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# Regionalisation of hydrological model parameters in nested catchments

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## ABSTRACT

A prediction in ungauged basins is one of the challenging tasks for a hydrologist of this century. Even though the physically based hydrological models can be the more appropriate in ungauged basins but data requirement limit the use. Conceptual hydrological models are simple and easy to use. But these model needs calibration before it can be used. Availability of data at all location in the basin limits the calibration of conceptual hydrological models. In this study, a calibration methodology is presented for discharge series limited condition using upstream and downstream data from nested catchment. It has been found that reasonable model parameters can be estimated for middle catchment using immediate upstream and downstream data. The regionalised parameter at the catchment outlet was tested at several locations inside the catchment to test the suitability of the outlet based model parameter for the interior location along the channel. It has been found that the model parameters obtained at the outlet of the catchment by regionalisation methods can be applied to the neighbouring points along the channel. A conceptual hydrological model, HBV-IWS was used for on upper Neckar catchment to demonstrate the methodology.

**KeyWord:** Regionalisation, HBV-IWS, Upstream downstream

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## Introduction

The stream flow data is an operational requirement for water resources management (Singh, 2016). However, it is not possible to gauge all catchments, due to many reasons like financial, maintenance, and access to the site (Bárdossy, 2007). As to construct any hydraulic structure we need to have a good record of hydrologic response at the location. Hence to predict flows in ungauged basin and to predict the effect of land-use change on basin response remains one of the most challenging goals of hydrology of this century (Blöschl, 2005; Sivapalan et al., 2003). Regionalization of conceptual rainfall-runoff models is an approach to estimating flows in ungauged basin. The technique involves calibrating models on gauged catchments, and determining relationships between model parameter values and catchments attributes (such as topography, geology, vegetation cover, land use). These relationships can then be used to estimate the parameter values for the ungauged catchments from their attributes (Götzinger and Bárdossy, 2007).

Due to non-linear nature, hydrological processes of a catchment are very complex to understand. Even hydrological knowledge has advanced tremendously but one cannot define a complete similarity between catchments (Singh et al., 2016; Wagener et al., 2007). Hence, one can only make a reasonable assumption that two adjacent catchments may have similarity in hydrological process if the catchment characteristics are similar. There has been many studies to define similarity (Singh et al., 2016; Wagener et al., 2007; Wang et al., 2013) and regionalisation of hydrological model parameters (Fernandez et al., 2000; Götzinger and Bárdossy, 2007; Samaniego et al., 2010; Seibert and Beven, 2009; Singh, 2010a; Wagener and Wheater, 2006). Due to complexity and uncertainty associated with these technique limits the application. Hence, there is always a need of simple technique for this purpose. One such example is study done by Merz and Bloschl (2004), they found that the best regionalisation methods are the use of the average parameters of immediate upstream and downstream neighbours. In this current study, it has been assumed that hydrological responses from a catchment are similar to immediate upstream and downstream. Hence the parameters of in between catchment can be regionalised by the help of upstream and downstream catchments.

The objective of prediction in ungauged basin or any regionalization method is to get discharge series at the point of interest. It is some time necessary to get discharge series at some interior points of a catchment for watershed developmental work. The objective of this study is to test “is it possible to apply upstream and downstream information to obtain the parameters at in between catchment in nested catchment setup.” and “is it possible to transfer the parameters obtained by regionalisation method at outlet to inner neighbouring points along the channel”.

## Study area and model

### Study area and data

The current study was conducted on part of Neckar basin situated in the region of Baden-Württemberg (south-west of Germany). The rivers in the catchment are not affected by larger hydropower plants or other water management structures or navigations, which may influence the runoff characteristics of the catchment. The upper Neckar catchment can be considered to be a typical example of a meso-scale catchment. The region is characterised by warm-to-hot summers with generally mild winters, and is wet during all seasons. The precipitation is distributed over catchment over entire year. The wettest month being June and the driest one October. The mean annual precipitation based on daily rain gauge record available for period 19161-2000 is 919 mm. The temperature varies highly from summer to winter. The coldest and hottest months in the study area are January and July respectively. The daily mean temperature observed between the periods 1961 to 2000 is 8.35°C.

Three upper most nested catchment of upper Neckar basin have been selected for the study (Figure 1). Upstream catchment Rottweil is having area of 456 $km^2$ and downstream catchment Horb is having area of 420 $km^2$. The in-between catchment Oberndorf having an area of 240 $km^2$ is assumed as ungauged catchment in this study.

The daily amount of precipitation and daily maximum, minimum and mean temperatures from 151 precipitation stations and 74 temperature stations respectively distributed in and around the study catchment were acquired from the Deutsher Wetterdienst, Germany, for the period from 1961 to 2000. The data obtained from the meteorological stations were point data. It was interpolated by the external drift kriging method (Ahmed and De Marsily, 1987) allowing the orographic effect to be taken into account by using the topography as an additional variable. The precipitation and temperatures was interpolated on 1 km × 1 km grid resolution and averaged for the catchment. In this study, Hargreaves and Samani (1985) method was used to estimates potential evapotranspiration using maximum and minimum temperature.

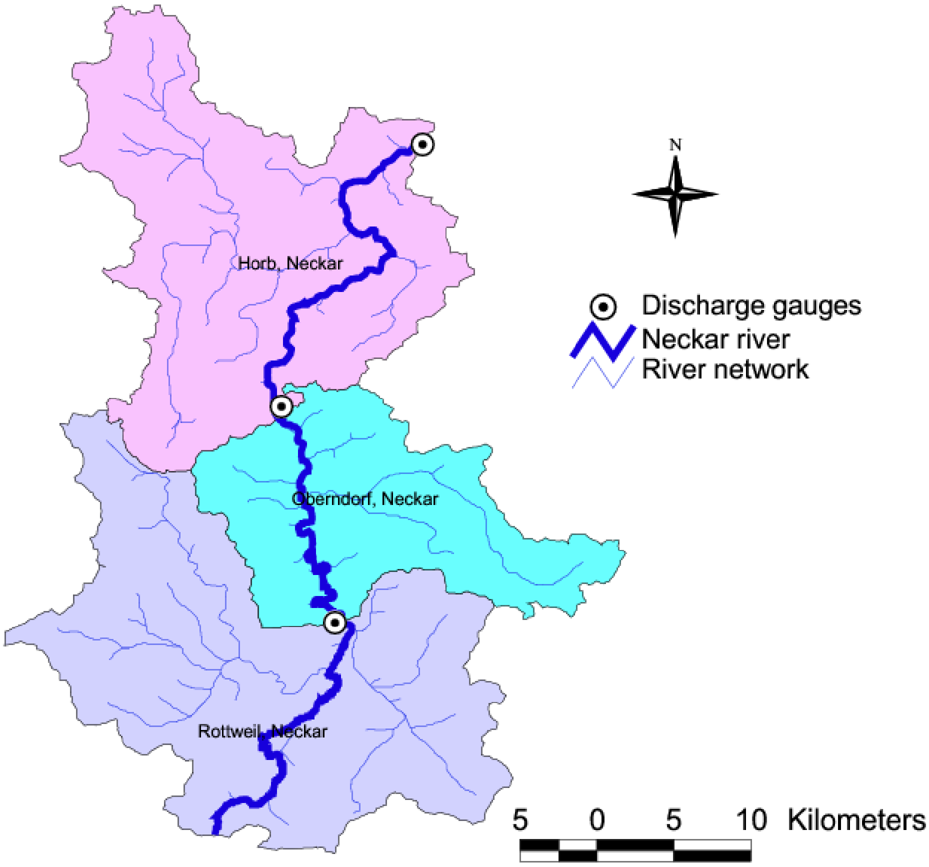

**Figure 1 Stream network and discharge gauges for nested catchments.**

## The HBV-IWS model

The conceptually based semi-distributed HBV-IWS model was used in this study (Figure 2). The HBV model concept (Bergström, 1995) was developed by the Swedish Meteorological and Hydrological Institute (SMHI) in the early 1970s and modified at the Institute of Hydraulic Engineering, University Stuttgart and termed as HBV-IWS. The basic structure of the model has been changed to semi-distributed model structure. The sub-division of subcatchmnets in to a number of different homogeneous zone was accomplished based on catchment characteristics that have influence on the runoff generation (Singh et al. 2012). The model consists of three main components:

- Snow accumulation and melt routine
- Soil moisture accounting routine
- Runoff response routine

The snow routine uses the degree-day approach. Soil moisture is calculated by balancing precipitation and evapotranspiration using field capacity and permanent wilting point. Runoff generation is simulated by a nonlinear function of the actual soil moisture and precipitation. The runoff concentration is modelled by two nonlinear reservoirs representing the direct discharge and the groundwater response. Flood routing between the river network nodes uses the Muskingum method. The physical meaning of model parameters is given in Table 1. Additional information about the HBV-IWS model in general can be found in (Bardossy and Singh, 2011; Bárdossy and Singh, 2008; Bergstroem et al., 1995; Hundecha and Bárdossy, 2004) .

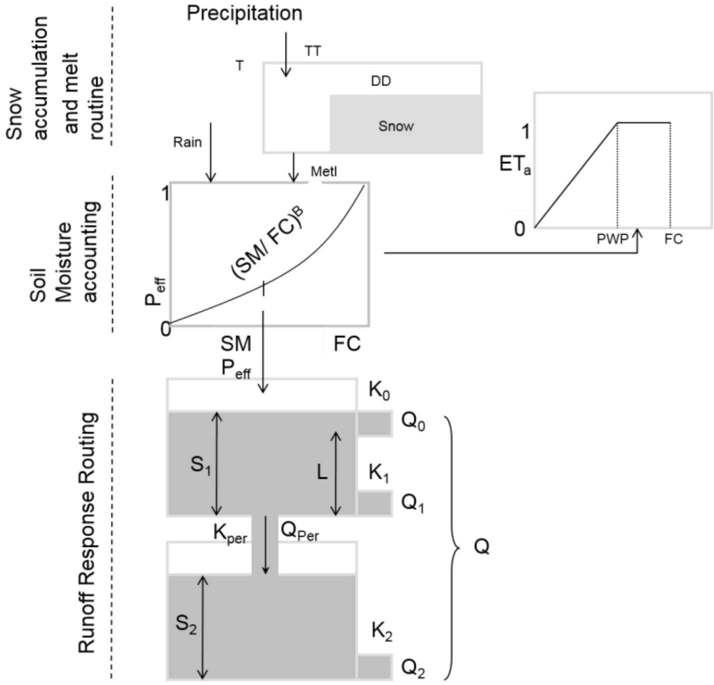

**Figure 2: HBV-IWS model structure (Singh, 2010b)**

**Table 1: HBV-IWS model parameters and their meaning**

| No | Parameter | | Unit |
|---|---|---|---|
| 1 | L | Depth of upper reservoir | mm |
| 2 | $K_0$ | Surface flow storage constant | 1/d |
| 3 | $K_1$ | Interflow storage constant | 1/d |
| 4 | $K_2$ | Baseflow storage constant | 1/d |
| 5 | $K_{PER}$ | Percolation storage constant | 1/d |
| 6 | TT | Threshold temperature | $^0$C |
| 7 | DD | Degree day factor | mm/$^0$C d |
| 8 | BETA | Model parameter | - |

## Methodology

### Regionalisation using upstream and downstream information

In this study, it has been assumed that hydrological responses from a catchment are similar to immediate upstream and downstream. Hence the parameters of in between catchment can be regionalised by the help of upstream and downstream catchments in nested catchments. The model was calibrated at upstream and downstream with respect to the ungauged catchment. Then, the complete set of parameters of upstream has been used for the immediate downstream catchment. In the second case, a complete set of parameters of downstream has been used to immediate upstream catchments.

### Transferring the parameter from outlet to neighbouring points

Generally, due to availability of observed flow at outlet of the catchment, models are calibrated at outlet of the catchment. But for several engineering as well as management purpose we need flow at internal location of the catchment. Hence, in this study we try to transfer the parameter from outlet of the catchment to internal location along the main channel. Firstly, we selected five internal location along the main channel and delineated five catchments. The parameters obtain at outlet of the catchment as described in previous section is transferred to these five locations. Hydrological model was run for these location and hydrological dynamic was compared with respect to the outlet as there was no observed flow at the five-inner location.

### Model Evaluation

The simulation results were compared using statistical criteria, namely, the Nash-Sutcliffe coefficient, Root mean squared difference and coefficient of correlation.

The Nash-Sutcliffe coefficient (*NS*) (Nash and Sutcliffe, 1970) is defined as:

$$NS = 1 - \frac{\sum_{i=i}^{N}(Q_o(t_i) - Q_s(t_i))^2}{\sum_{i=1}^{N}(Q_o(t_i) - \overline{Q_o})^2}$$

where:

| | | |
|---|---|---|
| $Q_o(t_i)$ | [m$^3$/s] | observed daily discharge |
| $Q_s(t_i)$ | [m$^3$/s] | simulated daily discharge |
| $\overline{Q}_o$ | [m$^3$/s] | mean observed daily discharge |
| N | [-] | number of time steps |

The value of NS varies from 1 to -infinity. NS is equal to 1 is perfect prediction.

The coefficient of correlation estimates the combine dispersion against the single dispersion of the observed and predicted series (Krause et. al., 2005).

The coefficient of correlation (*R*) is defined as:

$$R = \frac{\sum_{i=i}^{N}(Q_o(t_i) - \overline{Q_o})\ (Q_s(t_i) - \overline{Q_s})}{\sqrt{\sum_{i=1}^{N}(Q_o(t_i) - \overline{Q_o})^2}\sqrt{\sum_{i=1}^{N}(Q_s(t_i) - \overline{Q_s})^2}}$$

where:

| | | |
|---|---|---|
| $Q_o(t_i)$ | [m$^3$/s] | observed daily discharge |
| $Q_s(t_i)$ | [m$^3$/s] | simulated daily discharge |
| $\overline{Q}_o$ | [m$^3$/s] | mean observed daily discharge |
| $\overline{Q_s}$ | [m$^3$/s] | mean simulated daily discharge |
| N | [-] | number of time steps |

## Results and discussion

### Model calibration and Validation

A semi-distributed HBV-IWS model structure was setup for upstream catchment (Rottweil) in between catchment (Oberndorf) and downstream catchment (Horb). The model was calibrated using the simulated annealing global optimisation algorithm where the Nash-Sutcliff (NSE) (Nash and Sutcliffe, 1970) coefficient was used as the objective function. The model was calibrated at the outlet of the catchment. For calibration, the split sampling method was used. The whole data set was divided into two parts. The meteorological time series data from period 1961 to 1980 were used for the calibration of the model whereas the period 1981 to 2000 was used for the validation of the model. The model performance during calibration and validation are given in Table 2. Model performed well during the calibration and validation. NS varies from 0.64 to 0.74 during the calibration for all the three catchments. A similar NS was obtained during the validation, demonstrating the model was well calibrated.

**Table 2 Nash-Sutcliffe efficiency for validation period 1981-2000 for different scenarios**

| Catchment | Calibration | | Validation | |
|---|---|---|---|---|
| | R | NS | R | NS |
| Rottweill | 0.918 | 0.741 | 0.898 | 0.710 |
| Oberndorf | 0.901 | 0.682 | 0.905 | 0.672 |
| Horb | 0.912 | 0.738 | 0.922 | 0.726 |

### Regionalisation using Upstream and Downstream information

The calibrated model parameters from upstream and downstream were transferred to in between assumed ungauged catchment. The performance of both the cases in the validation period at the test catchment Oberndorf is given in Table 3. The Nash-Sutcliff Coefficient for the test catchment Oberndorf for upstream to immediate downstream and downstream to immediate upstream is 0.642and 0.674 respectively. The correlation coefficient for both cases is above 0.90 and the RMSE is about 6 $m^3$ /s. The hydrograph in validation period at test catchment Oberndorf is given in Figure 3. It is clear that method is over estimating the higher peaks but it has captured the lower peaks well.

From Table 3 one noticeable difference can be seen while transferring the parameters that the transfer of complete parameter sets from downstream to immediate upstream has outperformed the transfer of the complete parameter set from upstream to immediate downstream in terms of Nash-Sutcliff coefficient and coefficient of correlation. The reason may be that the downstream catchment is influenced from immediate upstream catchment.

The regionalised performance at Oberndorf is very similar to if one calibrated the model at Oberndorf (Table 2). This demonstrate that present simple regionalisation technique is efficient for calibrating ungauged catchment in nested catchment setup.

**Table: 3 Application of transfer whole parameter method in validation period at Oberndorf.**

| Case | Test Catchment | Nash-Sutcliff coefficient | Coefficient of correlation |
|---|---|---|---|
| Parameter of Rottweil used for Oberndorf | Oberndorf | 0.642 | 0.902 |
| Parameter of Horb used for Oberndorf | Oberndorf | 0.674 | 0.904 |

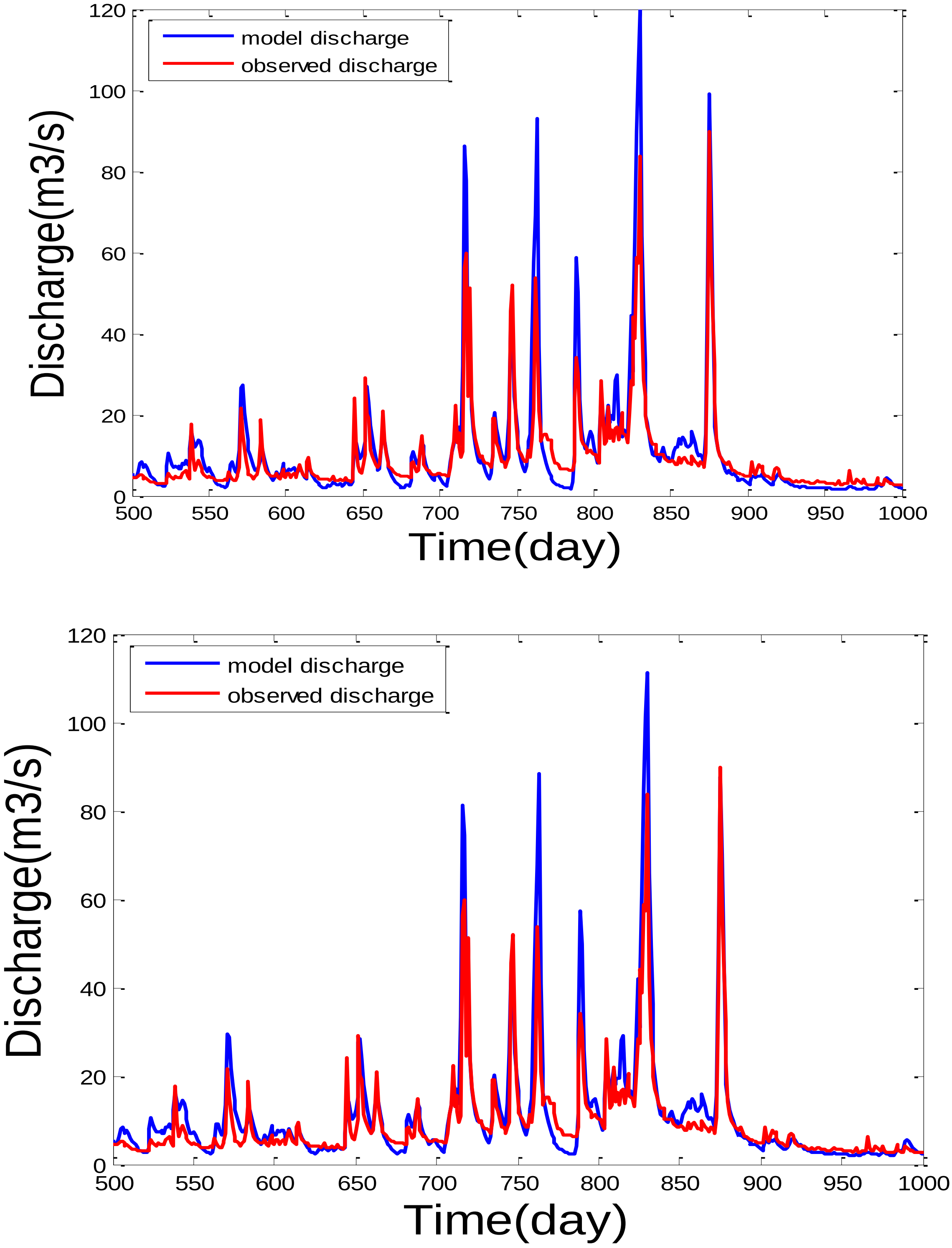

**Figure 3 Observed and modelled discharges at Oberndorf. (Top) upstream to downstream, (Bottom) downstream to upstream**

### Transformation of Regional Parameter from catchment outlet to neighbouring points along the channel:

The regionalised parameter at the outlet of the catchment (Oberndorf)is used for obtaining discharge series at all the five locations along the channel. The mean discharge and Standard deviation of discharge from mean at different location in Neckar River in Oberndorf catchment is given in Table 4. From the table, it is clear that as drainage area increases toward downstream of watershed, mean discharge increases as well as the standard deviation have also increased. The mean discharge obtained by transferring the parameters from outlet to inner points is in the range of 6 to 9 $m^3$ /s, whereas the mean discharge at these points, when the model was calibrated at that points using upstream and downstream data is in the range of 5 to 9 $m^3$ /s. It can also be observed that, near the outlet there not much difference in mean discharge, but this deviation increases as we move away from the outlet. This shows that when we transfer the parameters from outlet to inner points there is loss of information.

The specific discharge along the channel has varied from 93.36 to 96.85, whereas at outlet of the catchment Oberndorf, specific discharge is 82.81. A factor has been calculated if it multiplies to model discharge then specific discharge will be similar to specific discharge at outlet of Oberndorf. The approximate average factor being 0.87168. The factor calculated for making the specific discharge similar at all points by direct calibration, by using upstream and downstream method and transferring the parameters from outlets to inner points are very different. It shows this factor is not a unique value, hence a further detail study is requires to established a general factor.

**Table 4 Study along Neckar River in Catchment 2 by upstream and downstream**

| | point1 | point2 | point3 | point4 | point5 | gauge pt | Obser. |
|---|---|---|---|---|---|---|---|
| Area | 42.51 | 55.12 | 68.19 | 177.53 | 233.17 | 240.13 | 240.13 |
| Drainage area | 498.51 | 511.12 | 524.19 | 633.53 | 689.17 | 696.13 | 696.13 |
| Mean Disch. | 6.37 | 6.56 | 6.76 | 8.30 | 9.14 | 9.17 | 7.89 |
| STD | 8.84 | 9.01 | 9.19 | 10.67 | 11.45 | 11.50 | 9.26 |
| Specific Q | 93.36 | 93.74 | 94.21 | 95.71 | 96.85 | 96.20 | 82.81 |
| Factor | 0.88694 | 0.88334 | 0.87892 | 0.86521 | 0.85495 | 0.86074 | 1.000 |

The discharge hydrograph at all the five locations for certain period is given in Figure 4. When the parameter has transferred from outlet of the catchment to inner point along the channel; in validation period the model has captured very good dynamics as one can see from Figure 4. This shows the potential of this method that, the parameters obtained for the outlet of the catchment can be transfer to some neighbouring points. When we compare the hydrograph obtained by calibrating at that points by upstream and downstream method with transfer of parameters from outlet of the catchment to inner points, we can see transferring parameters from outlet has estimated higher discharge at all the location. This higher estimation may be due to loss of information from outlet to inner points and problem of equifinality. We do not have discharge series at all the five locations. It is very difficult to judge that, either calibrating the model at the required points along the cannel or transferring the parameters from outlet of the catchment to inner points is good. It is obvious that if we calibrate the model by upstream and downstream method at required point will be more accurate. Never the less if we do not have the input data for inner points we can transfer the parameters obtained at outlet of a watershed to inner points along the channel.

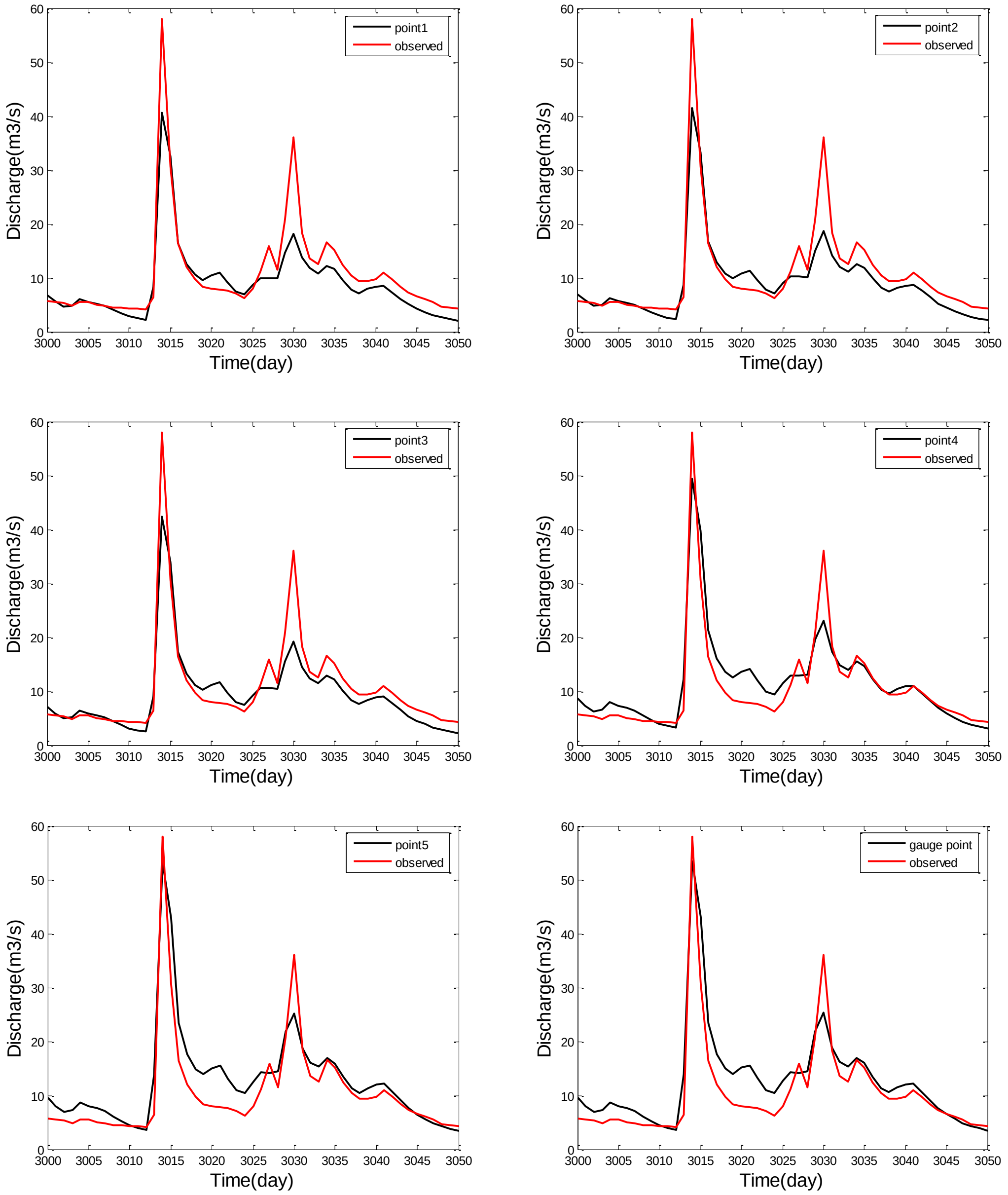

**Figure 4 Discharge hydrograph at all location, using upstream and downstream method**

## Summary

In this study two objective “is it possible to apply upstream and downstream methodology for neighbouring points” and “is it possible to transfer the parameters obtained by regionalisation method at outlet to inner neighbouring points along the channel” was studied. Firstly, the complete set of parameters of upstream has been used for the immediate downstream catchment. In the second case, a complete set of parameters of downstream has been used to immediate upstream catchments. It has been found that reasonable model parameters can be estimated for middle catchment using immediate upstream and downstream data. However, complete transfer of parameter from immediate downstream to upstream perform better than transferring upstream parameter to downstream catchment. To answer the second question, “is it possible to transfer the parameters obtained by regionalisation method at outlet to inner neighbouring points along the channel, two regionalisation method, firstly upstream and downstream method and It has been found that the parameters obtained by upstream and downstream at outlet, when transferred at inner points, estimate higher mean discharge but it captured relatively good dynamics. It has captured the dynamics except the extreme. It has found that there is loss of information, when parameter obtained at outlet of catchment is transfer to inner points along the channel. This loss of information has not completely clouded the capability of transferring the parameters from outlet to inner points along the channel because the dynamics captured by using these parameters is good. Hence it can be concluded that we can transfer the parameters from outlet to the inner points along the cannel with some loss of information.

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