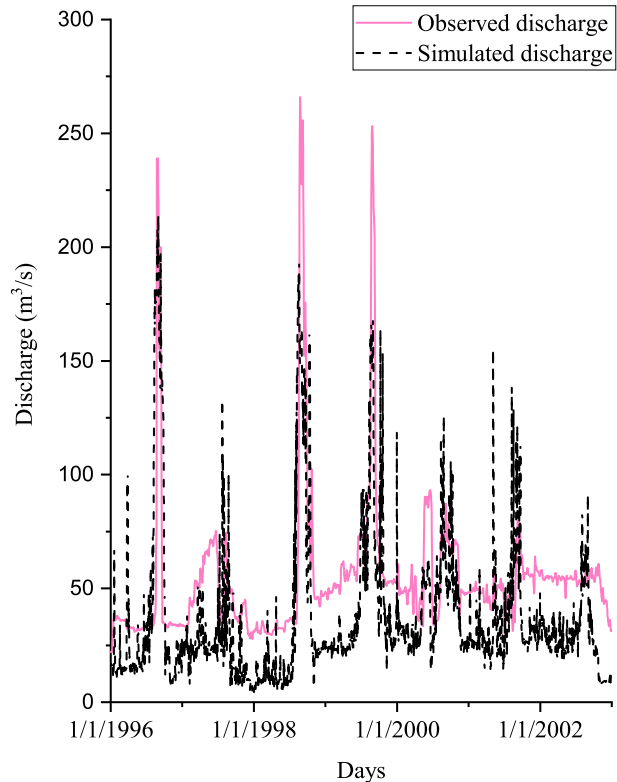
Further downstream the influence of lateral flows was affecting the discharge because the size of the catchment is increasing downstream. The flow trend on an observed and simulated discharge was similar, but the observed discharges were more than the simulated discharge as a result of the lateral flow as shown in Fig. 9. This discharge is a contribution from the rainfall on the downstream part of the basin. The SWAT model is stronger in considering such flows due to the model background which relies on the rainfall-runoff relationship.

The simulation outputs further at a downstream station indicates that a model to solve the modified hydrologic properties, requires a system capable to handle both, a modified flow from the dam outlets and a rainfall-runoff relationship simulation, independently. Catchment modification as a result of the construction of a dam was an important issue that needs due consideration in a practical environment. Simplification, while simulating physical events should not ignore such critical conditions. Most of the time, simulations were performed with a simplified model set up to ease the complication on mockup procedures and results.

6 Conclusion

Modified catchments hydrologic behaviors are common in most of the river basins. The simulation models were practiced without considering such conditions in most cases. Market available models do not have a direct application on such kinds of problems. The systematic study of the

Fig. 9 Simulated vs Observed daily flow at Tendaho station



model's background will assist in solving such problems with certain accuracy. An integrated model's approach such as SWAT and HEC-RAS is a good application, for a modified hydrologic characteristics cases, which can resolve the problem relatively with upright consideration of all the proceedings.

A modified catchment case requests an improved modeling approach that can simulate a rainfall-runoff process at an individual sub-basin level and a link to a modified flow discharges at a downstream basin. The model background studies provide information, how systematical such problems can be solved on a market available model. Each model has a good entitlement on solving a modified catchment hydrologic study. SWAT was good in considering rainfall and runoff relationships and lateral flows, while a one-dimensional model was favorite for managing a modified discharge.

The calibration of a model will not grant the effectiveness of a simulation task. In some cases, calibration can fit our data if it is forced without a full understanding of the effect of a parameter selection on a modeling process. Research results must not only rely on calibration and validation processes but also a catchment properties assessment has to be carried out before the selection of the best-fit parameters.

7 Recommendation

The SWAT model is well recognized in catchment-based hydrologic studies. The model needs a systematic improvement for implementation on a modified hydrologic behavior, due to the construction of dams. The models need an additional input system to provide a modified flow downstream of the dam, to accommodate a change in a natural river basin.

The simulation of a hydrologic behavior change in any catchment needs a hybrid modeling application. Currently, a model background learning demonstrates that a hydrologic model was good in considering the lateral flows. Whereas, the hydrodynamic models were able to consider the modified flow condition. Therefore, an integration of such models is good to solve the modified hydrological behaviors in the real world.

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Authors Contributions I have done all the work alone.

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Data Availability All the data sources were acknowledged and cited in the manuscript.

Declarations

Ethical Responsibilities The manuscript complies with all the ethical requirements, the paper was not submitted to any journal at a time. All the sources and contributors were acknowledged properly.

Consent to Participate I am very much to participate in the task for the journal including reviewing similar works.

Consent to Publish I have fully agreed to publish the manuscript “The influence of a dam construction on the catchment hydrologic behavior and its effects on a discharge forecast in hydrological models” after peer review on the journal of water resources management.

Conflict of Interest In this research paper, there is no conflict of interest.

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