Influence of land surface topography on flood hydrograph

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Abstract: Topography is one element that affects natural floods. This article examines the general effect of topography changes on flood parameters, such as maximum flood discharge and time to peak. The Erpe catchment is a base catchment, and then several artificial catchments are created that are dissimilar only in topography. ArcView GIS software was used to create the artificial topography maps. Twenty-four artificial catchments were created by ArcView. Nine out of 24 have a land surface slope less than the existing condition and others (25) have a land surface slope steeper than existing conditions. So NASIM rainfall runoff model is used to calculate flood hydrograph for both real and artificial catchments. According to the results, the catchments are divided into four categories: low land, medium lands, steep and very steep lands, which will be described.
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1. Introduction

Five elements affect every natural flood. The first is identified as meteorological elements (e.g. temperature, rainfall, evaporation, sunshine, wind, etc.). The second group comprises the soil information (e.g. soil type, hydraulic conductivity, field capacity etc.). The third element is known as topographical elements (land surface slope, river longitudinal profile, river cross section). The fourth is land use (agricultural area, settlements area, land cover. etc.), and the final one is river network elements (Chow, 1966; Linsley 1997). Topographical elements influence land use and drainage network elements. For instance, farm land and settlement areas are usually located on the low land surface slopes, while mountain catchments have steep land surface slope and also a more condensed drainage network. Examining the general effect of changes of topography on flood parameters is considered here by using the NASIM rainfall runoff model. The Erpe catchment is taken as a base catchment, and then various artificial catchments are produced that are dissimilar only in topography. Other information about catchment such as soil, land use, and climate data are the same. Arcview GIS software was used to produce the artificial topography maps.

NASIM rainfall runoff model is used to calculate the flood hydrograph. It is a distributed and physically based hydrological model for long-term and single-event simulation (DVWK, 1999). The model provides a full partition of a drainage basin into a tree structure of tributaries with the fundamental runoff producing units (either hill slopes or subcatchments) arranged as leaves on the channel tree. Processes are available for reservoir hydrology, flood routing, flow concentration, and water balance for soil and catchment. NASIM supports both rural and urban regions simulations. The main purpose of the NASIM hydrological model is the "continuous simulation of the entire water balance and illustration of all fundamental physical process of storage and water movement (snow, soil humidity, groundwater, and inshore waters)" (Hydrotec, 2002). The guiding principle is based on the hydrological calculation of the whole water cycle using long-term simulation with statistical analysis of the calculated series of runoff events. The model contains mainly hydrological (linear differential) equations. The model structure and algorithms defined aim for a compromise between a sufficient degree of sophistication and general applicability under the given condition.

1.1 Characteristics of Erpe Catchment

The Erpe catchment is located in northwest of Hesse, near the border of North Rhine-Westphalia in Germany and Erpe River flows from south to north. It joins the Diemel River in the north of Volkmarsen. The catchment's area is 153.27 km². Wolfhagen is the biggest city on the catchment in addition to many small cities such as Breuna, Niederelsungen, Oberelsungen, and Ehringen (Figure 1).

1.2 Topography

The Erpe is located on a low land area. The difference of altitude between the lowest point and the highest point is only 425 m. The lowest point of the catchment is located at the catchment mouth, which has an altitude of 175.4 m above sea level. The highest point of the catchment is 599 m high and located on top of the hill in the east of the catchment. There are also some small hills in the south and east of the catchment. The majority of slope is from south to north. In the light of low slope area and good soil, most of the area is farm land (Figure 2).

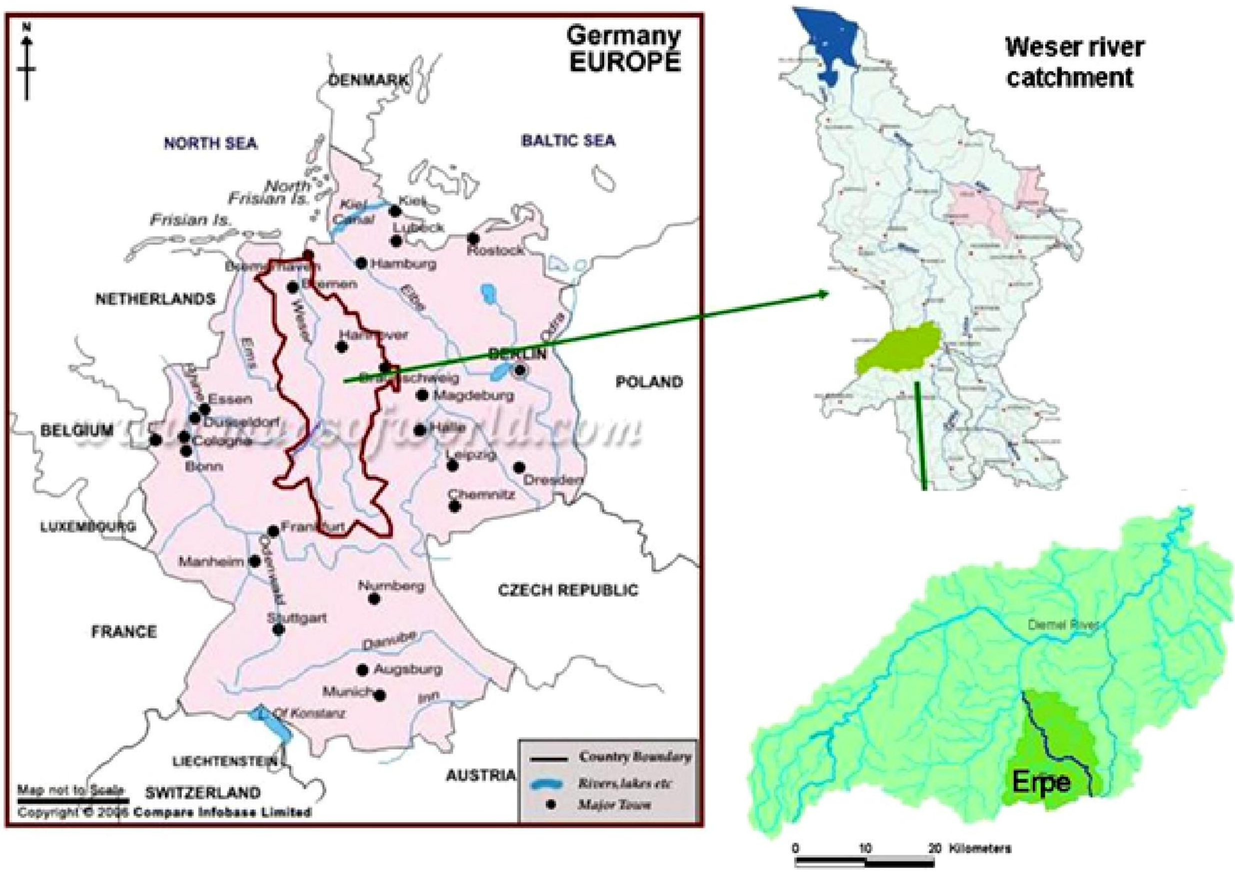


Figure 1: Location of Erpe catchment

1.3 Geology and soil types

According to the report of Erpe catchment (HWD, 2004), the soil information was derived from ATV-DVWK reports (2003). It is covered by four soil types: debris sand (gS), poor sandy loam (Ls2), clay (T), and silt (U) (Figure 2-B). In addition, the catchment soils are categorized by a combination of soil type and landscape that are characteristic of each type measured (e.g. wilting point, field capacity, total pour volume, hydraulic conductivity and maximum infiltration rate).

1.4 Climatological data

For the rainfall- runoff simulation, climatologic data (such as precipitation, temperature, evaporation, and evapotranspiration) are needed. This research uses one-hour rainfall over the whole catchment. The intensity and diversity of rainfall are the same with the result of the research by HWD (2004). Accordingly, the rainfall with one-hour duration and a 100-year frequency for the Erpe catchment is 52 mm (Masoudian, 2009).

1.5 Land use

The Erpe catchment is located in the low mountainous region. It contains a rural structure with multiple independent villages that are united and form cities. The city of Wolfhagen, part of Zierenberg, and Breuna are located in the Erpe catchment. Compared to other regions of Germany, the high portion of the catchment in the North Hesse is agricultural lands. This is due to the good soil and low land surface slope (HLUG, 1999). There are compositions of different land use that are shown in Figure 2-C. Farm lands covers 51.5 percent of the Erpe catchment and the rest area are, 16.1 percent mixed forest, 11.1 percent deciduous forest, and 9.3 percent green land. The physical parameters of the individual land uses (root depth, interception, factor, etc. There are large differences in the maximum interception and in the seasonal process, depending upon useful plants. In the context of the available treatment, the different agricultural lands are not differentiated but middle values are accepted. There are also the same situations for different kinds of forests. The factor of interception is relevant from April to July, from zero to one, and returns to zero again. For the settlement surfaces, it is assumed that 30 percent of the surface is sealed (Roettcher, 2001).

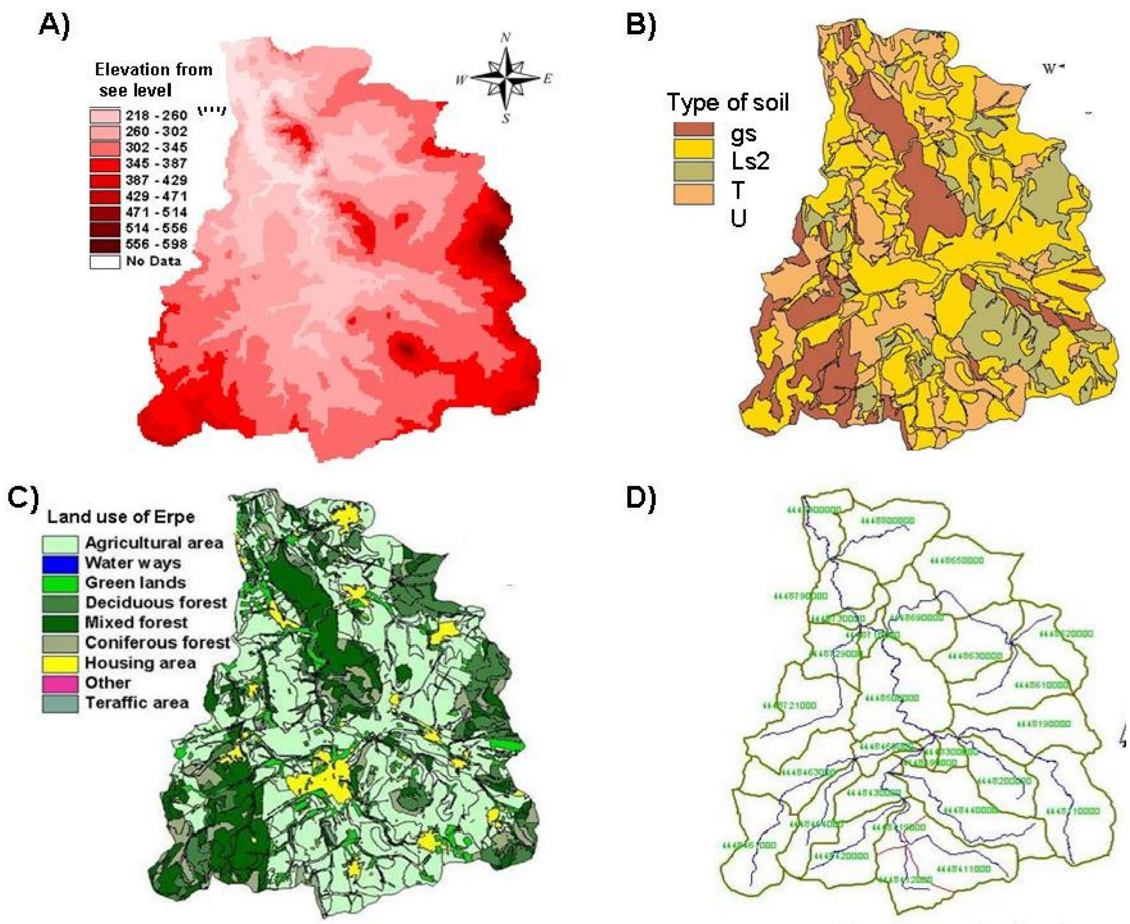


Figure 2: Data maps of Erpe catchment A) The topography, B) Type of soil, C) Land use, D) System plan

2. Material and Methods

2. 1 System plan

The system plan is the main window of the graphical user interface of NASIM. It visualizes the channel system, including all features of the catchment such as subcatchments, channels, storage basins, etc., which are generally called “system element” (hydrotec, 2002). The Erpe catchment is subdivided into 27 subcatchments. Every subcatchment is identified with a unique number. In the model, the hydraulic data (comprised of the river length, slope, and cross section) are entered separately. Usually these data are determined by using GIS maps and field measurements. From these data, NASIM calculates a discharge for steady and uniform flow.

The surface runoff concentration is determined by a time area function. With the digitalized subcatchment borderlines and the digital elevation model, a time area function is generated by using a special extension in GIS environment. The result is a table containing travel time and corresponding area between the isochrones. This table (TAPE20) is used by NASIM rainfall runoff model.

2. 2 Artificial catchments

It is supposed that there are many similar catchments in all specifications and details except for topography (Figure 3). It is clear that in nature there are not even two catchments that satisfy our objective. Therefore, concepts of artificial catchments are used. To produce the artificial catchments, which are identical to the base catchment, the digital topographical maps are used. The digital maps contain a numeric matrix of discrete points that are 40 meters away from each other in the plan view. Every point is defined with three parameters: longitude, latitude, and altitude. In other words, each point has three coordinates that can be defined in geographical or Cartesian coordinates. The base point for these coordinates may be defined locally or globally (UTM system). The altitudes of points are changed to produce the new topography maps.

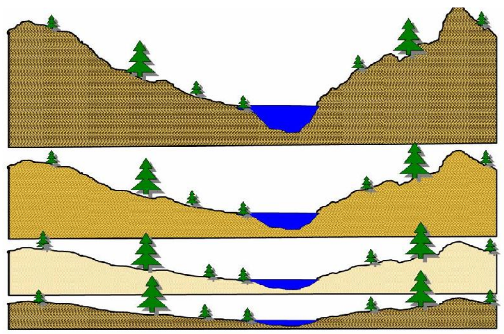


Figure 3: Schematic view of artificial topographies

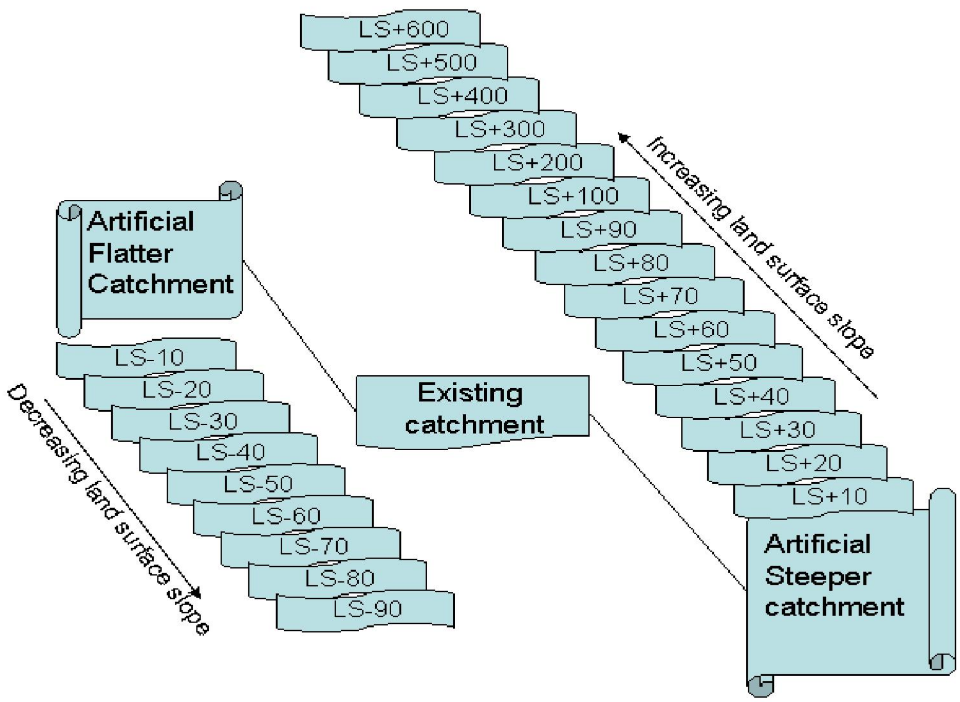


Figure 4: Different artificial catchments

Existing coordinates:

P(X, Y, Z) $\Longrightarrow$ P' (X, Y, Z') Artificial coordinates

Equation 1

$$Z' = Z + C_t \cdot (Z - Z_0)$$

Z_0: The altitude or elevation of the catchment mouth (for the Erpe catchments Z_0= 175 m)

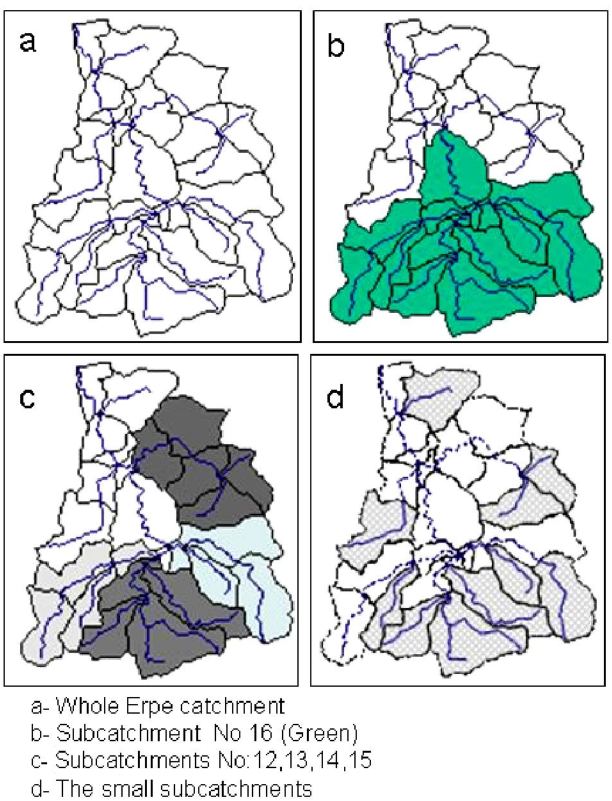
C_t: Coefficient of increasing or decreasing of elevation and it is between -0.9 and +6

According to the above formula, the topography of catchment will be steeper or flatter by different value of C_t. Then 24 artificial catchments were created by Arcview. Nine out of 24 have a land surface slope less than the existing condition (from 10 percent altitude decreased or C_t = -0.1 to 90 percent, altitude decreased or C_t = -0.9) and others (15) have a land surface slope steeper than existing conditions (from 10 percent altitude increased or C_t= 0.1 to 600 percent altitude decreased or C_t=6). The abbreviation of different artificial catchments is as follows: LS (meaning Land Surface Slope) plus or minus (meaning increase or decrease) of C_t multiple 100. For example, LS+100 indicates the artificial catchment with C_t=1 or the net elevation (from catchment mouth altitude) of which every point becomes twice as many (Z'=Z+1 (Z- Z_o)). Figure 4 shows the different artificial catchments with their short-form names.

In the hydrological model, the Erpe catchment is divided into 27 subcatchments with an area less than 10 km². This system is used as a rainfall runoff model. Sixteen stations are selected to examine the flood parameters on the Erpe river system. Figure 5 shows the selected points and their catchment areas. There are 10 stations with catchment areas of less than 15 km² and six stations with an area of more than 15 km². Other than that, there are 25 systems (the existing catchment and 24 artificial catchments) that are simulated by the NASIM rainfall runoff model. The model uses isochrones line of concentration time as an input file called TAPE20. This file is produced by the special extension in Arcview, and it uses the topography maps, subcatchment's borders' definitions, and drainage networks. The results are classified in two groups in accordance with the catchment area:

- Catchments with area less than 15 km² (10 subcatchments)
- Catchments with area more than 15 km² (six subcatchments).

3. Results and Discussions



Sub No	Subcatchment Name In the Model	Area km²	Sealed Area km²
1	4448110000	.9	0.176
2	4448200000	5.1	0
3	4448410000	12.9	0.121
4	4448420000	6	0
5	4448440000	9.5	0.451
6	4448464000	4.8	0
7	4448610000	6.6	0.0391
8	4448620000	4.65	0.116
9	4448721000	8.6	0.133
10	4448800000	8.7	0.251
11	4448900000	154	2.49
12	4448690000	31.5	0.36
13	4448469000	20.9	0.152
14	4448450000	32.7	1.08
15	4448300000	25.1	0.309
16	4448500000	90.4	1.54

Figure 5: The selected subcatchments and their information

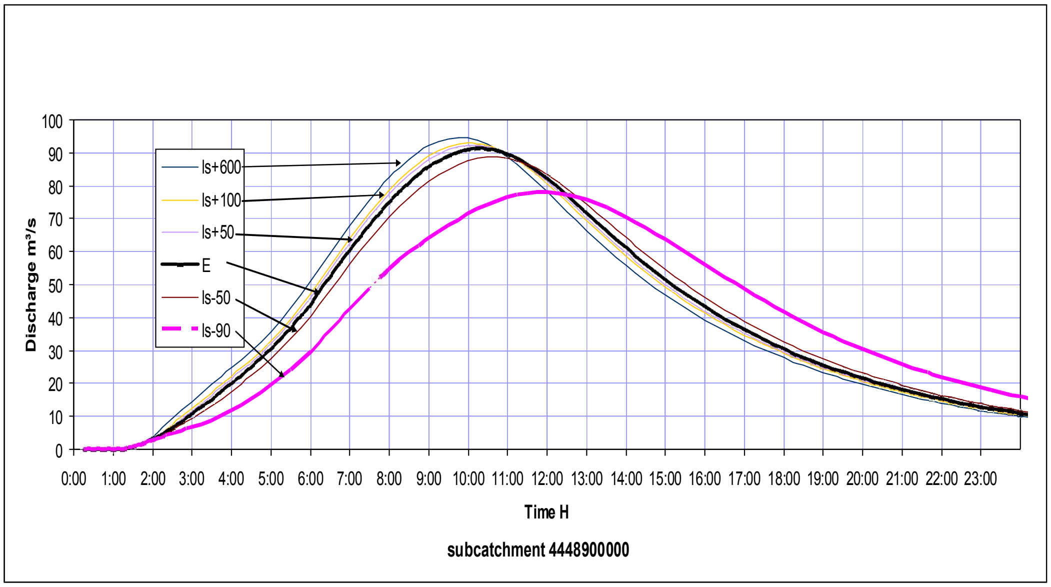


Figure 6: Flood hydrographs for different land surface scenarios (E is exist catchment)

The results of flood parameters (e.g. the flood hydrograph, the maximum discharge, and time to peak) are considered versus the mean land surface slope for each sub catchment. Figure 6 shows the general behavior of flood hydrograph. In the case of the land surface slope increasing, the maximum of the flood hydrograph goes up and left so that the rising limb will have been steeper, and it reveres in the case of land surface slope decreasing. The sensitivity of falling limb to changes of topography is less than rising limb for all scenarios. Consequently, when the catchment becomes flatter, the flood hydrograph will be flatter, too. In other words, the concentration time increases because of the reduction of land surface velocity. Figures 7 a and b show the good connection between relative maximum flood discharge and average land surface slope for small and large catchment area, respectively. It is obvious that the rate of changes for catchments with low land surface slope is very high and is very low for catchments with steep mean land surface slope. The relationship between the relative maximum discharge and the mean land surface slope is:

Equation 2

$$\frac{Q_{\max}}{(Q_{\max})_E} = \gamma \cdot \ln(S_m) + \delta$$

That Q_{max} is the maximum flood discharge for artificial scenario with S_m mean land surface slope, $(Q_{\max})_E$ is the maximum flood discharge for existing situation. The values of γ and δ depend on the catchment size and their amounts are shown in the Table 1.

Table 1: γ , δ , ε and θ are function of the catchment area

Catchment area	γ	δ	ε	θ
Small catchments (4 < A < 15 km²):	0.0851	0.8575	1.2557	0.1406
Large catchments (15 < A < 155 km²):	0.0561	0.899	1,159	0.084

The results show that the catchment topography is not affected on maximum flood discharge for very steep topography (mean land surface slope more than 20 degrees or 36 percent). The flow velocity on the land surface and also in the rivers is the main reason for these behaviors. On the other hand, it is very important for low land surface slope (the mean land surface slope less than 3.5 percent). The time to peak also has a good connection with the mean land surface slope. Figures 8 a and b show the relation between the relative times to peak for each scenario versus the mean land surface slopes. According to the data, the following formula is determined:

Equation 3

$$\frac{T_{\max}}{(T_{\max})_E} = \varepsilon \cdot (S_m)^{\theta}$$

That T_{max} is the time to peak for artificial scenario with S_m mean land surface slope, $(T_{\max})_E$ is the time to peak for existing situation. The values of

ε and θ depend on the catchment size, and are shown in Table 1.

According to the above results, the subcatchments are divided into four categories (table 2). The first category is catchments with a mean land surface slope less than 3.5 percent (2 Deg). In this category, the flood parameters are very sensitive to topography. The second category has a mean land surface slope from 3.5 percent to 10 percent (6 Deg) and is called medium lands surface slope. The flood parameters in this group are sensitive to topography while they are less in the first category. The third category is called steep lands. The mean land surface slope in this category is more than 10 percent and less than 28.6 percent (16 Deg). The fourth category is very steep lands with mean land surface slope more than 28.6 percent. Perhaps there are very small catchments in this category. The important point here is that the topography changes are not important and do not affect the flood parameters.

Table 2: Classification of catchments topographies

Land surface category	description	Mean land surface slope %	Mean land surface slope DEG	$Q_{max}/(Q_{max})_E$
I	Low lands	$S_m < 3.5$	$S_m < 2$	Very sensitive
II	Medium lands	$3.5 < S_m < 10$	$2 < S_m < 6$	Sensitive
III	Steep lands	$10 < S_m < 28.6$	$6 < S_m < 16$	Low sensitive
IV	Very Steep lands	$28.6 < S_m$	$16 < S_m$	Not sensitive

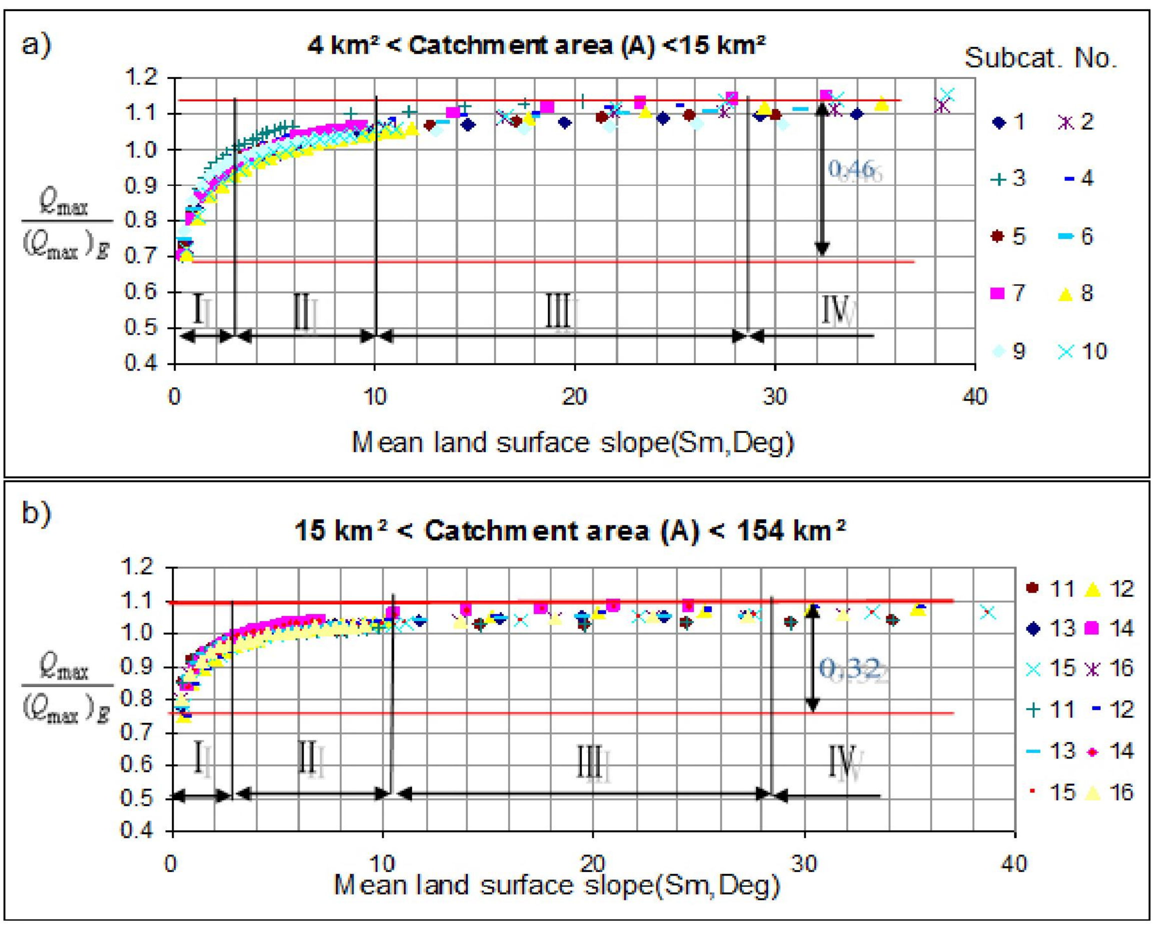


Figure 7: Relation between relative discharge and mean land surface slope for small catchments (above) and large catchments (below)

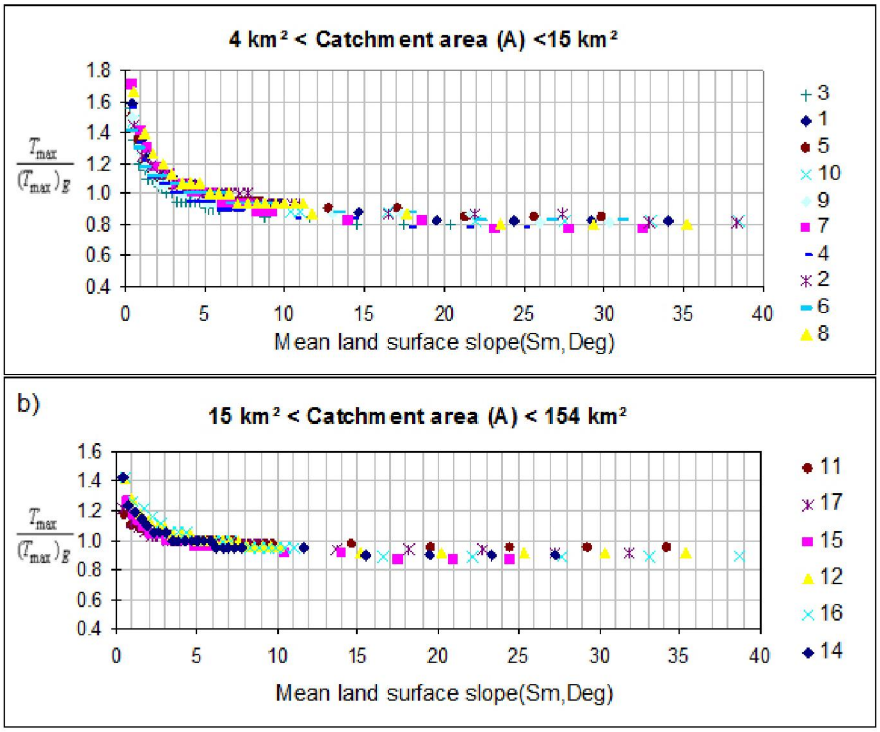


Figure 8: Tmax/(Tmax)E versus land surface slope that T is the time to peak for each scenario ,and TE is the same in existing condition

4. Conclusion

According to effects of the land surface topography on flood parameters, the catchment can be divided into four categories, which have been described. Topography of catchment in low land catchments is very important and the flood parameters are very sensitive to topography changes. By increasing the land surface slope, the sensitivity of flood parameters to topography decreases and finally in very steep catchment it is it has no sensitivity. The topography of catchments is very important while using of NASIM rainfall runoff model.

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