ADDITIONAL THESIS

Assessing the change in the performance of a hydrological model post integrating reservoirs for Cauvery river basin, India

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1 Introduction

All ecosystem services of river are governed by flow regime (1). The different components of flow regime like topography, geology, and climatic variation contribute to different ecological processes (2). These ecosystems provide a wide range of direct and indirect benefits to a human being (3; 4). The ecosystem services such as hydropower, irrigation, drinking water supply, fisheries, breeding ground for aquatic wild life, sanctuary reserves form the lifeline of many stakeholders. All the water management decisions are based on certain hydrological informations. However, the hydrological information these decisions are based on are not precise and is a simplified version of the actual system.

Anthropogenic effects of human intervention on natural flow regime significantly disturbs the natural characteristics of the hydrological flow. Hydrological alterations of river flow regime while benefitting human development in many ways have damaged the delivery of ecosystem services. Growth in human population, decline in resources, everchanging climatic condition, led to an increase in demand of the resources.The situation is further complicated by multitude of water users and stakeholders with conflicting interests this requires the accurate assessment of the river flow regime taking into account the anthropogenic effects of human intervention in the riverine ecosystem.Reservoir construction is one of the major human intervention to the riverine ecosystem. Construction of reservoirs are usually associated with substantial impacts on river hydrology and surrounding ecosystem. As a result, dams have been constructed to meet the needs of irrigation and energy. These constructions affect the connectivity of the river and eventually changes the entire ecosystem. Topography based hydrological models simulates the response of the catchment due to the different hydrological response units(HRUs). These HRUs are natural and doesn't take into account anthropogenic factors into account. Therefore, the present study aims to understand the effects of the integration of reservoirs into a Flex-Topo model to assess the model performance in predicting the river flow regime which will help us answer our research question:

How does the integration of reservoirs into a Flex-Topo changes the model performance?

2 Study Area

The Cauvery basin extends over states of Tamil Nadu, Karnataka, Kerala, and union territory of Puducherry, draining an area of 81,155 km^2 , which is nearly 2.7 percent of the total geographical area of the country with a maximum length and width of about 560 km and 245 km. It lies between $75^o27'$ to $79^o54'$ east longitudes and $10^o9'$ to $13^o30'$ north latitudes. The length of the river is about 859 km, and the river basin is about 85262.23 km^2. The river drains into the Bay of Bengal. The basin constitutes of 3 sub-basins, namely Cauvery Upper, Cauvery Middle, and Cauvery Lower sub-basin. There are 132 watersheds, each of which represents a different tributary system with the maximum number of watersheds falling in the Cauvery Middle Sub-basin (See table 1).

Table 1: Dams and watersheds in the Cauvery basin

S.no.	Sub-basin	Area (Sq. Km.)	No. of watersheds	Dams
1	Cauvery Lower Sub-basin	17386.45	28	2
2	Cauvery Middle Sub-basin	57280.98	86	86
3	Cauver Upper Sub-basin	10958.80	18	9
	Total	85262.23	132	96

The primary uses of the Cauvery river is providing water for irrigation, water for household consumption and the generation of electricity(5). There are around 96 dams constructed on Cauvery basin from the year 1000 to 2007, out of which 70.30 percent dams are used for Irrigation purpose, 19.80 percent for hydro-power generation, 6.93 percent for both Irrigation and hydropower generation, and 2.97 percent dams are used only for drinking and water supply. However, for this study 4 reservoirs have been shortlisted in the Karnataka region of Cauvery basin (see figure 1)

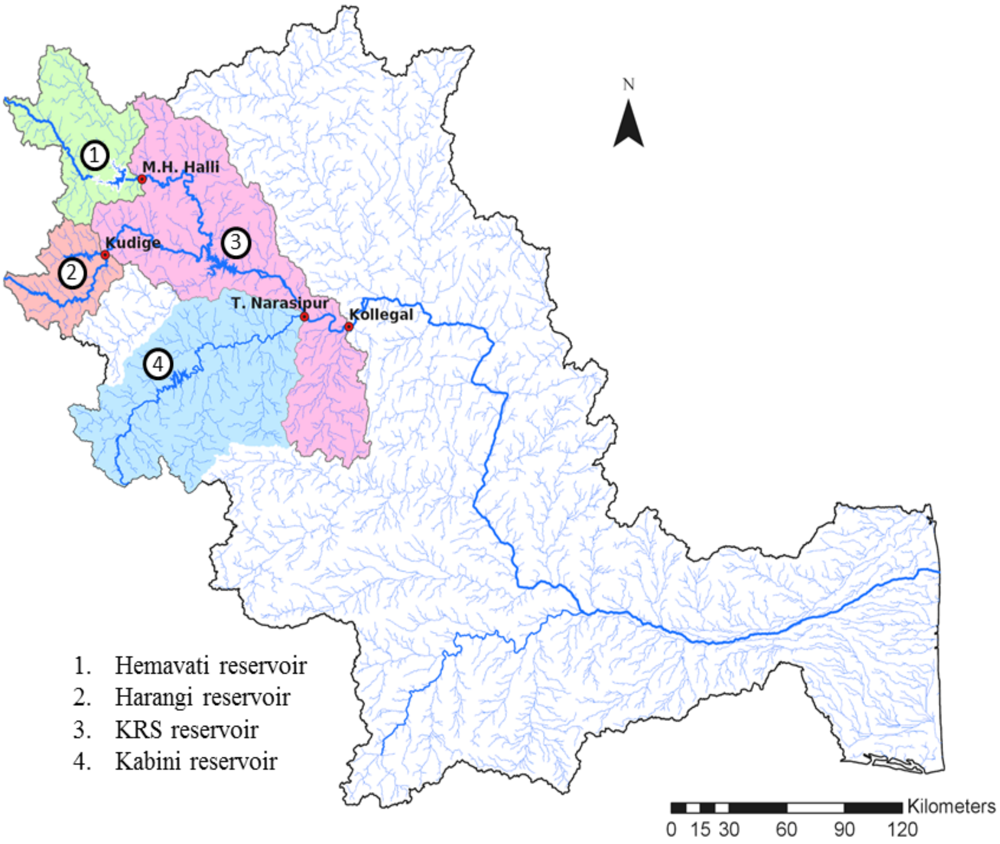


Figure 1: Details of sub-basin and reservoir location selected for study in Cauvery basin

3 Methodology

3.1 Data

The forcing data used for the study ranges from January 1979 to December 2013 and has been retrieved from Indian Meteorological Department, data product of National Climate Centre, Govt. of India and Central Water Commission India, Govt. of India. Data from January 1979 to December 2000 have been used for the calibration, leaving data from January 2001 to December 2013 for validation. For reservoir modelling data are limited to three years 2011-2013 and has been retrieved from the site of Karnataka State National Disaster Monitoring Centre, Govt. of India.

Due to limitation in the length of data the reservoirs have been assessed only for the calibration phase, they are then integrated into the Flex-Topo models and later the whole system of models have been assessed in calibration and validation phase.

3.2 Modelling

The modelling part consists of coming up with a reservoir model and then integrating it to the already existing Flex-Topo for the sub-basins.

3.2.1 Flex-Topo

The heterogeneity and complexity of hydrological processes makes it really difficult for modelers to imitate the hydrological responses. This leads to an introduction of further details in models or setting up of complicated models starting from the basic principles. This reductionist approach leads to higher levels of equifinality and further predictive uncertainty (6). Landscape based modelling helps in overcoming these complexities and also avoid oversimplification of the hydrological model. The landscape-based models are based on the dominant processes of the landscapes. The landscape classes are separated with topography as the main driver. The Flex-Topo model divides the landscape into different hydrological response units (HRUs). The classification has been made using the Height Above Nearest Drainage (HAND). The three HRUs identified for the different sub-basins are wetlands, plateaus, hillslopes. The modelled reservoirs are further added to take into account the anthropogenic effects to the response of the catchment. Each sub-basin is divided into two watersheds upstream and downstream with respect to the reservoir (figure 2). The outflow of the upstream watershed is an inflow to the reservoir and the outflow of the reservoir acts as an input to the downstream watershed. Finally, the outflow downstream of the sub-basin is the integrated model response.

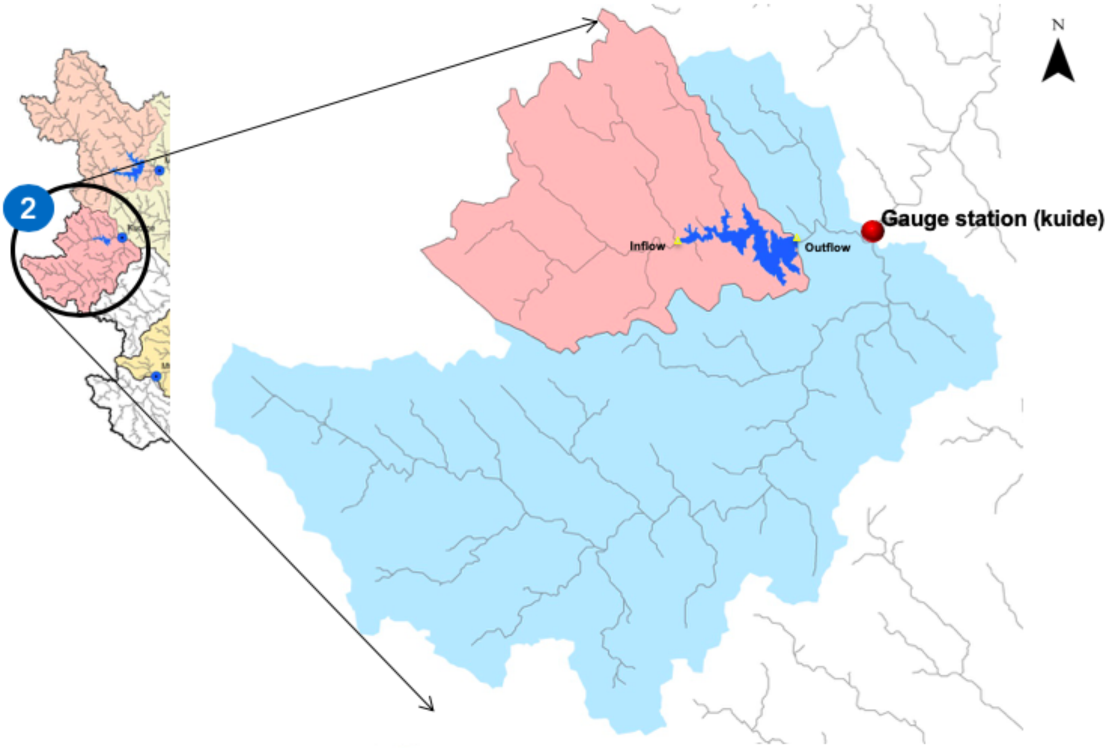


Figure 2: Kudige sub-basin divided into upstream catchment and downstream catchment w.r.t. Harangi reservoir.

3.2.2 Reservoir Modelling

Generally a reservoir is constructed to serve four purposes; irrigation, hydropower generation, flood control or drinking water supply. A reservoir can be constructed to serve one purpose or can be used for multi-purpose. All the four sub-basins in our study area consist of reservoirs. While three of them are used for irrigation, one reservoir serves the purpose of both irrigation as well as hydropower generation. Figure 3, illustrates the five storage zones of a usual multi-purpose reservoir in India.

Modelling a prototype of a system to analyze its behavior to different inputs are referred to as simulation modelling (Shanano, 2019). Simulation modelling have been extensively used in modelling reservoir behavior and analysis. Here, different reservoirs is modelled depending on the reservoir functions. Due to constraint in the reservoir information and functions, the dataset for

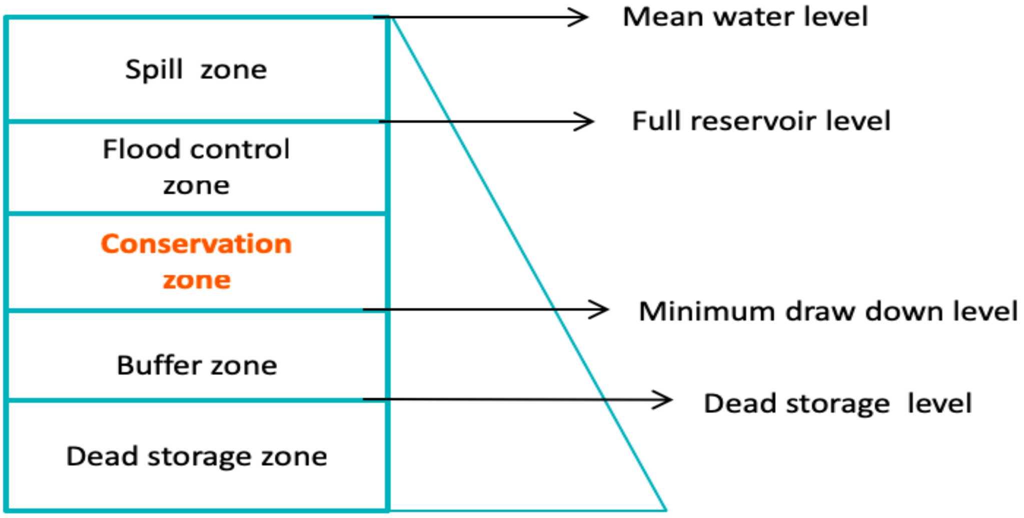


Figure 3: Reservoir storage allocation zones

reservoir modelling is limited to 3 years (2011-2013) with time steps of 1 day. Hence, only three years of data are used to calibrate the reservoir. The mass balance formula for each time step and for each reservoir used for modelling the reservoir is shown below:

$$St_{n+1} = max[0, St_n + In_n + Rain_n - Evap_n - Out_n - (L_n * Dem_n)] \tag{1}$$

where:

St_{n+1} = Storage at $n+1^{th}$ time step
In_n = Inflow at n^{th} time step
$Rain_n$ = Rain at n^{th} time step
$Evap_n$ = Evaporation at n^{th} time step
Out_n = Outflow at n^{th} time step

The reservoir operation is assumed to be based on the shortage rule curves, which defines zone within which specified proportion of the demand is met(7). Three operating rule curves for 100 percent demand supply, 80 percent demand supply and 50 percent demand supply is used here to get four operating zones. The operating rule curve is defined through a trigonometric function developed by Ndiritu&Sinha (2009)(8). Equation 2 shows the adopted equation for defining the operating rule curve:

$$L_{i,j} = t + (3-i)w + a(sin(2\pi(\frac{j}{365} - l))) \tag{2}$$

where:

$L_{i,j}$ = Operation curve i at j^{th} time step
t = Translational parameter
w = Width parameter
a = Amplitude parameter
l = Lag parameter

The operating rules assumed for the purpose of modelling are based on reservoir functions and which can be divided into two major types:

1. Irrigation

2. Hydro-power

Table 2 gives a rough idea of different types of reservoirs present in the basin and their primary functions.

Table 2: Reservoir specifications

Reservoir	Sub-basin	Catchment area (acres)	Gross storage (m^3)	Depletion period	Filling period	Purpose
Hemavathi	MH Halli	419.58	246356565.35	December-May	June - November	Irrigation
Harangi	Kudige	2810	1050639959.1	October-May	June - September	Irrigation
Krishna Sagar	Kollegal	10619	1400324697.67	October-May	June - September	Irrigation
Kabini	T Narasipur	2141.90	552744845.48	November - May	June - November	Hydropower

Irrigation: The reservoirs in the Kudige, MH Halli and Kollegal sub-basin serves the purpose of meeting irrigation demands. The four supply zones derived from the three operating rule curves serves as a metric to determine the extent to which demands are met all year round. The demand is calculated on a daily basis and depending on the state of the reservoir with respect to the three operating rule curves, generated after calibrating its parameters daily requirements are met.
The reservoir operating rules assumed are as follows:

- Flow threshold is considered to be the maximum of the three-year data.
- If the storage in the reservoir is in the 100 percent supply zone, the outflow from the reservoir is considered to be equal to the volume in excess of the 100 percent operating rule curve for that time step. However, constraints were put on the outflow which cannot be greater than the flow threshold for that particular reservoir.
- Modelling of the irrigation reservoir depends on the five parameters: t, w, a, l and st initial. "t" is the translational parameter, "a" refers to amplitude parameter, "w" is width parameter and "l" denotes lag parameter of the trigonometric function in equation 2 and "st initial" refers to the initial storage of the reservoir. Table 3 illustrates the range of these parameters.
- Depending on the state and position of the reservoir in the shortage rule curve the reservoir furnishes different levels of demand.

Table 3: Parameter range for Irrigation reservoir

Parameters	**Range**
t	0-1
w	0-0.5
a	0-1
l	0-1
st initial	Minimum storage - Maximum storage

Hydropower generation: The prerequisite for the reservoir serving the purpose of hydro-electricity generation is that it should maintain a particular level of water to provide minimum head for stipulated power generation. Hence, in order to simulate the reservoir outflow, the model needs to satisfy the requirement of minimum water level. Here the parameter "rl" (reference level) is used to make sure that the level of the water in the reservoir remains around this. Out of the four reservoir Kabini is the only reservoir serving the purpose of both hydroelectricity generation and irrigation.
The area capacity curve for the reservoir was found using least square fitting method. Area vary linearly with the capacity which is not a correct representation of the shape of the reservoir. However, for the simplicity of the project we will consider this as the area-capacity curve of the Kabini reservoir. Equation 3 below depicts the relation well:

$$Area_n = 0.0014 * Storage_n + 4711 \tag{3}$$

where:

$Area_n$ = Surface area of the reservoir at n^{th} time step
$Storage_n$ = Storage of the reservoir at n^{th} time step

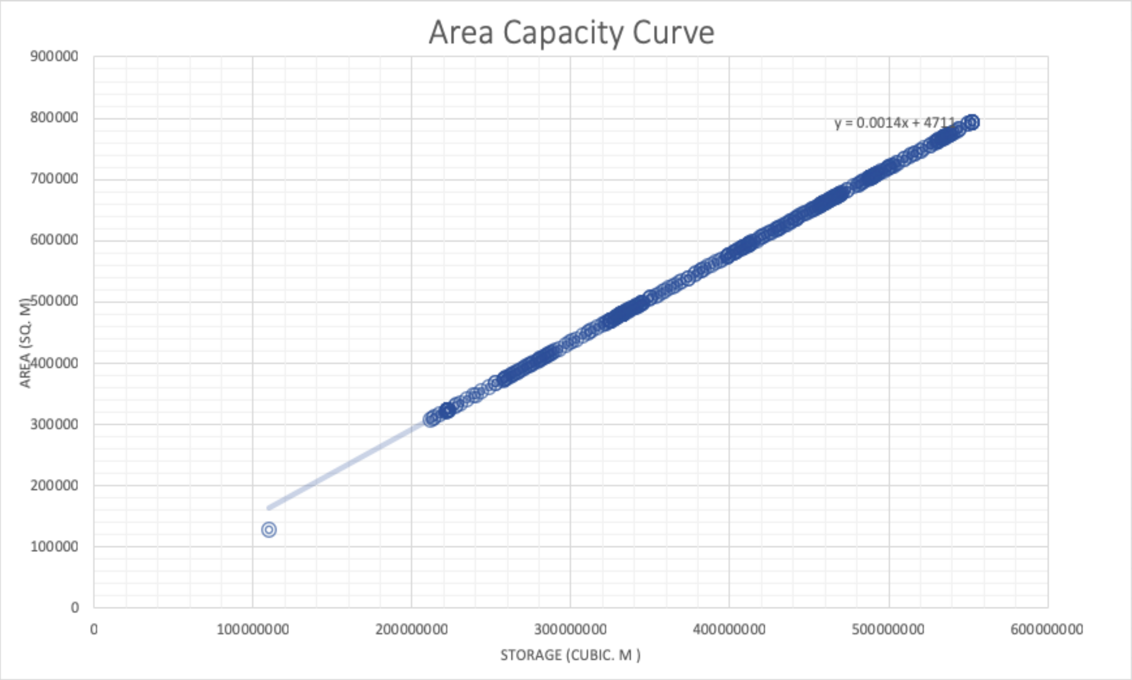


Figure 4: Area-capacity curve of the Kabini reservoir

Figure 4, shows the linear relation between area and the storage in the Kabini reservoir for the time space of the data. It is apparent that there is a linear relation in between area and the storage. However, we should be aware that the effects of sedimentation in the reservoir are usually not considered while coming up with storage readings in the reservoir. Which can impact the availability of water and hence, outflow from the reservoir over an extended time period.

A bunch of operating rules were used to simulate the reservoir:

- The level of water should not be above a reference level, if the level is above the calibrated reference level "rl", the amount in excess of the storage at the reference level becomes outflow.
- The outflow at any time should not be equal to the flow threshold which is the maximum outflow in the calibration data of three years.
- Storage threshold is calibrated, and it is made sure that if the reservoir storage is above the storage threshold all the inflow to the reservoir from the contributing areas are released downstream.
- For all the above scenarios the reservoir is above the 100 percent supply zone. Hence, 100 percent of the irrigation demand is being met in the command areas of the Kabini reservoir.
- Below the 100 percent operating curve demands are met as per their supply zone.
- Overall there are eight parameters that has been calibrated to get the descent model for the reservoir. Four of them t,w,a and l are same as in the irrigation reservoir. Four more parameters have been introduced in the Kabini reservoir. Those are: rl(reference level), up (storage threshold), st level(Initial level), st initial(initial storage). These parameters are then calibrated to get the best simulation of the reservoir outflow.

Table 4: Parameter range, Hydropower reservoir

Parameters	Range	Parameters	Range
t	0-1	up	Min level-Max level
w	0-0.5	rl	Min storage-Total storage
a	0-1	st initial	Min storage-Max storage
l	0-1	st level	Min level-Max level

3.2.3 Crop water demand

The four reservoirs modelled are very vital in furnishing the irrigation requirements of the respective command areas. Depending on the storage in the reservoir and its position in the shortage rule curve generated for that reservoir different levels of demands are furnished. This demand is an extraction from the reservoir and affects the storage and eventually the outflow. Hence, it is very vital for reservoir modelling to have an estimation of crop water requirements. The estimation of crop water requirement is also vital to schedule irrigation and increase crop yields based on the available water resources (9). According to Brouwer et.al (10) crop water need can be defined as ***"the depth (or amount) of water needed to meet the water loss through evapo-transpiration."*** The three factors affecting the full production potential of crops are:

1. Climate
2. Crop type
3. Growth stage of crop

The impact of the climate on crop water needs is represented by the potential or reference crop evapo-transpiration (11). The calculation of potential evapo-transpiration (ETo) is based on Hargreaves equation considering max, mean, and min temperature values(Equation 4). The relative humidity is not explicitly contained in the equation, but is implicitly present in the difference between maximum and minimum temperature, as the temperature difference is linearly related to relative humidity (12).

$$ET_o = 0.408 * 0.0023 * R_a * (T_{mean} + 17.8 * (T_{max} - T_{min})^2 \tag{4}$$

where:

ET_o = Potential evapo-transpiration (mm/day)
R_a = Radiation (MJm$^{-2}day^{-1}$)
T_{mean} = Mean Temperature (^oC)
T_{max} = Max Temperature (^oC)
T_{min} = Min Temperature (^oC)

The impact of the crop type and growth stage on crop water needs can be reflected by the crop coefficient. The crop coefficient is the property of crops used in predicting evapo-transpiration. Depending on the region and the growth stage of different crops the crop coefficient shows time and spatial variability. Therefore, the crop coefficient value (Kc) for each crop grown in the command area have been taken from the peer reviewed literature. Therefore, the actual crop evapo-transpiration for the specific crop is estimated by applying the crop coefficient to the calculated potential or reference evapo-transpiration (13)(11). The actual crop evapo-transpiration is calculated based on the following formula:

$$ET_a = ET_o * K_c \tag{5}$$

where:

ET_o = Potential evapo-transpiration (mm/day)
ET_a = Actual evapo-transpiration (mm/day)
K_c = Crop coefficient

The water requirement of crop is furnished by rainfall or irrigation and in some cases both(10). The spatial and temporal variability as well as the soil texture in water requirements of the crop often water, furnished by rain are not effective (10). The part of rainfall that gets stored in the root zone can be accessed by the crop, this amount is referred to as an effective rainfall.

Effective rainfall for daily time step is done by following the Indian-2 method(14). As per this method if the rainfall is less than 6.25mm the effective rainfall is considered zero (Re=0 when $P < 6.25$ mm). While, if the rainfall is more than 6.25 and less than 75 mm, the effective rainfall is considered equal to the observed rainfall (Re=P, $6.25 < P <= 75$ mm).

The irrigation requirement of a particular crop is the difference between crop water needs and effective rainfall. For this study the net irrigation requirement for the study area was calculated assuming 70 percent efficiency of the irrigation provided.

3.2.4 Flextopo-Reservoir-Flextopo (F-R-F)

Each sub-basin was further divided into two catchments with respect to the reservoir. It was assumed that the response of the upstream catchment will serve as an input to the reservoir and the outflow of the reservoir will be an input to the downstream catchment. An attenuation factor ranging from 0 to 1 was considered to account for any water loss from the outflow of the reservoir. Figure 5, gives a schematic representation of the whole modelling process.

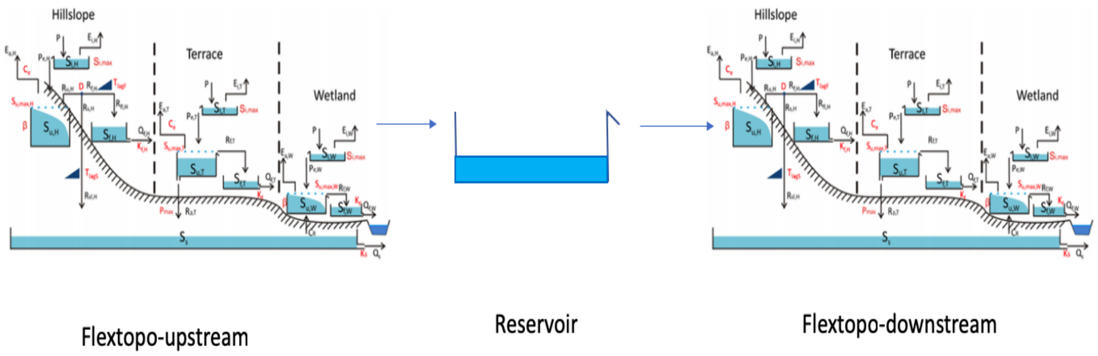


Figure 5: Flextopo-Reservoir-Flextopo model

4 Calibration and Performance

The dataset from January 1979 to December 2000 have been used to calibrate the Flex-Topo. While, the reservoir was calibrated using the limited dataset from January 2011 to December 2013. The models were calibrated using monte-carlo sampling, drawing parameter sets from a range of parameters. The parameters were considered independent of each other. Modelled runoff from each parameter set is compared using Nash-Sutcliffe Model Efficiency (NSE) and Mean Absolute Error (MAE). NSE penalizes errors in peak flows, hence is a better performance measure for the model prediction of high flows. The disadvantage with NSE is that the difference between the predicted and observed values are calculated as squared value resulting in an overestimation of larger values in the time series while neglecting the lower values (15). This leads to the over-estimation of model performance during peak flows and underestimation during low flows. To reduce this problem of squared differences the Nash Sutcliffe efficiency is often calculated with logarithmic values of observations and simulated data, NSE log penalizes error in the low flows therefore gives a better performance measure of the low flows. When we want to measure the model performance of both the high flows and the low flows, Multi-Objective optimization can be used. However, Multi-Objective optimization is out of the scope of this research. Mean absolute error has been used to indicate the errors in the units of the constituent in interest(16). MAE value of less than half standard deviation is low, and either is appropriate for model evaluation(17).

Overall three different methods are used to calibrate and assess the models

1. Reservoir and Flex-Topo calibrated separately.
2. Reservoir and Flex-Topo calibrated together using downstream gauging data.
3. Reservoir calibration followed by Flex-Topo calibration using downstream gauging data.

4.1 Reservoir and Flex-Topo calibrated separately.

Parameters of the Flex-Topo are transferable (18). Here, the reservoir and the Flex-Topo for the whole sub-basin are calibrated separately and then the calibrated parameters are used to run the system of model. The attenuation factor is then calibrated using the downstream gauging data for the four sub-basins. Finally, the top 5 percent of the 1000 simulations have been accepted and used to create the boxplot of model performances shown in the appendices.

4.2 Reservoir and Flex-Topo calibrated together using downstream gauging data.

In this calibration method the model generated for each reservoir in each sub-basin are first integrated into the model. Then the output of the system of models i.e. F-R-F model is calibrated using Monte-Carlo sampling. For each parameter sets, the modelled run-off is compared with the observed runoff using Nash-Sutcliffe Efficiency (NSE) and Mean absolute errors (MAE). The models for which, operating rule curves generated for the reservoir are within their range i.e. 100 percent, 80 percent and 50 percent supply lines are between 0 and 1, have been considered acceptable.

4.3 Reservoir calibration followed by Flex-Topo calibration using downstream gauging data.

Here, the parameters of the reservoir are calibrated first using reservoir data from January 2011 to December 2013. The reservoir parameters are then fixed to the best parameter set while the Flex-Topo parameters for the three hydrological response units (HRU) are calibrated using data of downstream gauging station for each sub-basin. Finally, the top 5 percent of the 1000 simulations have been accepted.

Note: The above calibration and validation methods have been compared to the model performances of the Flex-Topo without the reservoir for each sub-basin.

5 Result and Discussion

5.1 Reservoir calibration

The performances of the reservoirs in the calibration phase was assessed using Nash Sutcliffe efficiency(NSE) and Mean absolute errors(MAE). The models were calibrated using Nash Sutcliffe efficiency and then the feasible models were compared using NSE and MAE. Both the metrics gave somewhat different results, when the reservoirs were assessed using Nash Sutcliffe Efficiency, Harangi performs the best followed by Kabini and Krishna Sagar while Hemavathi performed worst (see figure 6)

When Mean Absolute Error was used as a metric for model assessment, Harangi performs the worst (figure 6). This can be due to the different objectives that these evaluation indices (NSE and MAE) are used for. While, Mean absolute error gives us an estimation of error between the simulated and observed values Nash Sutcliffe gives us an estimation of feasibility of using simulated values over mean observed value as a predictor for future hydrological analysis. (16).

Figure 7 shows that the model depicts the high flow really well which is intuitive as the models have been calibrated using NSE but as we can observe from the hydrograph that other than the peak flows relatively moderate flows are not simulated well. This explains the contradiction in the model performance of Harangi. Simultaneously, it also highlights the importance of different metrics in simulating different parts of the flows
This gives us a whole new opportunity to delve into the discussion of these efficiency metrics which

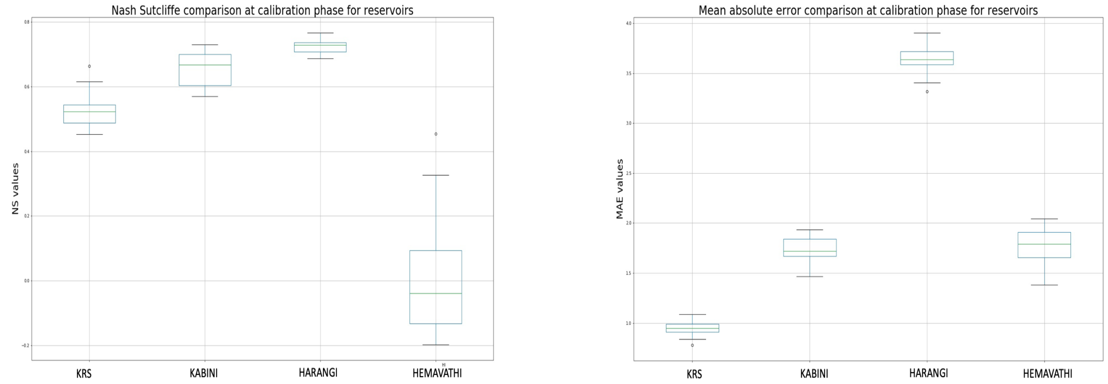


Figure 6: Reservoir model performance

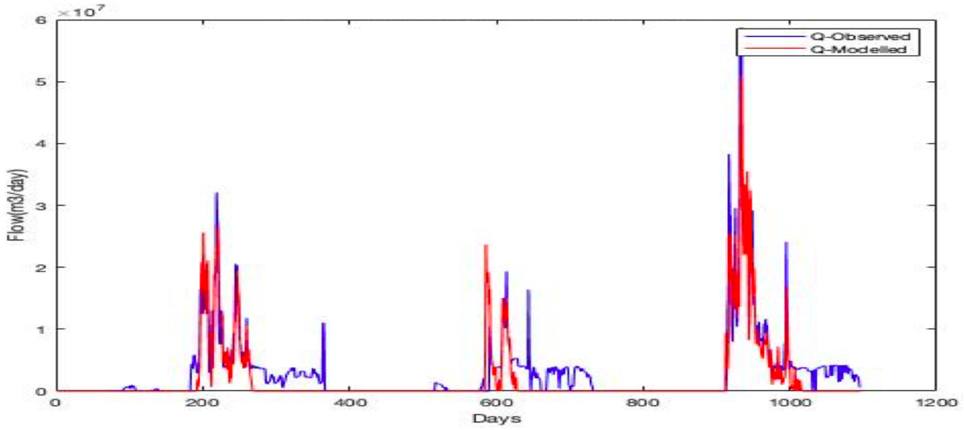


Figure 7: Model performance of Harangi reservoir

can be a part of further research. For now, we limit ourselves to the performances of models calibrated using Nash Sutcliffe optimization, assessed over two metrics Nash Sutcliffe Efficiency and Mean Absolute error methods.

5.1.1 Reservoir and Flex-Topo calibrated separately (R and F separate).

This calibration techniques involved taking the best parameter set for the reservoir and the best parameter set for the Flex-Topo calibrated over the whole sub-basin and use them as parameters to the F-R-F models. However, attenuation factor to the effect of reservoir is calibrated post calibration of the reservoir and the Flex-Topo models. We notice that since we are limiting the parameters of the reservoir and the Flex-Topo to the best parameter sets, there is not much variation in the NSE or MAE values (Appendix A and B). Slight variation can be attributed to the effects of varying attenuation factor. The NSE calibration for all the four sub-basins have improved (Figure 11 and 12, Appendix A). There seems to be slight deterioration in the median of NSE validation for the Kudige sub-basin compared to median values for the F-R-F model. At the same time NSE validation for optimum parameter set for the Kudige sub-basin is equal to 0.67(Table 5) while its 0.63 (Table 6) for the F-R-F model. Contrary to other calibration methods, the performance of MH Halli is better when reservoir and Flex-Topo are calibrated separately (Figure 12, Appendix A and Figure 14, Appendix B). This seems logical as both the reservoir and Flex-Topo are performing with their best parameter sets. The transferability of Flex-Topo allows the upstream Flex-Topo to perform at its best (Gao et al, 2014). For Kollegal as well, we see a slight improvement in the NSE calibration and validation phase which can be assessed with an increase in the median NSE values with respect to Flex-Topo for both calibration and validation phase (Figure 11, Appendix A). Though, there is a decrease in the variability there is a deterioration in the NSE **validation** of the F-R-F model for the T Narasipur sub-basin (Figure 11, Appendix A). The deterioration in the NSE validation of F-R-F model of T Narasipur can be due to deterioration in the NSE validation for the upstream Flex-Topo of the sub-basin with respect to its NSE calibration (Figure 15, Appendix C), while the NSE validation at the upstream of the reservoirs for the Kollegal and MH Halli is better than their respective NSE calibration.

With very insignificant change in the MAE values of the Kudige sub-basin we see a slight improvement in the MAE calibration while a slight deterioration in the MAE validation of the F-R-F model of the Kudige sub-basin (Figure 13,Appendix B). This is consistent with the results we got for the Kudige sub-basin when we used NSE as a metric for assessing the model performances. For the Kollegal sub-basin the MAE values for the F-R-F model are higher than the Flex-Topo model which contradicts the results of the performance we got using Nash Sutcliffe efficiency as a metric for model performances (Appendix A). For the T Narasipur sub-basin there is a slight improvement in MAE calibration values while the median for MAE validation is slightly higher than what we get from the Flex-Topo of the T Narasipur sub-basin (Appendix B). This result is also consistent with what we get from the Nash Sutcliffe performance efficiency of the T Narasipur sub-basin.

Table 5: Method 0, Flex-Topo model of different sub-basins prior to integration of reservoirs

Method 0	Flex-Topo model without the reservoir			
Sub-basins	Kollegal	T Narasipur	Kudige	MH Halli
NSE calibration	0.1731	0.5566	0.8471	0.2643
NSE validation	0.0588	-0.115	0.6671	-0.785
MAE calibration	1.6377	0.9327	1.5859	1.2253
MAE validation	1.562	0.9826	1.8535	0.865

Table 6: Method 1, Reservoir and Flex-Topo calibrated separately (R and F separate)

Method 1	Reservoir and Flex-Topo calibrated separately (R and F separate)			
Sub-basins	Kollegal	T Narasipur	Kudige	MH Halli
NSE calibration	0.29	0.60	0.85	0.35
NSE validation	0.07	-0.24	0.63	-0.35
MAE calibration	1.72	0.91	1.61	1.13
MAE validation	1.69	1.03	1.98	0.77
NSE reservoir	0.59	0.73	0.75	0.40
MAE reservoir	0.84	1.63	3.43	1.42

5.2 Reservoir and Flex-Topo calibrated together.

Reservoir here is calibrated together with the Flex-Topo to get the best possible simulation of the catchment response. However, F-R-F models for all the sub-basins tend to have more variations in both the calibration and validation values of Nash Sutcliffe and Mean Absolute Error (Appendix A and Appendix B). One possible explanation to this can be that the reservoirs in combination with the Flex-Topo did not get calibrated effectively. Out of 1000 simulations there might not be a single case where Flex-Topo and the reservoir are optimally calibrated and hence, have an optimum performance at the validation phase. The number of parameters being calibrated at a time also increases. This increases the chances of equifinality which reflects in high variability when it comes to the range of NSE and MAE values of the F-R-F models for the four sub-basins. The median values for Kudige, MH Halli, and T Narasipur deteriorates than the reference values that we get from the Flex-Topo models of those sub-basins (Appendix A). This can be due to bad performance of the upstream Flex-Topo (Appendix C) integrated into the F-R-F model or as a result of inefficient performance of the integrated reservoirs (Figure 6). For, the MH Halli sub-basin where the NSE values for both calibration and validation phases for the Flex-Topo model ranges from 0 to -2 (Figure 8) it is logical to say that the disintegration of the Flex-Topo model further deteriorated the overall performance of the sub-basin which can be inferred from inferior performance of F-R-F model of MH Halli (Figure 8). However, the integration of reservoir in the MH Halli sub-basin attenuated the effects of the bad performance of the upstream Flex-Topo (Figure 16, Appendix C). Thus, the integration of reservoir in the model helps attenuate the anomalies generated by dividing a simple Flex-Topo into a F-R-F model. When we take Kudige sub-basin into account the size of the reservoir and the area it occupies in the sub-basin is just 0.09 percent of the whole sub-basin which is quite insignificant when compared to the total catchment response of the Kudige sub-basin. Hence, the deterioration in the performance and increase in variability can be attributed to equifinality as a result of introducing six new parameters. The performance of the T Narasipur also deteriorates when F-R-F model is calibrated using this method. The deterioration in the performance of the upstream Flex-Topo at the validation phase seems to be the only logical explanation.

When we use the MAE metric to assess the model performance, we can observe some pretty apparent contradiction as compared to NSE based model performances. As expected, there is an increase in the variability of the model performances in both the calibration and validation phase. One peculiarity is that the models perform better in all the validation phase as compared to the calibration phase for all the sub-basins (Appendix B). This contradicts Nash Sutcliffe performance of the model at the validation phase and can be attributed to different objectives these metrics serve. Figure 8 and 9 can be used to get a better idea of the inconsistency between the two metrics. In the validation phase the peaks are not being simulated well. While, there is good representation of the low flows in the validation phase this justifies the inconsistency between the results of Nash Sutcliffe Efficiency and Mean absolute error values of the model. When the peaks are simulated well the NSE values are bound to be high but at the same time the low flows are not simulated well and overall the MAE worsens. The Kudige, MH Halli and T Narasipur sub-basins tend to perform worse than respective Flex-Topo model for both the calibration and validation phase. The Kudige catchment shows the highest increase in variability for both the calibration and validation phase which is also true when the models are assessed using Nash Sutcliffe efficiency. Kollegal sub-basin shows no significant change when compared using MAE. However, there is a slight increase in the variability.

Table 7: Method 2, Reservoir and Flex-Topo calibrated together (R and F)

Method 2	Reservoir and Flex-Topo calibrated together (R and F)			
Sub-basins	Kollegal	T Narasipur	Kudige	MH Halli
NSE calibration	0.59	0.65	0.82	0.04
NSE validation	0.28	-0.11	0.65	-0.79
MAE calibration	1.32	0.85	1.59	1.31
MAE validation	1.39	0.97	1.84	1.29
NSE reservoir	0.45	0.65	0.71	-0.17
MAE reservoir	1.03	1.81	3.69	1.85
Optimum NS reservoir	0.66	0.78	0.75	0.50
Optimum NS reservoir	0.79	1.26	3.43	1.65

5.2.1 Reservoir calibration followed by Flex-Topo calibration using downstream gauging data.

When the F-R-F model is calibrated using R then F, we observe that for the Kudige sub-basin there is no major change in the performance. The NSE calibration and validation values are similar to the Flex-Topo model(Appendix A). The medians for the Kudige sub-basin is almost similar for both Flex-Topo as well as F-R-F model. There is however a slight increase in the variability of the F-R-F model, this can be due to the combined effect of variation in performance of the three models integrated into one. The reason behind the negligible change in the model performances can be because of pretty insignificant area and storage of the Harangi reservoir with respect to

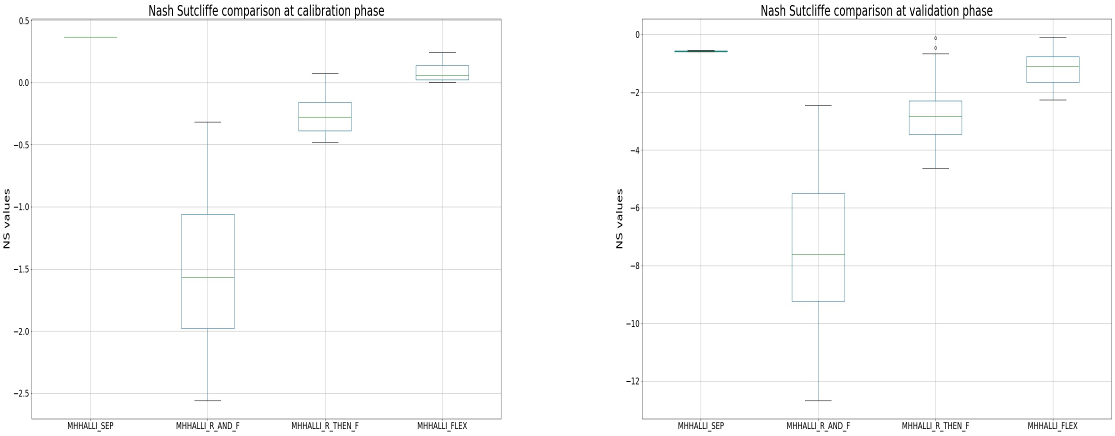


Figure 8: Nash Sutcliffe performance MH Halli

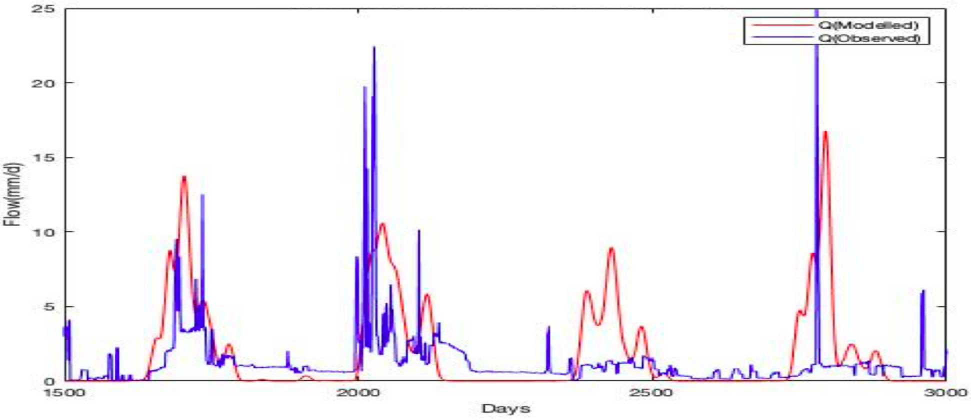


Figure 9: Nash Sutcliffe performance calibration phase of MH Halli sub-basin when both reservoir and flex-topo are calibrated together

the Kudige sub-basin as discussed in the above sub-section. For the MH Halli sub-basin there is a deterioration in the performance which is quite contrary to the results for other sub-basins. This can be a classic example of propagation of errors. If we delve deep into the models made for the MH Halli sub-basin, neither the typical model made for irrigation reservoirs (figure 6) nor the Flex-Topo for the MH Halli sub-basin is performing well(Appendix A). NSE calibration corresponding to the best parameter set for the upstream Flex-Topo in the MH Halli sub-basin is -0.85 (Table 9). The inter-quartile ranges are around -245 to -360 (Appendix C). When the catchment is divided into two sub-catchments the error in the upstream Flex-Topo propagates, this can be one of the main reasons behind deterioration in the performance of MH Halli sub-basin. For the Kollegal and T Narasipur sub-basins this way of calibration and assessment of model performance proved to be quite effective. Kollegal sub-basin is showing significant improvement in the model performance at both the calibration and validation phase (Appendix A). T Narasipur shows an improvement in the calibration phase. There is an improvement in the NSE validation of the Kollegal sub-basin while T Narasipur shows no improvement in the NSE validation values. Better performance of the upstream Flex-Topo of Kollegal sub-basin as compared to the T Narasipur sub-basin at the validation phase can be one of the reason of insignificant improvement of the R then F model of the T Narasipur sub-basin in the validation phase. We should keep in mind that these performances in the upstream Flex-Topo might not be representative for the whole F-R-F model as both are calibrated over different time periods.

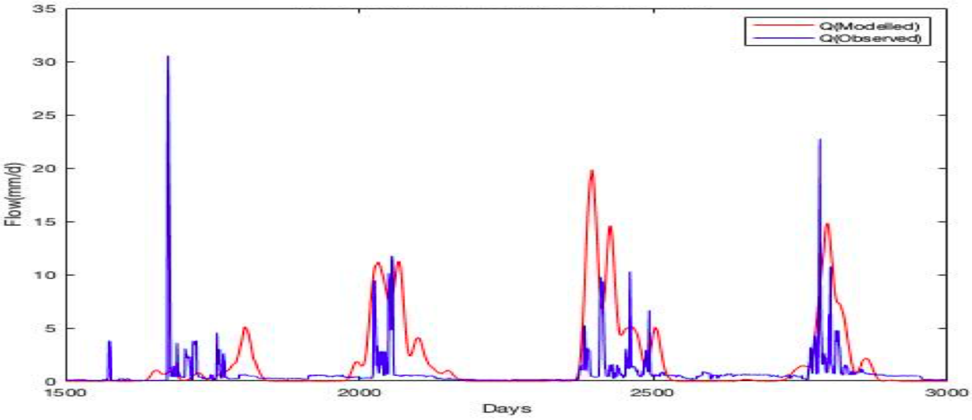


Figure 10: Nash Sutcliffe performance in validation phase of MH Halli sub-basin when both reservoir and flex-topo are calibrated together

For MAE metric as expected, the F-R-F model for the Kudige sub-basin didn't show much improvement(Appendix B), with almost no variation in MAE calibration values and slight deterioration in the MAE validation values. There is a decline in the model performance for the MH Halli sub-basin quite coherent with the results we get from the Nash-Sutcliffe efficiency metric. There is an improvement in the model performance of the Kollegal and T Narasipur for an F-R-F model. The variability for both the MAE values in both the sub-basins is almost same, with slight decline in variability for the Kollegal sub-basin and slight rise in the variability of the T Narasipur sub-basin.

For the MH Halli sub-basin with Hemavathi reservoir, both the metric, NSE and MAE shows really bad performances (Appendix C) for upstream Flex-Topo, which should have only worsened the performance of the F-R-F model when simulating the whole sub-basin. Therefore, we can infer that the presence of reservoir in the F-R-F model attenuated the worsening of the model simulations and thus improved the model.

Method 3	Reservoir calibration followed by Flextopo calibration (R then F)			
Sub-basins	Kollegal	T Narasipur	Kudige	MH Halli
NSE calibration	0.60	0.65	0.85	0.13
NSE validation	0.14	0.19	0.59	-1.33
MAE calibration	1.34	0.79	1.59	1.40
MAE validation	1.43	0.90	2.05	1.19
NSE reservoir	0.59	0.73	0.75	0.39
MAE reservoir	0.84	1.63	3.59	1.47

Table 8: Method 3,Reservoir calibration followed by Flextopo calibration (R then F)

6 Conclusions and recommendation

Overall amongst the three different methods of calibrating the integrated Flex-Reservoir-Flex model the third method i.e. reservoir calibration followed by the Flex-Topo calibration using the downstream gauging station performed the best. Integration of reservoir in Kudige sub-basin didn't change much in the model performance. Therefore, residence time of the reservoir compared to the residence time of the whole catchment shall be calculated before integrating the reservoir in the Flex-Topo model. The R and F separate way of calibration where reservoir and Flex-Topo models are calibrated separately proved to be the best for the MH Halli sub-basin, while other methods of calibration were not that effective for the MH Halli sub-basin. However, R and F separate method of calibration is not a true representation of reality as only the best parameter sets have been used to calibrate both the reservoir and the Flex-Topo. Future research shall take into account the first 5 percent of the total number of parameter combinations. R and F together involves calibration of many parameters which shall lead to equifinality and hence, more uncertainty. In all the three methods performance of the upstream Flex-Topo shall be good enough to disintegrate the Flex-Topo model into a Flex-Reservoir-Flex (F-R-F) model. Apart from these some further research is required. It must be made sure that the water balance with different sources of data are being closed. The rainfall and evaporation data used are of different resolutions they should be of same resolution to assure that the water balance is closed at pixel levels. Besides, gaps in data shall be addressed.

A Appendix A

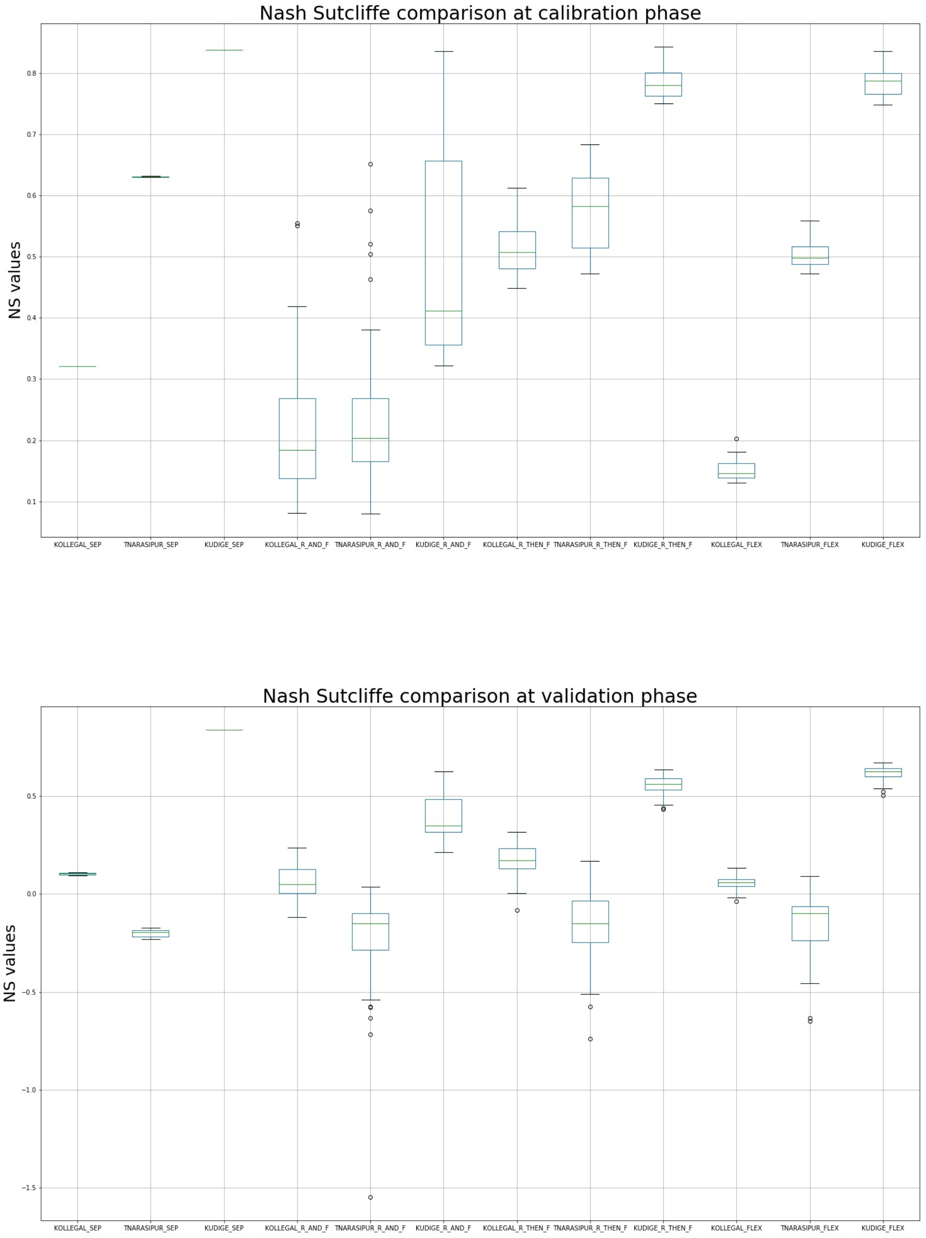


Figure 11: Nash Sutcliffe performances of different sub-basins except MH Halli

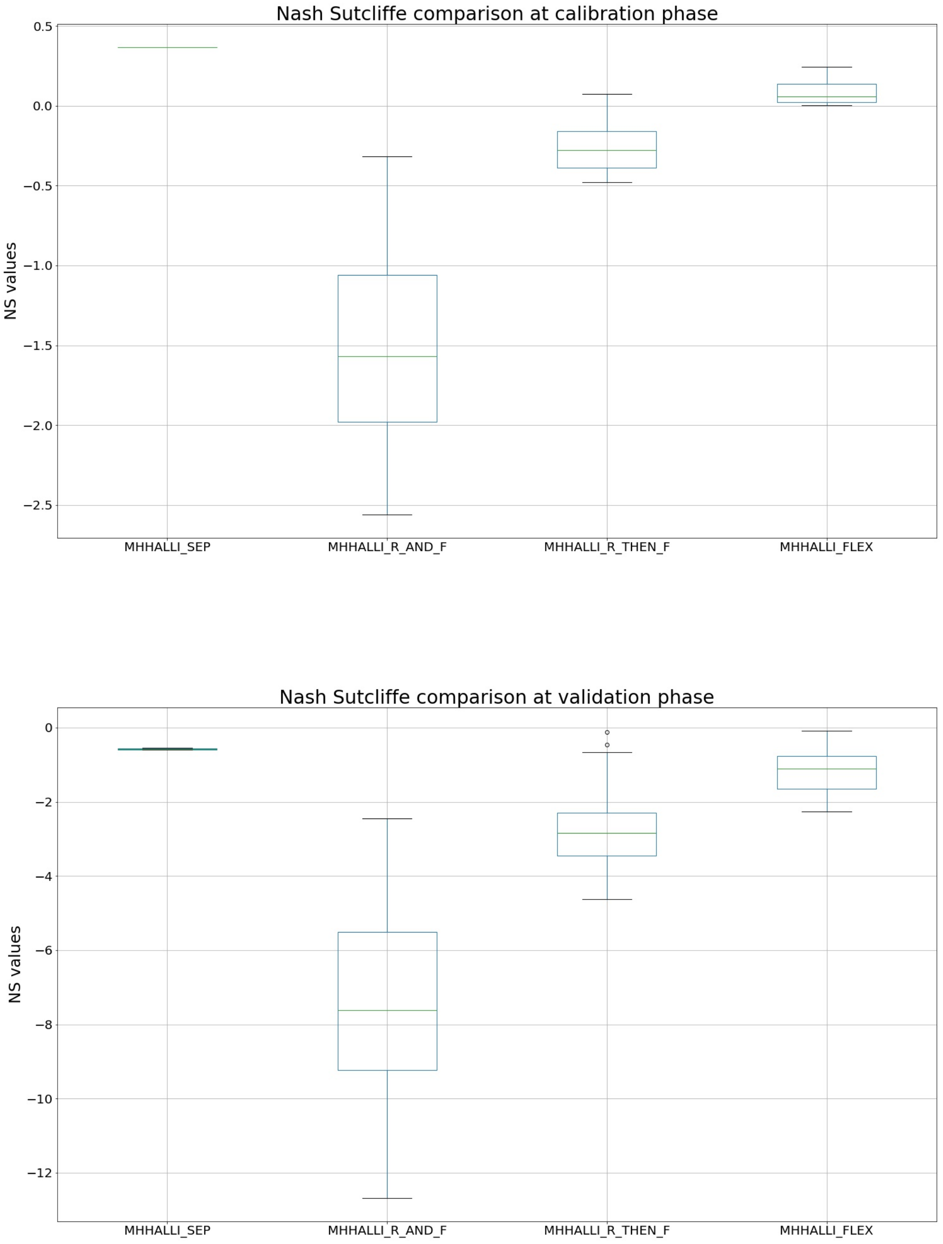


Figure 12: Nash Sutcliffe performances of different models of MH Halli sub-basin

B Appendix B

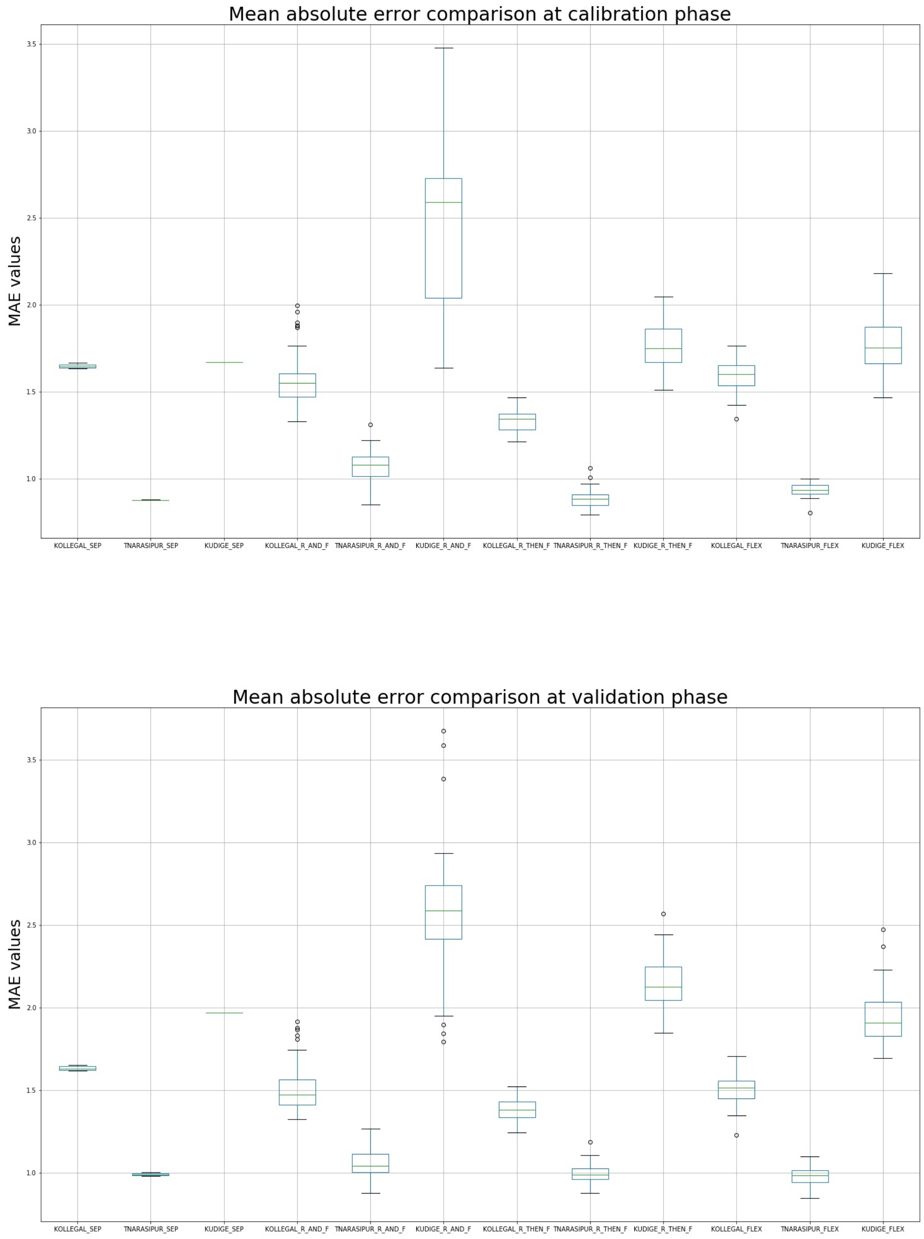


Figure 13: Mean Absolute Error performances of different sub-basins except MH Halli

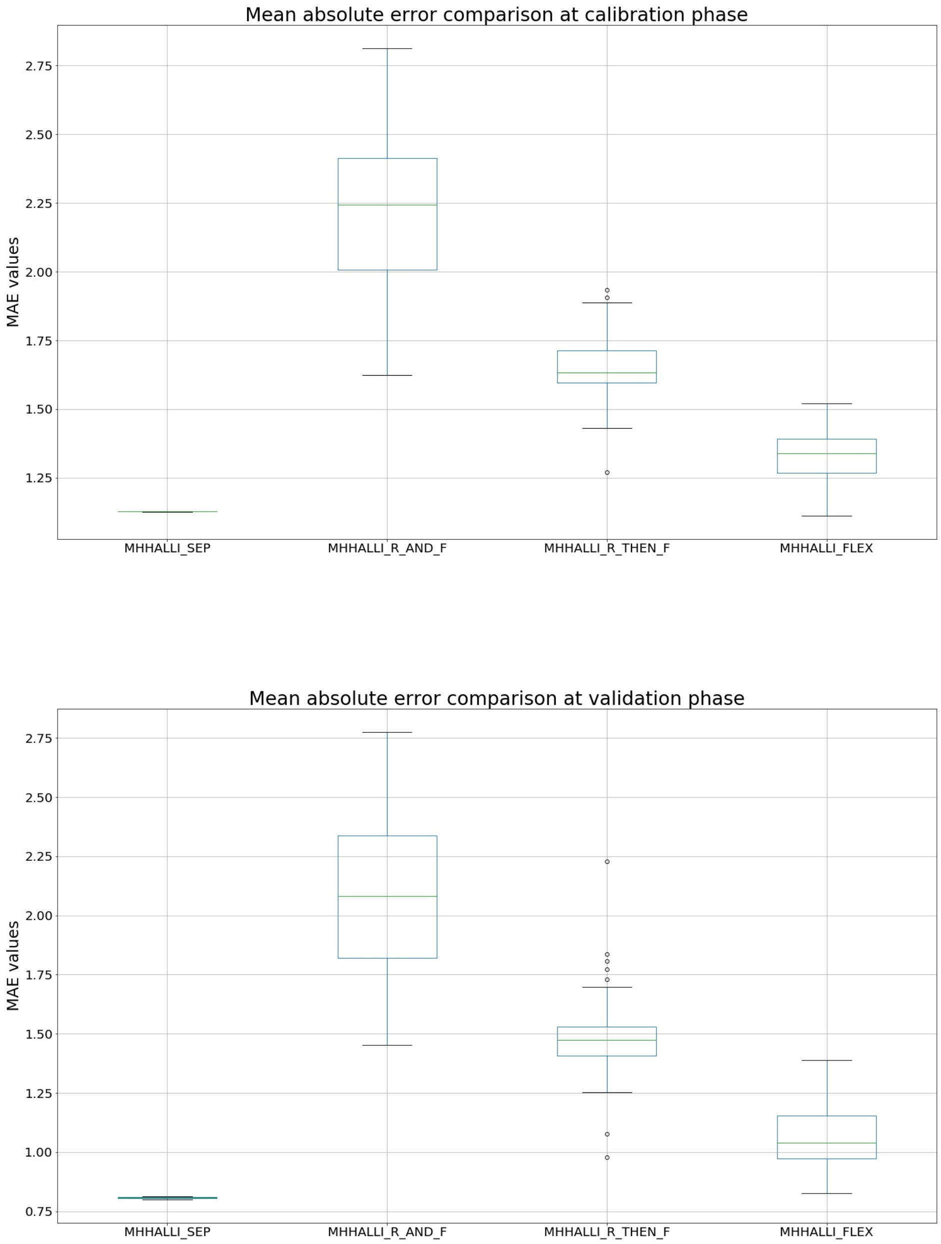
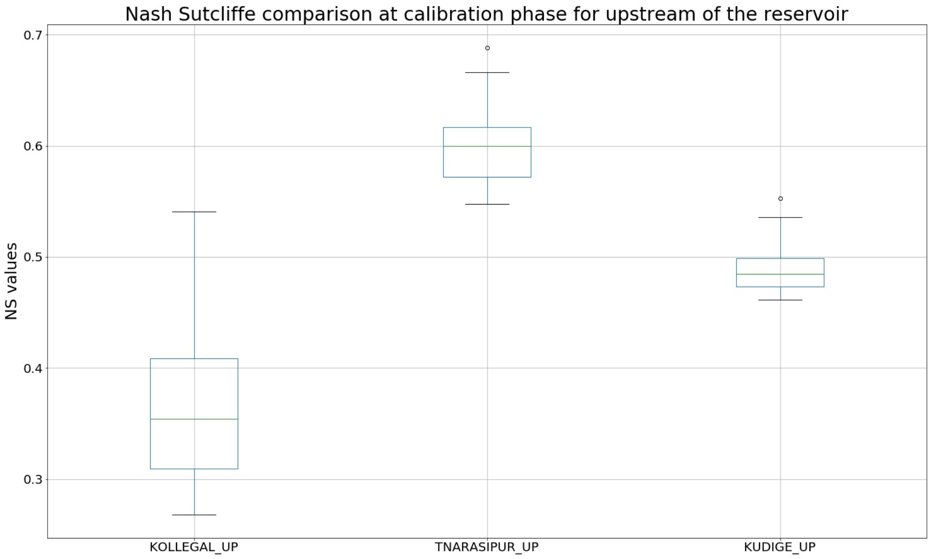


Figure 14: Mean Absolute Error performances of different models of MH Halli sub-basin

C Appendix C



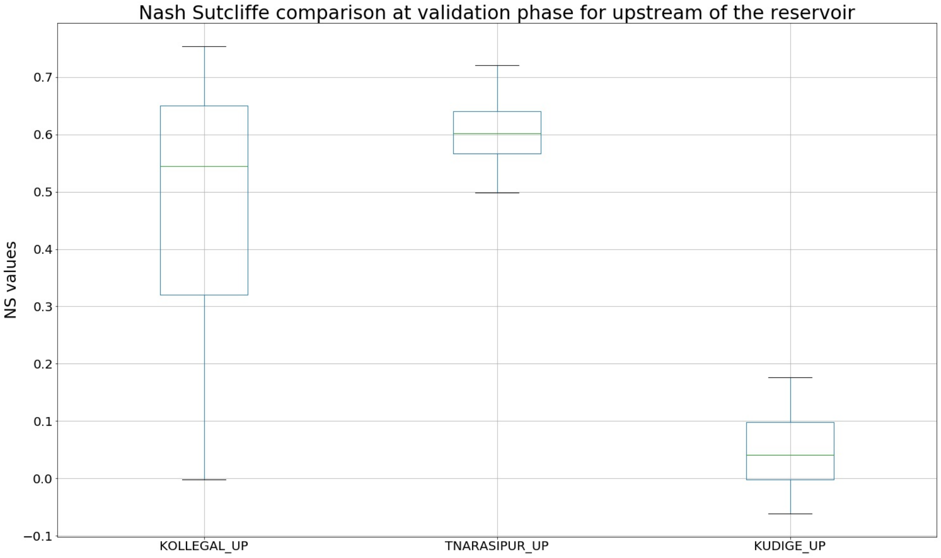
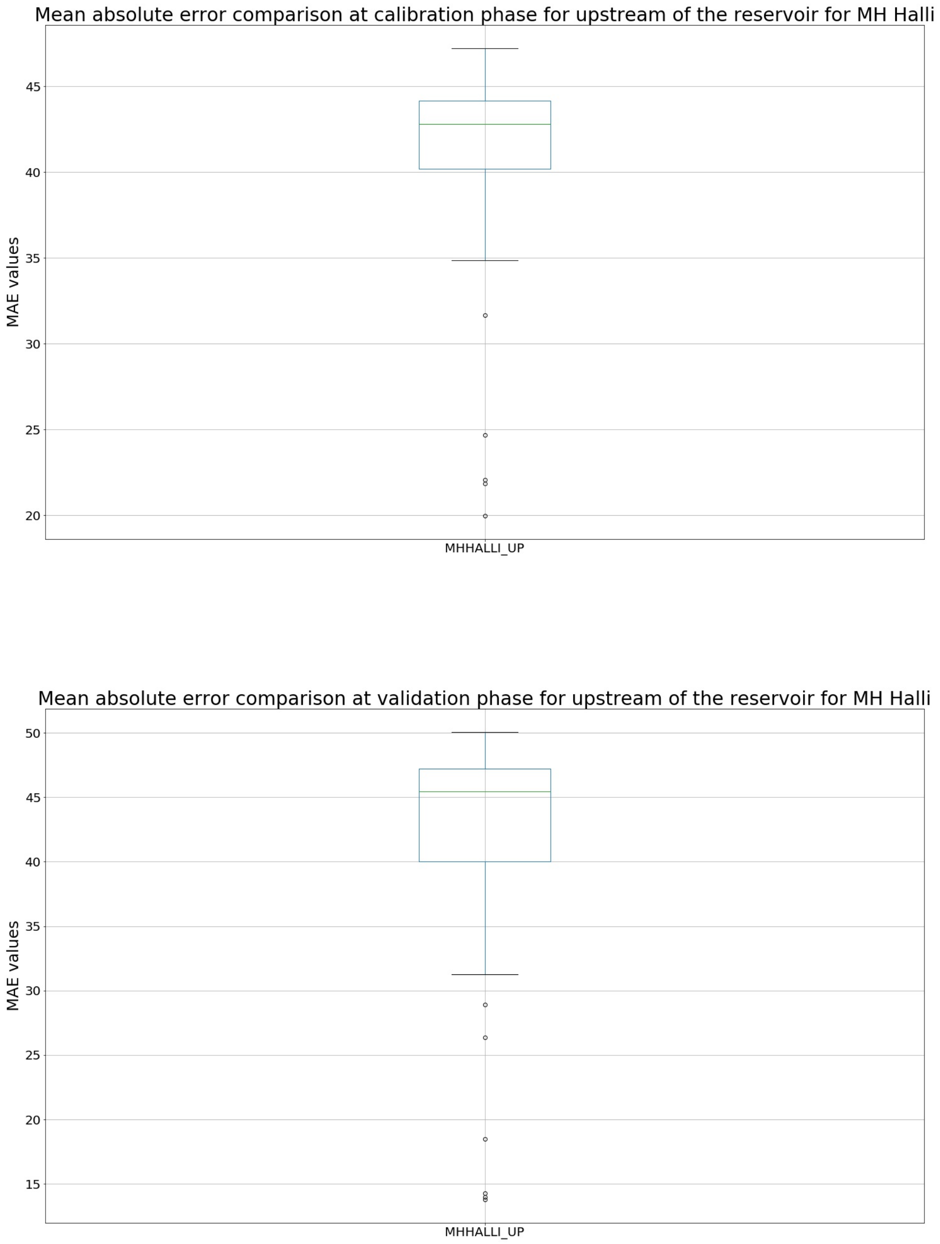


Figure 15: Nash Sutcliffe performances of upstream of the reservoir for different sub-basins except MH Halli



Mean absolute error comparison at calibration phase for upstream of the reservoir for MH Halli

Mean absolute error comparison at validation phase for upstream of the reservoir for MH Halli

Figure 16: Mean Absolute Error performances of different models of MH Halli sub-basin

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