

# DEVELOPMENT OF A TRANSFERABLE HYDROLOGIC MODELING IN TOPMODEL FRAMEWORK ACROSS SCALE AND REGION

Nawa Raj PRADHAN<sup>1</sup>, Yasuto TACHIKAWA<sup>2</sup> and Kaoru TAKARA<sup>3</sup>

<sup>1</sup>Student member of JSCE, Graduate Student, Dept. of Civil Eng., Kyoto University,  
(Yoshida Honmachi, Sakyo-ku, Kyoto, 606-8501, Japan)

<sup>2</sup>Member of JSCE, Dr. Eng., Associate Professor, DPRI, Kyoto University, (Gokasho, Uji, 611-0011, Japan)

<sup>3</sup>Fellow of JSCE, Dr. Eng., Professor, DPRI, Kyoto University, (Gokasho, Uji, 611-0011, Japan)

Development of a transferable rainfall runoff model and transferable model parameter values seeks connections among physical processes at disparate scales and possible linkage of hydrological similarities between catchments, which makes scale transformation and scale invariance as the fundamental requirement. We successfully transferred 50m DEM resolution TOPMODEL parameters identified at Kamishiiba catchment (210 km<sup>2</sup>, Japan) to Kuwanouchi catchment (187 km<sup>2</sup>, Japan) and Balaphi catchment (650 km<sup>2</sup>, Nepal) by downscaling the topographic index distribution for the later catchments from coarse resolution DEM with 1 km grid size to target resolution DEM with 50m grid scale. This leads to the conclusion that the method of transferring scale independent hydrological relationships can serve as a potential tool for regionalization of parameters and for predicting ungauged basins.

**Key Words:** Scale invariance, transferability, ungauged basin, topographic index distribution, downscale

## 1. INTRODUCTION

Change of scale or the resolution of spatial data sets involves the loss of information at higher spatial frequencies, leading to significant biases in simulation results, due to the strong non-linearity of many hydrological processes. Linking catchment physical properties to a hydrological model parameters, without overcoming the scale problem, often gives rise to unrealistic parametric values. Moreover, a model may be physically based in theories but not consistent with observations if the scale of modeling is inappropriate. This primarily comes from the mismatch in scales between the scale of observable state variables and the scale of application. Thus scale transformation and scale invariance seems a fundamental step for developing a process based method to identify similarities between catchments and for the development of an effective regionalization technique.

In this study we focus on the development of an approach for a transferable rainfall runoff model and transferable model parameters to assist prediction in ungauged basins. Development of a transferable rainfall runoff model and transferable

model parameters seeks connections among physical processes at disparate scales and possible linkage of hydrological similarities between catchments which makes scale transformation and scale invariance as the fundamental requirement.

Pradhan *et al.*<sup>1)</sup> developed a scale invariant model for the topographic index of TOPMODEL for the effective translation of the scale dependence relations of topography into effective hydrological model, TOPMODEL. Here, we use the scale invariant model for the identification of physically based hydrological relationships independent of region and scale. In section 2, we discuss the scale dependencies of dominating geomorphometric parameters and development of the scale invariant model for topographic index. In section 3, we discuss the methodology to transfer physically based parameters across regions. In this section we have shown the significance of linking physically based parameters across scales for a priori estimation of the effective model parameters set for ungauged region. Finally in section 4, we make discussion on the application of the proposed method for the validation of the similarity response function and the possible transferable model parameters set in

that specific region.

## 2. SCALE INVARIANT MODEL FOR TOPOGRAPHIC INDEX <sup>1)</sup>

TOPMODEL <sup>2)</sup> allows for spatial heterogeneity by making calculations on the basis of the distribution function of an index of hydrological similarity, soil topographic index, given by Equation (1):

$$SI = \ln \left\{ \frac{a}{To \tan \beta} \right\} \quad (1)$$

where  $SI$  is the soil topographic index,  $a$  is the area draining through a point,  $\tan \beta$  is the local slope angle at that point and  $To$  is the local down-slope transmissivity at soil saturation. Points with the same value of the index will be predicted as having the same hydrological responses. Specifying a spatial distribution for  $To$  being much more problematic in most applications, it has been assumed to be spatially homogeneous. In the case the similarity index defined by Equation (1) reduces to Equation (2).

$$TI = \ln \left\{ \frac{a}{\tan \beta} \right\} \quad (2)$$

where  $TI$  is the topographic index. Topographic index is scale dependent which leads identified parameter values to be dependent on DEM resolution <sup>1), 3), 4)</sup>. For this, purpose notions of scale transformation and scale invariance are needed. Pradhan *et al.* <sup>1)</sup> developed the scale invariant model for topographic index of TOPMODEL for the effective translation of the scale dependence relations into effective hydrological models.

When the resolution of DEM change for a catchment, the spatial distribution of topographic index also change. In this scenario keeping the same effective parameter value of  $To$  for changed topography index cannot fulfill the hydrological similarity concept of TOPMODEL across different DEM resolutions in the catchment. For this purpose notions of scale transformation and scale invariance are needed. Thus, we developed a method to downscale topographic index which is given by equation (3):

$$TI_{scaled} = \ln \left( \frac{C_i}{W_i R_f \theta_{scaled}} \right) \quad (3)$$

**Table 1.** Effective parameter values identified by 50m DEM resolution TOPMODEL in Kamishiiba catchment.

Lateral transmissivity of soil at saturation condition, $To$ [ $m^2/hr$ ]	decay factor of transmissivity with respect to saturation deficit, $m$ [m]	lateral zone storage, $Rzmax$ [m]	Maximum root storage,
9.8	0.07	0.001	

where  $TI_{scaled}$  is the scaled topographic index,  $C_i$  is the upslope contributing area of the coarse resolution DEM and  $W_i$  is the unit contour length of coarse resolution DEM,  $i$  is a location in catchment.  $R_f$  is a resolution factor defined by equation (4):

$$R_f = \frac{Coarse\ DEM\ Resolution}{Target\ DEM\ Resolution} \quad (4)$$

where  $\theta_{scaled}$  is the downscaled steepest slope of the target resolution DEM defined by equation (5):

$$\theta_{scaled} = \alpha_{steepest} d_{scaled}^{(1-D)} \quad (5)$$

In equation (5)  $d_{scaled}$  is the steepest slope distance of the target resolution DEM,  $\alpha_{steepest}$  is the coefficient whose values are derived directly from the steepest slope of the available coarse resolution DEM and  $D$  is the fractal dimension.

Equation (3) is coupled with TOPMODEL to develop the Scale Invariant TOPMODEL <sup>5)</sup>. The Scale Invariant TOPMODEL is applied to the Kamishiiba catchment (210  $km^2$ ). The physical significance of the Scale Invariant TOPMODEL is analyzed by deriving the effective parameter values of TOPMODEL from 50m-grid resolution DEM, refer Table 1, and applying the same parameters for 1000m-grid resolution DEM.

Figure 1 shows that the simulated runoff from Scale Invariant TOPMODEL applied at 1000m-grid resolution DEM, with the same effective parameter values derived from 50m-grid resolution DEM, has matched with the simulated runoff of 50m DEM resolution TOPMODEL and also with the observed runoff with high efficiency. Figure 1 also shows the blunder in simulated result of 1000m DEM resolution TOPMODEL, without Scale Invariant TOPMODEL, with effective parameter values identified at 50m-grid resolution DEM.

The result clearly shows that scale transformation and scale invariance are the fundamental steps for developing a process based method to identify the similarities between catchments and for the development of an effective regionalization technique. Thus we use scale invariant model for topographic index of

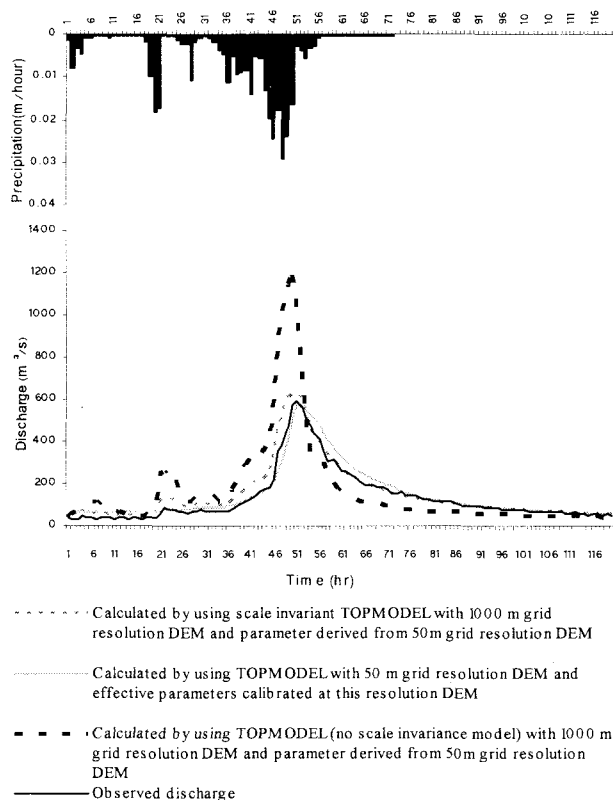


Fig. 1 Simulation results of TOPMODEL applied to Kamishiiba catchment (210 km<sup>2</sup>) with and without scale invariant function for topographic index distribution.

TOPMODEL as a tool for developing a method for possible transformation of dominating hydrological model parameters from physically measurable catchment attributes.

### 3. TRANSFERING HYDROLOGICAL MODEL PARAMETERS ACROSS SCALE AND REGION

#### (1) Assessment of physically based parameters across scales

Catchment topography with detail resolution of DEM is the base to build a transferable hydrological model. Topographic index distribution is a physically measurable catchment attribute and directly influence the value of the lateral transmissivity of soil. Table 1 shows that the lateral transmissivity of soil  $T_o$  is 9.8 m<sup>2</sup>/hr which is identified at 50m DEM resolution of the Kamishiiba catchment. Figure 2 shows that the soil-topographic index distribution in Equation (1) obtained from 1000m DEM resolution has not matched with the soil-topographic index distribution of 50m DEM resolution when the same  $T_o$  value identified at 50m DEM resolution is used.

It is also observed that the distribution of soil

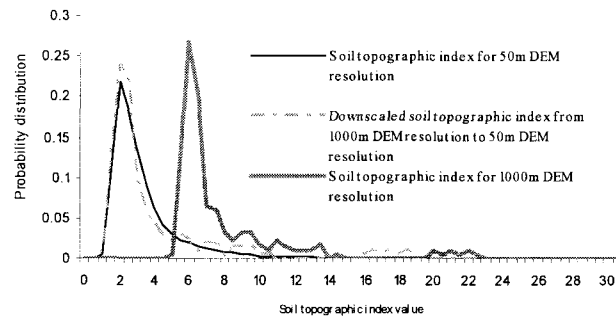
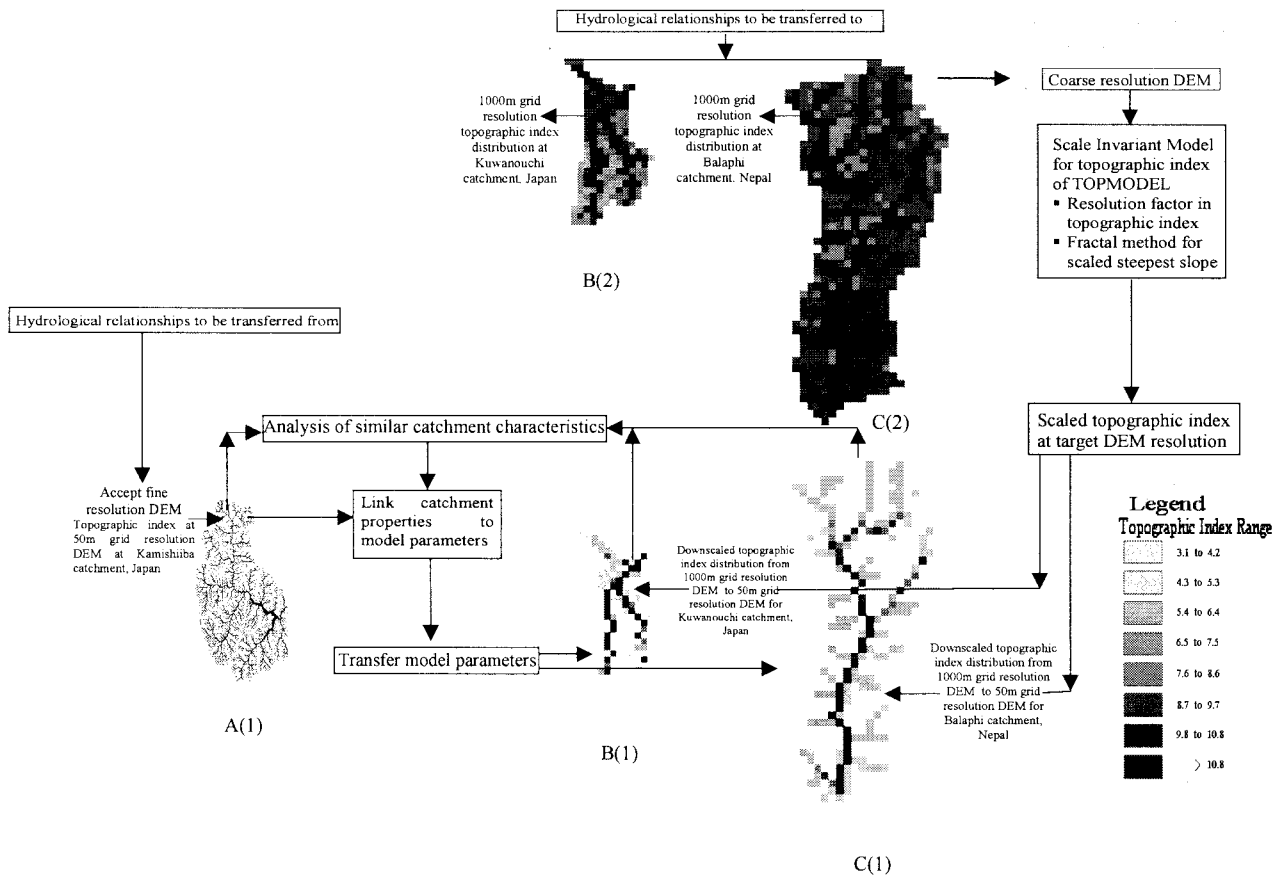


Fig. 2 Analysis of soil topographic index by applying the method of downscaling the topographic index

topographic index, defined in Equation (1), from 1000m DEM resolution can match with that of 50m DEM resolution if the  $T_o$  value is increased. In this case, the  $T_o$  value reached 500 m<sup>2</sup>/hr, exceeding the physically acceptable range. Moreover, such high values of  $T_o$  may preserve subsurface flow properties for coarse resolution DEM in a desirable way, but at the same time changes the infiltration behaviour of Green-Ampt equation that can be coupled with TOPMODEL concept, saturation excess model<sup>6)</sup>. From this point of view it is quite clear that if not taken into account the physically reliable lateral transmissivity,  $T_o$  value, it can be a dangerous tendency to extrapolate the findings of studies in a region to suggest generalizations for all regions, especially where saturation excess overland flow and infiltration excess overland flow are equally dominant as discussed by Pilgrim<sup>7)</sup>.

This is why the detail DEMs (e.g. 50m DEM) are requested to have a basic parameter values to be transferred. Figure 3 shows a schematic draw to represent the process for transferring hydrological relations from one region to another. Some gauged basins may only have coarse resolution DEM and in that case the topographic index should be downscaled before the catchment attributes are linked to the model parameters. Figure 2 shows that the soil-topographic index distribution obtained from the downscaled topographic index from 1000m to 50m DEM resolution and using  $T_o$  value 9.8 m<sup>2</sup>/hr has matched with the soil topographic index distribution of 50m DEM resolution.

At this point, the method to downscale topographic index distribution has solved two problems. Firstly, it fulfilled the hydrological similarity concept of TOPMODEL across different DEM resolutions of a catchment by keeping the same effective parameter value of  $T_o$  and the topographic index. Secondly, it has given consistency to the effective parameter (which



**Fig. 3** Process description for transferring physical based hydrological relationships between catchments in the same region or at different regions. A(1): Kamishiba catchment (210 km<sup>2</sup> in Japan) with 50m DEM resolution topographic index distribution. B(2): Kuwanouchi catchment (187 km<sup>2</sup> in Japan) with 1000m DEM resolution topographic index distribution. B(1): Kuwanouchi catchment (187 km<sup>2</sup> in Japan) with downscaled topographic index distribution from 1000m DEM resolution to 50m DEM resolution. C(2): Balaphi subcatchment (650 km<sup>2</sup>) in Sunkoshi basin in Nepal with 1000m DEM resolution topographic index distribution. C(1): Balaphi subcatchment (650 km<sup>2</sup>) in Sunkoshi basin in Nepal with downscaled topographic index distribution from 1000m DEM resolution to 50m DEM resolution.

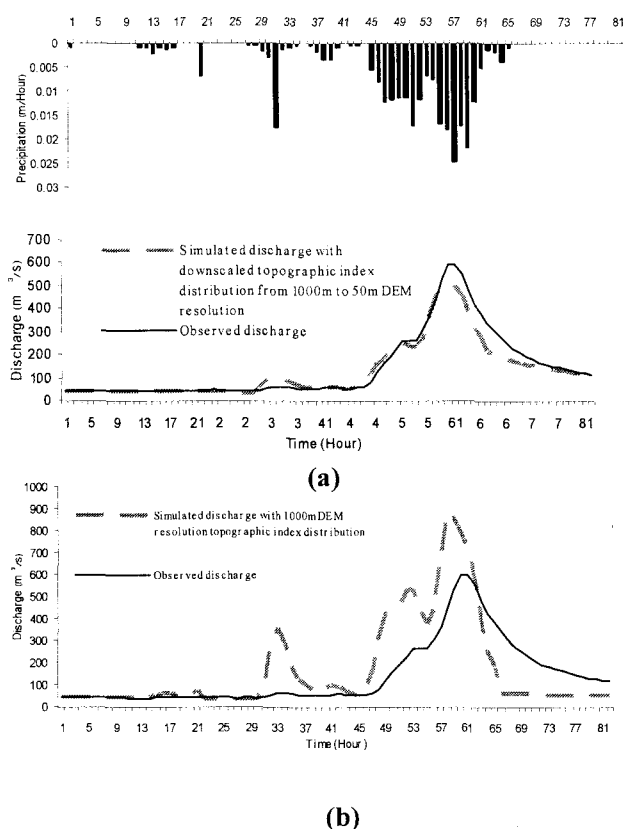
otherwise is influenced by DEM resolution) with observations at the scale of interest. Moreover, it is also equally important to have a well defined hydrological data, rainfall runoff data, in time and space to identify effective parameter values from a catchment for generalizing to other catchments. Kamishiba catchment in Japan has rainfall runoff data that is well defined in time and space.

## (2) Transferring physically based parameters across regions

The mismatch in scales between the scale from which effective model parameters are derived and the scale of application can lead to significant bias in predicting ungauged basins and hence should be avoided. At least all the ungauged basins in the world have 30 arc second global topography data. In this case, to make the existing hydrological similarity to be independent of spatial scale, the topographic index should be downscaled to target

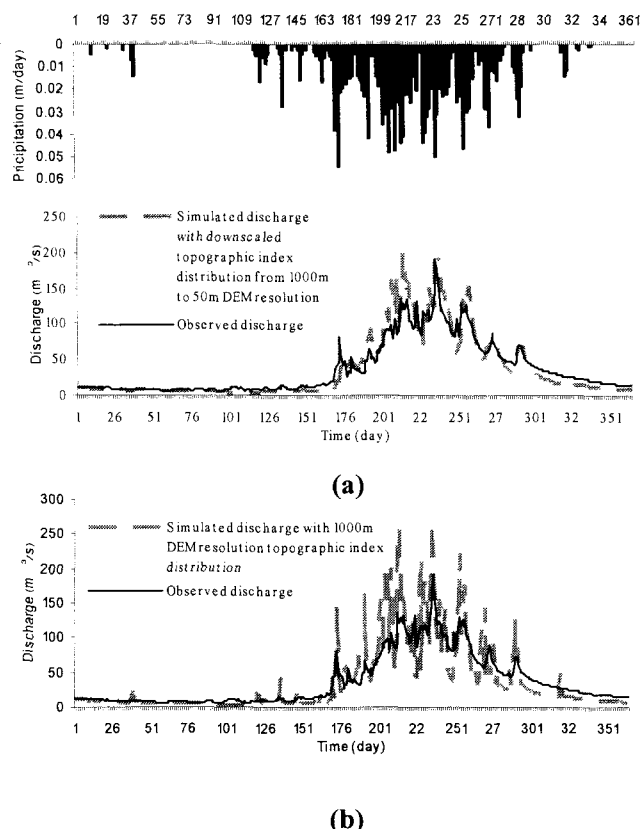
fine resolution DEM. Figure 3 B(2) and C(2) are the topographic index distribution of 1000m DEM resolution in the Kuwanouchi catchment (187 km<sup>2</sup>, adjacent to the kamishiba catchment) and the Balaphi catchment (650 km<sup>2</sup>, in the Koshi basin in Nepal) respectively. The Kuwanouchi catchment and the Balaphi catchment are used here to analyze the validity of transferability of parameters from catchment to catchment in a region and from one region to another when there is lack of fine resolution DEMs. Figure 3 B(1) and C(1) are the downscaled topographic index distribution to 50m DEM resolution from 1000m DEM resolution in the Kuwanouchi catchment and the Balaphi catchment respectively.

Analyzing the similarity of hydrological response on the basis of field evidence of hydrological processes finds an important task for the transformation of parameters. The Balaphi catchment lies in the Sun Koshi basin having



**Fig. 4** Simulation results by applying the parameters identified at 50m DEM resolution TOPMODEL in Kamishiiba catchment (210 km<sup>2</sup>) and applied at Kuwanouchi catchment (187 km<sup>2</sup>) with (a) downscaled topographic index from 1000m DEM resolution to 50m DEM resolution that gave Nash efficiency of 92% and (b) 1000m DEM resolution topographic index distribution that gave Nash efficiency of 5%. Kamishiiba and Kuwanouchi catchments are adjacent catchments in Japan.

subtropical climate and monthly average humidity rising up to 80% during the rainy season. Humidity in the dry season, on the other hand, varies widely during a one-day period and is much lower than of the rainy season. Rainfall distribution in the Sunkosi basin is in a concentric circular pattern. Maximum rainfall in the Sun Kosi is 3,500mm with a minimum of 2,000mm per year. The Kamishiiba catchment and the Kuwanouchi catchment lies in Kyushu island of Japan that also experience subtropical climate with high humidity in summer and comparatively lower humidity in winter. The average annual rainfall is 2500mm. The defined catchments' regions in Japan and Nepal have tectonic activity leading to weaker geological formation. The mountainous setting in both the regions in Japan and Nepal creates rivers that have steep channel slopes. Thus, there are possibilities that the parameter values obtained at the kamishiiba catchment in Japan is applicable at the Balaphi catchment in Nepal.



**Fig. 5** Simulation results by applying the parameters identified at 50m DEM resolution TOPMODEL in Kamishiiba catchment (210 km<sup>2</sup>, Japan) and applied at Balaphi catchment (650 km<sup>2</sup>, Nepal) with (a) downscaled topographic index from 1000m DEM resolution to 50m DEM resolution that gave Nash efficiency of 83%, year 1992 and (b) 1000m DEM resolution topographic index distribution.

#### 4. VALIDATION OF MODEL AND PARAMETER TRANSFERABILITY

Having set the conditions mentioned in above steps we validate the transferability of the model parameters from one catchment to another in the same region and to the specified another region.

The identified parameter, shown in Table 1, by 50m DEM resolution TOPMODEL at the Kamishiiba catchment (210 km<sup>2</sup>, Japan), is used at the Kuwanouchi catchment (187 km<sup>2</sup>, Japan) and the Balaphi catchment (650 km<sup>2</sup>, Nepal). For the Kuwanouchi catchment 50m DEM is available but for the validation purpose to effectively solve the problem of unavailability of fine resolution DEM, we downscaled the topographic index distribution from 1000m DEM resolution to 50m DEM resolution shown by Fig. 3 B(1). The simulated discharge with the same parameter given in Table 1 gave Nash efficiency of 92% in simulation result

shown in Fig. 4 (a). This shows that the proposed methodology for transferring hydrological relationships between catchments can be a potential tool for predicting ungauged basins in a region.

For the catchments in Nepal only the available DEM is the 30 arc second (about 1 km) global topography data. We downscaled the topographic index distribution of the Balaphi catchment from 1000m DEM resolution to 50m DEM resolution shown by Fig. 3 C(1) and used the same parameter given in Table 1 which gave Nash efficiency of 83% in simulation result shown in Fig. 5 (a). The rainfall used is the daily rainfall data from the nearest available gauging stations; gauging station numbers are 1006, 1008 and 1009, and the evaporation data for year 1992 is obtained from Climatological records of Nepal <sup>8)</sup>; meteorological station number 1103. This shows that the proposed methodology for transferring hydrological relationships between catchments can be a potential tool for predicting ungauged basins at another specified region.

On the other hand, applying the same parameters given in Table 1 at 1000m DEM resolution topographic index distribution in the Kuwanouchi catchment and the Balaphi catchment gave drastically dropped down Nash efficiency of 5% in Fig. 4 (b) and 50% in Fig. 5 (b) respectively. The use of coarser resolution DEM shifts the average topographic index,  $\lambda$ , to a higher value. In TOPMODEL formulation  $\lambda$  plays a significant role. As  $\lambda$  increases, the average saturation deficit decreases that leads to most of the part of the catchment to be saturated. This is why the overestimation of the simulated discharge during rainfall duration in Fig. 4 (b) and 5(b) are observed. The increase in  $\lambda$  value also results in less variability of subsurface flow. This is the reason for the underestimation of the simulated discharge during no rainfall hours in Fig. 4 (b) and 5(b).

This makes clear that linking parameterizations across scales is the fundamental requirement to transfer the hydrological relations from one catchment (location) to another (ungauged catchment).

## 5. CONCLUSION

We purpose a method to develop a transferable rainfall runoff model and transferable model parameters to assist prediction in ungauged basins. We use the scale invariant model for topographic index as the landscape specific transfer function to allow for a priori estimation of the effective model parameters set for ungauged catchments based on available catchment properties in that region. The

research basis for the development of a hydrologic transferable model are a) the understanding of the dominating hydrological processes linked to typical properties of the basin; b) the assessment of the physically realistic basin properties with appropriate scale of measurement; c) linking the identified catchment properties across scales; d) linking between these typical catchment properties as scale independent hydrological relationships; and e) validation of the similarity response function for the compilation of the possible transferable model parameters set in that specific region. The results shown based upon the proposed method leads to the conclusion that the method of transferring scale independent hydrological relationships can serve as a potential tool for regionalization of parameters and for predicting ungauged basins.

**Acknowledgement:** A part of this study was supported by Grant-in-Aid for Scientific Research (A)(1) 16206050 (PI: Prof. K. Takeuchi, Yamanashi Univ.) and CREST program of JST (PI: Prof. K. Takara, Kyoto Univ.).

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(Received September 30, 2004)