Assessment of Hydrologic Impacts of Spatial Discretization in Koshi River Basin by GIS and HEC-HMS Semi-Distributed Model

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Abstract—Most hydrological modeling are complex process to recognize due to immense spatial and temporal variability of catchment characteristics, vegetation distinctiveness, precipitation data, snow pack and number of concerned variables in modeling the physical processes. The hydrological models are useful for spatial and temporal extrapolation of hydrological data. These models help in admitting the conceptualization of governing hydrologic methods working in catchments. Hydrological models are mainly classified as lumped, semi-distributed and distributed models. The model describing catchment in terms of average spatial and temporal quantities is considered lumped model while describing spatially variable system are termed “distributed models”. Hydrological models that fall between lumped and distributed is known as “semi distributed models”. Semi-distributed hydrological models generally have advantages of short calculation time, low calibration needs and high model efficiency. The sensitivity of this model in simulating the rainfall runoff, as a role of sub basin descriptions, was investigated for the Koshi river basin by using digital elevation model, climate data, land use and soil type of Koshi watershed. The results showed that increasing the number of subdivision from 7 to 35, decreases hydrograph peak discharge, average stream flow, total runoff volume but increasing efficiency of model with increasing sub basin divisions. However this trend becomes less significant when number of subdivisions exceeds twenty-five subdivisions.

Key words: hydrologic model, catchment, simulation, semi distributed, DEM, efficiency, subdivisions

I. INTRODUCTION

Hydrology is defined as the physical science that deals with the occurrence, circulation and distribution of water system of the earth, various phase of the hydrological cycle and describes chemical and physical properties of water, and their relation with living beings and environment [1]. Hydrological system is mainly analyzed by two approaches i.e. Physical science approach and system approach.

The principal study of the physical phenomena of water resources and eventually application in actual engineering works is maintained in physical science approach. In this system determination of output from a given system normally requires specification of: a) system input, b) System structure, c) physical laws and d) initial and boundary conditions. This approach is treated as theoretical approach.

System approach uses past proceedings for prediction of future events. Nature of the system or physical laws governing its operation is not considered. The system operation is connected between input and output only. The three essential features of systems approach are input, system function, and output [2].

Most hydrological modeling are complex processes to examine due to the incredible spatial and temporal variability of catchment characteristics, vegetation characteristics, snow pack, and precipitation data, as well as a number of variables concerned in modeling the physical phenomenon. The hydrological models are useful for spatial and temporal extrapolation of hydrological data. The concept of principal hydrologic processes of water resources is accessed with hydrological model in operating catchments [3]. Usually, hydrological models can be categorized into empirical (black-box), conceptual and physically-based models based on the description of the hydrologic processes. Models are also classified either lumped or distributed based on spatial variation of the catchment characteristics and other concerned data [4]. A lumped models play involves simple physical and biological interaction to determine hydrological response of catchment. Distributed models are physical based models which involving theoretically acceptable continuum equations. So approximate numerical solutions, based on a finite difference or finite element discretization of the space and time dimensions is implemented in distributed models [4]. Semi-distributed hydrological models are in between lumped and physical based models. They operate based on conceptual relationships for hydrological processes that are applied to several relatively homogeneous sub-areas of the catchment. This model is effective in matching simulated and observed flows at a variety of sites in different geographical and geomorphologic settings [4].

Various models are means of integrating measured data gathered spatially and temporally from the catchment and is used for further analysis with provides related analysis tools by calibrated and verified models on catchments. The model can be used to test hypotheses and stipulate how catchments behave under different conditions in the future. Also From the research point of view of building model is needed to combine and solve the equations of mass, energy and momentum describing the movement of water over and through the soil , in stream channels and aquifers to gain a better understanding of the effect of watersheds on the hydrological cycle.

Many Rivers in Nepal are either ungauged or poorly gauged due to extreme complex terrains, monsoon climate and lack of technical and financial supports. In this context the role of hydrological models are extremely useful. Large number of hydrological models exists that ranges from black box to physically based models. There are also various types of semi distributed models and they have their own capabilities and efficiency to simulate the catchment’s response. The size of a sub-basin influences the homogeneity. Usually larger subdivisions are more prone to have variable conditions than smaller grid cell sizes. However, smaller grid size requires more labor, input data
and computing time for modeling. But it provides qualitative simulation results. Hence, appropriate size of subdivision is to be identified that can efficiently and adequately simulate the behavior of a watershed [5]. Finding optimal size of subdivision required for spatial heterogeneity of local variation is a major challenge to hydrologist. To justify increased time and labor, use of smaller grids or subareas produces improved model performance. Spatial discretization in terms of number of sub divisions in hydrological modeling of watersheds is a primary objective of this research paper.

Semi-distributed hydrological models generally have the advantages of short calculation time, comparative low calibration needs and high model efficiency. Therefore, the main objective of this research is to determine effect of sub division of watershed and finding the constant number of sub divisions of basin in a particular watershed to give best results in semi-distributed rainfall-runoff modeling.

II. TOOLS FOR MODELING

In this study runoff hydrograph simulation of Koshi river basin was computed by HEC-HMS model, HEC-RAS, HEC- GEORAS models, HEC –GEOHMS 1.1, Digital elevation model, and GIS program

III. STUDY AREA (KOSHI RIVER BASIN)

The Koshi River basin is the biggest river of Nepal which lies in the Eastern development region of Nepal between latitudes 27°00'23” to 28°09'50” N and longitudes 88°22’36” to 88°23’37”. The total Catchment area is approximately 60,000 sq Km. The catchment area estimated for an outlet at Chatara is 25923 sq km which is about 18% of total area of the Country. The highest elevation in this basin is 8848m (Mt. Everest) and the lowest elevation is 140m at Chatara. The location map of the studied basin is shown in figure 3.1

The major tributaries forming the Saptakoshi in koshi river basin are Indrawati, Bhotekoshi, Tamakoshi, Dudhkoshi, Likhu, Arun and Tamur. Among them, three main confluences of the koshi are the Sunkoshi in West, Arun in the central region and Tamur in the Eastern part. Downstream of the confluence, the river is named as Saptakoshi whereas in the upstream it is named after the name of three major tributaries namely Sunkoshi, Arun and Tamur.

<table>
<thead>
<tr>
<th>River’s name</th>
<th>Gauging station</th>
<th>River’s length, km</th>
<th>Drainage area, Sq.km</th>
<th>Maximum flood flow, cumecs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunkoshi</td>
<td>KAMPUGHAT</td>
<td>330</td>
<td>19,000</td>
<td>2,890</td>
</tr>
<tr>
<td>Arun</td>
<td>TUNKILINTAR</td>
<td>510</td>
<td>3,600</td>
<td>1,481</td>
</tr>
<tr>
<td>Tamur</td>
<td>MULGHAT</td>
<td>190</td>
<td>6,000</td>
<td>1,407</td>
</tr>
<tr>
<td>Saptakoshi</td>
<td>BARAHKSHETRA</td>
<td>720</td>
<td>61,000</td>
<td>6,981</td>
</tr>
</tbody>
</table>

Table 3.1 Hydrological Characteristics of Koshi River and its tributaries

All these rivers are perennial out of which some is snow fed rivers. There are altogether eleven discharge gauging stations namely at Majhimtar and Mulghat in Tamur river, Uwagaon and Tukdeghat in Arun river, Rabuwaghat in Dudhkoshi, Sangutar in Likhu, Rasnalo in Khimti, Busti in Tamakoshi, Pachawarghat in Sunkoshi, Jalbire in Balephi and Chatar in Saptakoshi.

IV. METHODOLOGY OF THE MODELING

The semi-distributed model was used to simulate Koshi river basin. GIS extension tools were used for the extraction of physical characteristics of sub basin and rivers. DEM of whole Nepal was downloaded and DEM for Koshi basin was clipped out. Stream and watershed delineation was conducted using HEC-GeoHMS Extension. Required other model parameters such as daily precipitation, evapotranspiration are collected from DHM and analyze by thienessen polygon method. Hydraulic conductivity, suction head, initial moisture deficit and roughness coefficient are extracted on the basis of soil and land use map of the study area and these models parameters are used in HEC-HMS model simulation.

Hydraulic parameters are routed by using kinematic wave method for overland and Muskingum cunge method for channel routing. Simulated flow is compared with the observed flow at the outlet of the basin and analyzes the performance of the result to achieve the objective of the study. Metrological and hydrological data such as precipitation and discharge respectively are acquired from the Department of Hydrology and meteorology (DHM) whereas topographical data of 100m x 100m resolution Digital map (DEM) was extracted by using GIS. After having data, HEC-HMS model are operated. The main output from model is discharge at the outlet of the catchment. Kinematic wave method was used at both catchment and channel routing. Hydrological modeling was carried out by using the HEC-HMS and HEC- geoRAS Model. Finally, the output was compared with the real discharge at selected gauging of the basin. HEC-GeoRAS was used to generating geometric data like cross-section geometry, stream center line, bank stations, and flow path and for evaluation of hydraulic models. The overall conceptual framework is as shown in figure 4.1.
This study examines the effect of increasing the number of sub-basin on the hydrograph at Koshi river basin’s outlet by considering the model’s response of two-year separate precipitation. The basin is divided into number of sub-basin on the basis of river networks, landuse, and soil type. The model is run separately four times for 7, 14, 25 and 35 number of subdivisions. Runoff from each of the sub basin is estimated and routed using kinematic wave method to calculate total flow at the outlet of the basin. The results obtained from each simulation compared with observed flow to access specified objective.

V. SIMULATION OF MODEL

The model is calibrated using 1995 daily rainfall runoff data. Manual and automatic calibration techniques are applied to estimate values of parameters. In these simulation run, the whole study area is divided from seven to thirty-five subdivision. After subdivision, the sub-basins are assumed to be homogeneous and the model parameters are assigned according to the type of soil and landuse pattern within sub-basin.

1) Simulation-1

In this simulation, the whole study area is divided into 7 subdivisions. The shape of simulated hydrograph from model run and observed hydrograph at outlet of basin and their scatter are shown in figure 5.2 and 5.3. The time to peak remains constant. The volume deviation and Nash efficiency are +15% and 77.1%.
2) **Simulation - 2**

In this simulation, the study area is divided into 14 subdivisions. The shape simulated hydrograph from model run and observed hydrograph at outlet of basin and their scatter are shown in figure 5.4 and 5.5. This result shows that the low flows and peak flow are matched with observed but total runoff volume is overestimated but results near to observed than 7 subdivision. Total volume deviation and Nash efficiency for 14 subdivision are +8.5% and 86.2%.

3) **Simulation-3**

In this simulation, the study area is divided into 25 subdivisions. The shape of simulated hydrograph from model run and observed flow at outlet of basin and their scatter are shown in figure 5.6 and 5.7. This result shows that the low flows and peak flow are well matched with observed also total runoff volume is nearly equal. Time to peak flow is same as observed flow. Total volume deviation and Nash efficiency for 25 subdivisions are -1.1% and 90.6%.

4) **Simulation-4**

In this simulation, the study area is divided into 35 subdivisions. The shape of simulated hydrograph from model run and observed flow at outlet of basin and their scatter are shown in figure 5.8 and 5.9. The results obtained from this simulation nearly equal to 25 subdivisions. Total volume deviation and Nash efficiency for 35 subdivisions are -1.2% and 90.5%.
B. Observed and simulated hydrographs at Validation period of model

The model is again run for one year’s daily rainfall runoff data using calibrated parameters. In model verification, the runoff is simulated using 1994 daily rainfall-runoff data. The procedure applied in model verification is same as that applied in model calibration. Fig 5.10 to 5.17 shows the observed and simulated hydrographs at validation of model.

Simulation: From simulation for validation period 1994 shape of simulated hydrograph from model run and observed hydrograph at outlet of basin and their scatter are shown in figure respectively.

1) Simulation-5

The time to peak remains constant. The volume deviation and Nash efficiency are +14.0 % and 71.46 %.

Fig. 5.10 Basin hydrograph generated using 7 sub-basin division for calibration period

Fig. 5.11 Scatter plot for 7 sub-basin divisions for calibration period

2) Simulation-6

This result shows that the low flows and peak flow are matched with observed but total runoff volume is overestimated but results near to observed. Also time to peak remains constant Total volume deviation and Nash efficiency for 14 subdivision are +4.3% and 89.11%.

Fig. 5.12 Basin hydrograph generated using 14 sub-basin division for calibration period (1994)

Fig. 5.13 Scatter plot for 14 sub-basin divisions (1994)

3) Simulation run-7

This result shows that the low flows and peak flow are well matched with observed also total runoff volume is nearly equal. Time to peak flow is same as observed flow. Total volume deviation and Nash efficiency for 25 subdivision are -1.35% and 92.34%.

Fig. 5.14 Basin hydrograph generated using 25 sub-basin divisions for validation period (1994)

Fig. 5.15 Scatter plot for 25 sub-basin divisions (1994)

4) Simulation run-

The results obtained from this simulation nearly equal to 25 subdivisions. Total volume deviation and Nash efficiency for 35 subdivisions are -1.4% and 92.43%.

Fig. 5.16 Basin hydrograph generated using 35 sub-basin division for calibration period (1994)
VI. ANALYSIS OF HYDROLOGICAL MODELING

Through the analysis of all the hydrographs (graphically and statically) and model performance with respect to catchment subdivisions, the effects of numbers of subdivision in the runoff simulation are summarized as follows:

A. Effect of numbers of subdivision on average stream flow discharge

The figure 6.1 shows the simulated average annual stream flow discharges that occurred at the outlet of basin in response to the number of subdivisions during calibration and verification period. In general, the simulated averaged stream flow discharge is decreasing at a much greater rate in response to increasing numbers of subdivision. A sharp decrease in averaged stream flow discharge occurs when the number of sub-division increases from 7 to 14, but the rate of decrease least significance for delineation that exceeds 25 subdivisions. The results indicate that there is a threshold or critical level of sub-basin scaling for simulated stream flow discharge for basin and that delineation occurs at a delineation of 25 subdivisions. Subdividing basin greater than 25 subdivisions do not produce a clear improvement in the stream flow discharge but fewer than 25 subdivisions could result in less stable results. The average stream flows with respect to number of subdivision are presented in table 6.1.

<table>
<thead>
<tr>
<th>Number of sub division</th>
<th>Observed average flow m³/sec in calibration period (1995)</th>
<th>Simulated average flow m³/sec in calibration period (1995)</th>
<th>Observed average flow m³/sec in validation period (1994)</th>
<th>Simulated average flow m³/sec in validation period (1994)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>1465.91</td>
<td>1667</td>
<td>1275.56</td>
<td>7950.2</td>
</tr>
<tr>
<td>14</td>
<td>1591</td>
<td>1135.54</td>
<td>1194.73</td>
<td>5783.36</td>
</tr>
<tr>
<td>25</td>
<td>1467</td>
<td>1129.95</td>
<td>5978.5</td>
<td>4785.6</td>
</tr>
<tr>
<td>35</td>
<td>1463</td>
<td>1126.59</td>
<td>1467</td>
<td>5968.5</td>
</tr>
</tbody>
</table>

Table: 6.1 Average stream flow during calibration and verification of model

B. Effect of Numbers of Subdivision on Peak Discharge and Total Run Off:

The figure 6.2 shows the simulated peak discharges that take place at the outlet of catchment in response to different levels of simulated subdivisions for 1994 and 1995 years. The peak outflow discharge and total runoff volume are presented in table 6.2 and 6.3. This result indicates that peak discharge and total volume decrease with number of subdivision but the rate is less significant after 25 subdivisions.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>7663.88</td>
<td>7950.2</td>
<td>5722.9</td>
<td>5783.36</td>
</tr>
<tr>
<td>14</td>
<td>6522.6</td>
<td>5978.5</td>
<td>4785.6</td>
<td>4773.8</td>
</tr>
<tr>
<td>25</td>
<td>5978.5</td>
<td>5968.5</td>
<td>4785.6</td>
<td>4773.8</td>
</tr>
<tr>
<td>35</td>
<td>5968.5</td>
<td>5968.5</td>
<td>4785.6</td>
<td>4773.8</td>
</tr>
</tbody>
</table>

Table: 6.2 Peak flow and total runoff volume during calibration and verification of model

<table>
<thead>
<tr>
<th>Number of sub divisions</th>
<th>Simulated volume (10⁷ m³) in 1995</th>
<th>Observed volume (10⁷ m³) in 1994</th>
<th>Simulated volume (10⁷ m³) in 1994</th>
<th>Observed volume (10⁷ m³) in 1994</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>4611</td>
<td>3609</td>
<td>4099.71</td>
<td>3764.47</td>
</tr>
<tr>
<td>14</td>
<td>5004.19</td>
<td>4566.67</td>
<td>3560.18</td>
<td>3560.17</td>
</tr>
<tr>
<td>25</td>
<td>35</td>
<td>4558.99</td>
<td>3560.17</td>
<td>3560.17</td>
</tr>
<tr>
<td>35</td>
<td>4558.99</td>
<td>3560.18</td>
<td>3560.17</td>
<td>3560.17</td>
</tr>
</tbody>
</table>

Table: 6.3 Total runoff volumes during calibration and verification of model

Fig. 6.3 volume of flow in sub division of basin.
C. Effect of numbers of subdivision on model performance:

Figure 6.4 shows the variation of model efficiency with respect to sub-division. The Nash efficiency of the model is corresponding to the number of subdivisions 7, 14, 25 and 35 are given in table. It indicates that model efficiency varies from 62.0% to 90.6% in calibration period and 64.46% to 92.34% in verification period. Also indicate that the model efficiency and \( R^2 \) values are increasing with increasing number of subdivision up to 25 subdivisions and remain constant beyond 25 subdivisions. The minimum number of required subdivision could be set to 17-25, as the efficiency of model does not improve beyond this. The model efficiency and \( R^2 \) value with respect to number of subdivision are presented in Table 6.4.

<table>
<thead>
<tr>
<th>Number of Subdivision</th>
<th>1995</th>
<th>1994</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Efficiency in ( % )</td>
<td>( R^2 ) values</td>
</tr>
<tr>
<td>7</td>
<td>77.1</td>
<td>0.89</td>
</tr>
<tr>
<td>14</td>
<td>86.2</td>
<td>0.915</td>
</tr>
<tr>
<td>25</td>
<td>90.6</td>
<td>0.92</td>
</tr>
<tr>
<td>35</td>
<td>90.5</td>
<td>0.92</td>
</tr>
</tbody>
</table>

Table: 6.4 Model efficiency and \( R^2 \) value

**Fig.-6.4 Effect of subdivision on model performance**

VII. OUTCOME FROM ANALYSIS

From the simulation results, it appears that peak discharge, average stream flow discharge and total runoff volume decreases with the cause of increases of the number of sub-divisions. However, increases model efficiency with increases of the sub divisions of the basin. Above results becomes less significant when the number of sub-divisions increases beyond 25 and it is nearly constant after 25 subdivisions.

It is clear from simulated hydrographs that diverse subdivisions explain different degree of conformity between simulated and observed discharge. There are obtained following results from the analysis of simulation

1) Poorer results are obtained in heterogeneous characters (topography, soils and land use) of Basins than homogenous basins.

2) Stream flow is decreased by increasing the number of subdivisions of the catchment. Surface runoff is directly related to the hydraulic conductivity, soil suction and moisture deficit and these parameters are affected by the size of the sub basin.

3) Predicted runoff were directly related to sub basin size .This variation is due to the sensitivity of overland slope, slope length, channel slope and drainage density. Changes in these parameters cause changes in simulation results.

4) As size of sub-basin increases, drainage density decreases. When drainage density is reduced, earlier defined channels and their contributing areas are replaced by simplified overland flow elements that must affect the routing phenomena and decrease the accuracy of prediction. The drainage density increases as the number of subdivision increase 

VIII. CONCLUSION AND RECOMMENDATION

A. Conclusion

For modeling purpose, the basin is divided into smaller a area that provides initial procedure for determining a suitable level of subdivision that will efficiently and satisfactorily simulate the rainfall runoff process from basin. In this study, Koshi river basin was taken for the study area. Kinematic wave method was used for overland routing and Muskingum cunge method was applied for channel routing to describe the discharge on Koshi River and peak flow attenuation and dispersion observed in the direct runoff hydrograph. Channel cross section parameters are extracted using HEC GeoRAS extension tool of GIS. From this study result, Annual runoff, Peak flow and at the outlet are similar to the observed flow in calibration and verification period using trapezoidal channel. Hence Hydrological modeling is a powerful technique in the planning and development of integrated approach for management of water resources.

The sensitivity of the model according to sub basin descriptions in simulating the rainfall runoff was analyzed for the Koshi basin using DEM, land use, soil type, precipitation data and climate data. The results show that increasing the number of subdivision from 7 to 35, decrease in hydrograph peak discharge, average stream flow, total runoff volume and increasing efficiency of model with increasing sub basin divisions; but this trend becomes less significant when the number of subdivisions exceeds twenty-five subdivisions. Also simulated peak discharge, stream average flow and total volume are nearly equal to observed at twenty-five subdivisions. The results from the study reported can be utilized as a guideline to delineate sub basins for a similar basin. Restricting the subdivision of a basin to the threshold levels reports would reduced input preparation efforts and subsequent computational evaluation.

B. Recommendations

The simulation results can be used as a basis for several additional topics of future research with this watershed runoff model. Specifically, this model analysis recommends the following topics as those considered most interesting and most beneficial to the model.
The channel cross-sections have been considered as trapezoidal. But the cross-sections could be triangular, rectangular. So, model study with other sections should be done to find optimum result.

It is recommended to use hourly data for better results.

The analysis was done based on Kinematic wave method. It is recommended to use Muskingum Cunge method, a distributed runoff model. It can describe the effect of reach storage, instead are manifested in the peak flow attenuation and dispersion observed in the direct runoff hydrograph which is obviously realistic.

This study ignored the snow and glacier melts contribution to runoff. For more realistic result this option should be incorporated.

REFERENCES


