1 **Prediction of geomorphologic parameters of catchment without GIS to**

2 **estimate runoff using GIUH model**

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14 **Abstract:**

15 Estimation of flood in ungauged catchments has great importance in the design of hydraulic

16 structures. The geomorphologic instantaneous unit hydrograph (GIUH) technique uses

17 geomorphologic parameters to estimate catchment runoff. In this research, regression equations

18 were developed based on geometrical characteristics of nine catchments such as area, length and

19 slope of the main river to estimate geomorphologic data of other catchments with no need for

20 GIS and digital elevation model. These equations were used for verification of stream-order-law

21 ratios as well as geomorphologic parameters corresponding to the Gagas, Heng-Chi and Kasilain

22 catchments. In this study, the effect of stream-order-law ratios on the rate of runoff in Kasilian

23 catchment was examined, and the sensitivity of each ratio was analyzed. The GIUH model was

24 assessed in two cases of GIS-supported and GIS-unsupported. The mean errors of the regression

25 equations in estimation of ratios R_B, R_L, R_A, R_S and R_{SO} in three study catchments were 4.7%,

26 23.5%, 7.1%, 41.3%, and 22.9%, respectively. The direct runoff hydrograph for the Heng-Chi

27 and the Kasilian catchments were computed by GIUH model and compared with observed

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28   runoff. According to the results, the errors of peak discharge for four rainfall-runoff events in

29   GIS-unsupported case were, on average, 10% more than the error in the case of GIS-supported

30   GIUH. The results of GIUH for the two cases are very close to each other. The mean coefficient

31   of efficiency of the model was computed as 0.87.

32   **Key words:** GIUH, GIS, Stream-order-law ratios, Geomorphologic parameters

33   **1. Introduction**

34   Estimation of design flood in catchments is a vital issue in design of flood control structures.

35   Most catchments are ungauged and the statistical methods are not efficient, hence the rainfall-

36   runoff models are employed to estimate runoff. GIUH is a rainfall-runoff model for estimating

37   runoff in ungauged catchments using their geomorphologic parameters (GP).

38   Studies on streams orderings of catchments were first introduced by Horton (1932, 1945). Later,

39   modifications were made on Horton's method by Strahler (1952, 1957, 1964) leading to a new

40   method of ordering.

41   The idea of GIUH was introduced by Rodriguez-Iturbe and Valdes (1979). They suggested an

42   instantaneous unit hydrograph (IUH) model in which time to peak and peak flow of the

43   catchment were functions of geomorphologic features. The geomorphologic parameters of the

44   catchments are calculated by GIS software such as ArcGis and hydrologic extensions such as

45   ArcHydro. For this purpose, DEM of the catchment is necessary. First, stream networks are

46   delineated and, GP such as the number of streams, lengths, slopes, and drainage areas in each

47   order of streams is carried out based on stream orderings (Horton-Strahler method).   GIUH

48   model was extended and used by other scientists in different catchments (e.g. Gupta et al. 1980;

49   Rodriguez-Iturbeet al. 1982; Lee and Yen 1997 and Kumar and Kumar 2008).

50   An alternative approach was provided by Lee and Yen (1997). The travel times for different

51   orders of overland areas and channels were derived using the kinematic-wave theory and then

52   substituted into the GIUH model to develop a kinematic wave-based GIUH model for watershed

53   runoff simulation.

54   Lee and Chang (2005) offered a GIUH model to estimate surface and subsurface flow of

55   catchments. In their research, special importance was given to separation of surface flow from

56   subsurface flow in catchments. Sabzevari et al. (2013) modified the model presented by Lee and

57 Chang (2005) for estimation of surface and subsurface flow of Kasilian catchment. They have

58 also given a saturation model for separation of saturated and unsaturated zones of overland

59 regions.

60 Sabzevari and Norouzpoor (2014) suggested a GIUH model which is capable of taking plan

61 shape and profile curvature in complex hillslopes in computation of surface and subsurface travel

62 time. Also, the effect of geometry of complex hillslopes on the runoff in sub-catchment No. 125

63 of Walnut Gulch was investigated.

64 Kumar et al. (2004, 2007) rendered the runoff estimation of ungauged catchments by applying

65 the GIUH-based Nash and Clark models. They used stream ratios to estimate Nash and Clark's

66 parameters. Kumar and Kumar (2008) focused on estimation of runoff in Ramganga catchment,

67 India, applying GIUH based on kinematic wave theory. The model was used in the cases where

68 the inputs were geomorphologic parameters and stream-order-law ratios. Travel time of the

69 streams and overland regions in the two above cases were given as analytic equations based on

70 Horton-Strahler stream-ordering system.

71 Choi et al. (2011) used a concept of geomorphologic dispersion to estimate Nash model

72 parameters from spatial heterogeneity of flow path within a catchment.

73 Based on GP of catchment, stream-order-law ratios such as bifurcation ratio (R_B), stream-length

74 ratio (R_L), stream-area ratio (R_A), and stream-slope (R_S) ratio could be computed. According to

75 the GIUH offered by Yen and Lee (1997), the travel times of overland region and stream could

76 be worked out regarding stream-order-law ratios prior to IUH estimation.

77 Due to the lack of topographic map and DEM for most of the catchments, application of GIS-

78 based GIUH models is practically useless. One goal of this research is to provide a technique by

79 which one could compute geomorphologic parameters without the need for GIS. Calculating the

80 GP by means of GIS is costly and takes a long time. For example, extensions such as ArcHydro,

81 though capable of calculating the number, length, and slope of streams at any order, provide no

82 information about overland surface slopes or drainage area at any order which ought to be

83 calculated manually by GIS specialists which is time consuming. For this purpose, GP of twelve

84 catchments of various sizes with diverse stream networks were collected. The values of stream-

85 order-law ratios and the actual GP of the catchments obtained from GIS were derived.

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86   To study the relation between data, linear and nonlinear regressions were used using the SPSS

87   software. In general, length and slope of the main stream and area of the catchment are among

88   the geometric parameters that are easily computable for every catchment. It is also important to

89   present empirical equations which could predict all stream-order-law ratios based on the

90   geometrical catchment information.

91   The important aims of this research are:

92   (1) to present equations which can predict, without the use of GIS and DEM of the catchment,

93   the stream-order-law ratios on the basis of length, slope of the main stream and area of

94   catchment (geometrical features).

95   (2) to analyze sensitivity of stream ratios and its effect on direct runoff hydrograph (DRH).

96   (3) to estimate runoff of ungauged catchments by means of GIUH without the use of GIS.

2. GIUH model

98   Surface runoff of the overland regions moves, through stream networks, to the outlet of

99   catchment. If a catchment is ordered via Strahler ordering scheme, the water travel paths from

100   the overland regions to the outlet are specified. Each flow path is comprised of different states,

101   the first of which is the overland region and the others are the streams. The probability of water

102   motion in a certain path $w : x_{o_i} \rightarrow x_i \rightarrow x_j \rightarrow ... \rightarrow x_\Omega$ is expressed as:

$$P(w) = P_{OA_i} P_{x_{oi} x_i} P_{x_i x_j} ... P_{x_k x_\Omega} \tag{1}$$

104   where P_{OA_i} is the initial state probability of rain drop moving from ith order overland region to

105   the ith order stream, which can be approximated as the ratio of ith order overland area to the total

106   catchment area; $P_{x_{oi} x_i}$ which is the probability of raindrop moving from ith order overland region

107   (x_{o_i}) to ith order stream equals one; and $P_{x_i x_j}$ is the transitional probability of rain drop moving

108   from ith order stream (x_i) to jth order channel (x_j).

109   The number of streams at each order and how they are connected to each other specify the

110   probabilities in Eq. (1).

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111   The value of IUH of a watershed comprising different runoff paths is given by Eq. (2)

112   (Rodriguez-Iturbe and Valdes 1979).

113   $$u(t) = \sum_{w \in W} [f_{x_{o_i}}(t) * f_{x_i}(t) * f_{x_j}(t) * .... * f_{x_\Omega}(t)]_w \times P(w) \qquad (2)$$

114   where $f_{x_k}(t)$ denotes the travel time probability density function (PDF) in state x_k with a mean

115   travel time value (T_{x_k}) and the function f is indeed the IUH of any state x_k calculated by the

116   formula $f(t) = (1/T_{x_k}) \exp(-t/T_{x_k})$. The PDF is a function of the travel time of each state in the

117   overland regions and streams. Asterisk (*) denotes a convolution integral. $w \in W$, W being

118   $W = \langle x_{o_i}, x_i, x_j, ..., x_\Omega \rangle$, $i = 1, 2, 3, . . . , \Omega$ and t is the time.

119   To solve Eq. (2), one could resort to the Laplace transformations. In the process of GIUH

120   derivation, computation of travel time is the most intricate part of the work because its value

121   depends on GP of the catchment.

122   The ordinates of DRH for the catchment were estimated by convoluting the effective rainfall

123   hyetograph with the derived IUH.

124   The equation for estimation of DRH is:

125   $$Q(t) = \int_0^t u(t - \tau) I_e(\tau) d\tau \qquad (3)$$

126   where I_e is the excess rainfall and $u(t)$ is the catchment IUH.

127   **2.1. Travel time of overland planes and streams**

128   According to the kinematic wave theory, the travel time of an overland plane depends on the

129   length, slope, Manning coefficient, and excess rainfall intensity. Eq. (4) which is due to Yen and

130   Lee (1997) gives the travel time of the ith overland plane.

131   $$T_{X_{oi}} = \left(\frac{n_0 A P_{OA_i} \sum_{i=1}^{\Omega} R_L^{i-\Omega}}{2a^{1/2} S_{c_\Omega}^{b/2} L q_L^{m-1} R_B^{\Omega-i} R_L^{i-\Omega} R_S^{b(i-\Omega)/2}} \right)^{1/m} \qquad (4)$$

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132   where R_B, R_L, R_A, and R_S are bifurcation ratio, stream-length ratio, stream-area ratio, and stream-

133   slope ratio, respectively; A is the area of the catchment; a and b are 5.463 and 1.083,

134   respectively; q_L is the excess rainfall intensity; n_0 is the Manning's roughness coefficient for

135   overland flow; $S_{c\Omega}$ is slope of the highest order stream; the constant m can be recognized as 5/3

136   from Manning's equation and L is sum of mean length of the streams of different orders.

137   The travel time of the ith-order channel in each path is obtained, based on its GP, through Eq. (5)

138   (Yen and Lee 1997):

$$T_{X_i} = \frac{B_\Omega L R_L^{i-\Omega} R_B^{\Omega-i} \sum_{i=1}^{i} R_L^{i-\Omega}}{q_L A P_{OA_i} (\sum_{i=1}^{\Omega} R_L^{i-\Omega})^2} \left[\left(h_{co_i}^m + \frac{q_L A P_{OA_i} n_c \sum_{i=1}^{\Omega} R_L^{i-\Omega}}{B_\Omega S_{c\Omega}^{1/2} R_S^{(i-\Omega)/2} R_B^{\Omega-i} \sum_{i=1}^{i} R_L^{i-\Omega}} \right)^{1/m} - h_{co_i} \right]$$ (5)

140   where h_{co_i} is the inflow depth of the ith-order channel due to water transported from upstream

141   reaches, is given as:

$$h_{co_i} = \left(\frac{q_L n_c A (R_B^{\Omega-i} R_A^{i-\Omega} - P_{OA_i}) \sum_{i=1}^{\Omega} R_L^{i-\Omega}}{S_{c\Omega}^{1/2} B_\Omega R_S^{(i-\Omega)/2} R_B^{\Omega-i} \sum_{i=1}^{i} R_L^{i-\Omega}} \right)^{1/m}$$

142   (6)

143   Where n_c is the Manning coefficient of stream, B_Ω is the width of the stream. The value of h_{coi} is

144   equal to zero for i=1.

145

146   **3. Geomorphologic parameters (GP)**

147   As observed in the Eqs. (5) and (6), the stream-order-law ratios particularly, R_S, R_A, R_L, R_B are of

148   high importance. These affect the travel time, IUH, and DRH; also, they are computed according

149   to the GP. For this purpose, the stream network is delineated by means of GIS. In the GIS, the

150   streams are ordered via Horton-Strahler method, and the number, length, and slope of the

151   streams are calculated at each order.

152   The value of R_B is given by the following equation regarding the number of stream segments at

153   each order:

154 $$R_B = N_{i-1} / N_i \quad , i = 2, 3, ..., \Omega \tag{7}$$

155 N_i denotes the number of ith-order channels. The length ratio (R_L) is:

156 $$R_L = \overline{L_{c_i}} / \overline{L_{c_{i-1}}} \quad , i = 2, 3, ..., \Omega \tag{8}$$

$\overline{L_{c_i}}$ is the mean length of ith-order channels. Eq. (9) yields the value of R_A: 157

158 $$R_A = \overline{A_i} / \overline{A_{i-1}} \tag{9}$$

159 where $\overline{A_i}$ is the mean area of catchment of order i. It should be noted that the mean area of a

160 given stream segment is, in fact, a cumulative value, for example, the area of a third-order

161 catchment is a sum of the areas of the first, second and third-order streams. Computation of R_A is

162 not so easy a task for the GIS users.

163 The value of R_S depends on the streams slope and is obtained by Eq. (10):

164 $$R_S = \overline{S_{c_i}} / \overline{S_{c_{i-1}}} \quad , i = 2, 3, ..., \Omega \tag{10}$$

165 where $\overline{S_{c_i}}$ is the mean slope of the ith-order streams.

166 As a result of experiments in the natural catchments, the following ranges are observed:

167 $3 \le R_B \le 5$ and $1.5 \le R_L \le 3.5$. Slope of the streams and overland planes for different catchments

168 at each order are different. The mean values of these slopes at each order take a considerable

169 time to compute by GIS, especially in large catchments.

170 In this research, a new slope ratio named the overland slope ratio (R_{SO}) is introduced that is given

171 in terms of the mean slope of the overland plane by:

172 $$R_{SO} = \overline{S_{o_{i-1}}} / \overline{S_{o_i}} \tag{11}$$

173 where $\overline{S_{o_i}}$ is the mean slope of the ith-order overland plane.

174 In this research we intend to find the relationship between R_{SO} and the other stream-order-law

175 ratios.

176 Herein, a way for computing GP via regression equations is sought. These equations attained by

177 regression methods work through statistical analysis of the information of catchments possessing

178 geomorphologic attributes. The way these equations perform computations will be explained in

179 the next sections.

180 **4. Case Study**

181 To study the relationship between geomorphologic parameters, knowledge of the GIS based GP

182 (i.e the GP derived from GIS) of some natural catchments is required. This research uses

183 information received from twelve catchments in different countries. Table (1) shows the GIS

184 based GP along with stream order ratios of the case study catchments. The catchments Long chi

185 (Shuyou et al. 2010); Long men (Shuyou et al. 2010); Chaukhutia (Kumar 2014); Al-Malaqi

186 (Shadeed et al. 2007); Debarwa (Alemngus and Mathur 2014); Gherghera (Alemngus and

187 Mathur 2014); San-Hsia (Chang and Lee 2008); Al-Badan (Shadeed et al. 2007); Al-Faria

188 (Shadeed et al. 2007) were used for training and estimation of regression equations, and the

189 Gagas (Kumar and Kumar 2008), Heng-Chi (Lee and Chang 2005) and Kasilian (Sabzevari et al

190 2013) catchments were used for verification of the suggested equations.

191 The columns Table (1) (from left to right) illustrate, respectively, the catchment name, stream

192 order (i), number of streams, mean stream length, mean stream area, mean stream slope, mean

193 overland slope, R_B, R_L, R_A, R_S, and R_{SO}.

194 The Heng-Chi catchment is located in northern Taiwan and has an area of 53 km^2 (Lee 1998).

195 The Gagas catchment lies in the middle and outer range of the Himalayas in Uttarakhand State of

196 India and has an area of 506 km^2 (Kumar and Kumar 2008). The Kasilian Catchment is located

197 between 53° 18$^{'}$ E and 53° 30$^{'}$ E longitudes and 35° 58$^{'}$ N to 36° 7$^{'}$ N latitudes in the north of Iran

198 and has an area of 67.8 km^2. Figure (1) shows the Gagas and Kasilian catchments.

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205   Table 1. GP of twelve case study catchments

Catchment Name	Geomorphologic parameters									
	Order	N_i	$\overline{L_i}$	$\overline{A_i}$	$\overline{S_c}$	$\overline{S_o}$	R_B	R_L	R_A	R_S	R_{SO}
1. Gagas	1	121	1.74	3.02	0.172	0.810	4.8	2.4	5.4	0.4	2.6
	2	23	3.04	18.58	0.141	0.655					
	3	6	7.63	79.22	0.041	0.172					
	4	1	23.4	506	0.017	0.065					
2. Heng-Chi	1	30	0.66	1.043	0.087	0.450	3.3	2.6	4	0.6	1.1
	2	6	2.74	6.919	0.050	0.419					
	3	2	1.6	19.9	0.012	0.349					
	4	1	4.97	53.23	0.012	0.347					
3. Kasilian	1	42	1.6	0.915	0.241	0.345	3.5	1.5	4.3	0.4	1.1
	2	11	1.79	4.813	0.070	0.297					
	3	3	2.45	20.75	0.047	0.263					
	4	1	4.65	67.8	0.008	0.261					
4. San-Hsia	1	69	0.92	1.15	0.161	0.314	4.2	2.9	5	0.4	1.1
	2	16	2.08	4.99	0.092	0.203					
	3	3	3.88	18.15	0.037	0.364					
	4	1	17.8	125.9	0.013	0.293					
5. Al-Badan	1	41	1.38	1.37	0.170	0.140	4	1.5	4.5	1	1.7
	2	6	3.2	10.12	0.092	0.062					
	3	2	5.03	40.73	0.140	0.051					
	4	1	3.17	85	0.135	0.029					
6. Al-Faria	1	49	1.03	0.937	0.154	0.117	4	1.5	4.3	1.1	1.6
	2	8	2.12	6	0.085	0.058					
	3	3	3.5	19.4	0.161	0.033					
	4	1	2.62	64	0.125	0.031					
7. Al-Malaqi	1	62	1.92	1.81	0.146	0.140	9	1.3	17	0.8	4.3
	2	16	2.61	5.83	0.122	0.063					
	3	1	3.21	185	0.081	0.010					
8. Debarwa	1	23	2.26	5.6	0.032	0.135	4.9	3	6	0.6	1.2
	2	6	4.2	27.8	0.018	0.091					
	3	1	17.7	195	0.010	0.098					
9. Gherghera	1	58	2.45	5.9	0.027	0.136	2.9	1.4	3.3	0.9	1.4
	2	14	4.19	30.6	0.018	0.087					
	3	5	10.2	101.0	0.010	0.064					
	4	2	4.47	259.9	0.016	0.025					

	5	1	4.19	525.7	0.011	0.117					
10. Long chi	1	46	1.13	2.5	0.210	0.444	3.7	2.4	4	0.6	1.1
	2	10	3.45	11.8	0.124	0.487					
	3	4	3.19	32	0.073	0.514					
	4	1	9.94	141.8	0.054	0.364					
11. Long men	1	58	1.31	2.74	0.560	0.256	4	2.2	4.7	0.9	1.8
	2	13	2.48	12.3	0.560	0.123					
	3	3	9.33	77.11	0.560	0.056					
	4	1	8.18	246.8	0.385	0.056					
12. Chaukhutia	1	134	1.41	2.27	0.191	0.910	5.3	2.5	5.7	0.5	2.4
	2	31	2.65	12.28	0.123	0.567					
	3	7	7.21	60.18	0.041	0.174					
	4	1	20.7	452.3	0.019	0.074					

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(a)   (b)
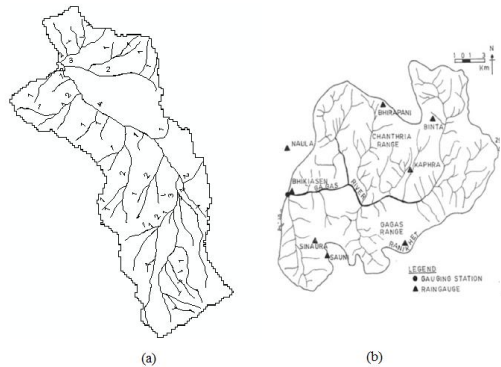
Fig. 1 a) Kasilian catchment stream network   b) Gagas catchment   208

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5. Relationships of geomorphologic parameters

5.1. Estimation of bifurcation ratio (R_B)

To estimate the bifurcation ratio of a catchment, the information concerning 80 watersheds with areas between 1 km^2 and 600 km^2 were used which had known values of R_B and area, with the presumption that R_B is a function of two variables, catchment area (A) and the main stream length (L). With the help of SPSS18 software and using the information of 37 catchments an optimum relation was obtained as:

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217    $R_B = 0.0027A + 3.47$ (12)

218   Admittedly, the value of R_B was not dependent on L. The correlation coefficient of the fitted

219   equation is 0.8 and the real mean bifurcation ratio of the catchments is 4. Eq. (12) indicates that

220   in small catchments with area less than 200km^2, the value of R_B runs between 3.47 and 4. It is

221   suggested that Eq. (12) be applied to catchments of areas beneath 600km^2. It should be noted

222   that, regarding Eq. (7) and R_B, the values of N_i are calculated for $i \leq \Omega$. Ω is the maximum order

223   of the catchment. $N_{i=\Omega} = 1$ is considered and $N_{i-1} = R_B N_i$, $i \leq \Omega$.

224   **5.2. Computation of stream-length Ratio (R_L)**

225   To calculate the length ratio R_L, it was taken as a function of the main stream length and the

226   whole catchment area. The fitted regression equation for the nine selected catchments according

227   to Table (1) is, as follows:

228    $R_L = 2.59 L^{0.41} A^{-0.2}$ (13)

229   The correlation coefficient is equal to 0.91. Based on Eq. (8) and R_L, the values of $\overline{L_{c_i}}$ are

230   calculated for $i \leq \Omega$. $\overline{L_{c_\Omega}} = L$ is considered and $\overline{L_{c_{i-1}}} = \overline{L_{c_i}} / R_L$, $i \leq \Omega$.

231   **5.3. Computation of area ratio (R_A)**

232   The area ratio was assumed to be a function of the bifurcation ratio and the length ratio with

233   fitted equation:

234    $R_A = 0.597 R_B^{1.553} R_L^{-0.177}$ (14)

235   The correlation coefficient is 0.99. $\overline{A_\Omega} = A$ is considered and $\overline{A_{i-1}} = \overline{A_i} / R_A$, $i \leq \Omega$.

236   **5.4. Computation of stream slope ratio (R_S)**

237   Stream slope ratio was assumed to be a function of R_B, R_L, and R_A. Equation (15), having

238   correlation coefficient 0.79, represents the fitted regression relation for the data.

239    $R_S = 1.198 R_B^{1.26} R_L^{-0.97} R_A^{-1.04}$ (15)

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5.5. Computation of overland slope ratio (R_{SO})

A nonlinear regression equation consisting of the parameters R_B, R_L, R_A, and R_S was used to calculate the slope ratio of the overland plane with the fitted relation:

$$R_{SO} = 0.366 R_B^2 R_L^{-0.58} R_A^{-0.66} \tag{16}$$

The correlation coefficient of Eq. (16) is 0.93, and there is no strong correlation between R_{SO} and R_S. By the Eqs. (16) and (11) the slope of overland planes of the catchment could be obtained. It is to be noted that the Eqs. (12) to (16) which are gained via the information about nine catchments may be calibrated by adding more data. Given that the length of the main river and the area in all catchments are known, the R_B, R_L, R_A, R_S, and R_{SO} ratios can be calculated by Eqs. (12) to (16).

The area of the catchment, the length and slope of the main river could be determined from the simple topographic maps of the catchment. If a catchment has a maximum stream order Ω, it is inferred that the stream should be located at the end of the catchment with the mean slope $(\overline{S_{c_\Omega}})$ and the mean slope of the lateral overland planes $(\overline{S_{o_\Omega}})$. For instance, Fig. 2 shows a small catchment with three subcatchment (I, II, III). The maximum stream order is two $(\Omega = 2)$. The subcatchment III is created with two lateral overland planes and stream III is positioned at the end of the main catchment. Fig. 2 shows the mean slope of the stream III $(\overline{S_{c_2}})$ and mean slope of the two lateral overland planes $(\overline{S_{o_2}})$.
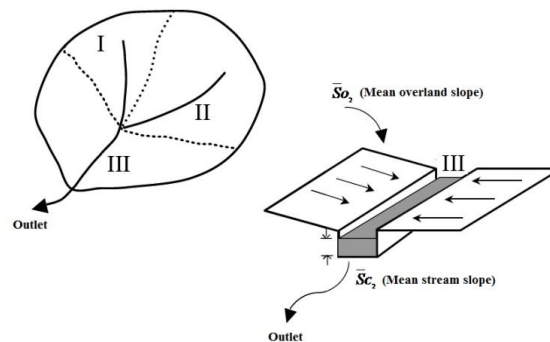
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Fig. 2. Catchment with maximum stream order 2   260

261   If the values of the $\overline{S_{c_\Omega}}$, $\overline{S_{o_\Omega}}$, R_S and R_{SO} are known , with regard to Eqs. (10) and (11), the

262   value of the $\overline{S_{c_i}}$ and $\overline{S_{o_i}}$ are computable for lower orders $i < \Omega$ ($\overline{S_{c_{i-1}}} = \overline{S_{c_i}}/R_S$, $\overline{S_{O_{i-1}}} = \overline{S_{O_i}} R_{SO}$).

263   6. Effect of ratios R_B, R_L, R_A, R_S and R_{SO} on DRH

264   In the previous section of this study, empirical equations were presented to obtain

265   geomorphologic ratios. Now, we apply the GIUH model to look into sensitivity analysis of these

266   ratios and their effects on DRH and on peak flood. To this end, the information of the Kasilian

267   catchment was utilized.

268   Fig. (3a) illustrates the effect of bifurcation ratio upon DRH of the Kasilian catchment on 4th

269   May, 1993.
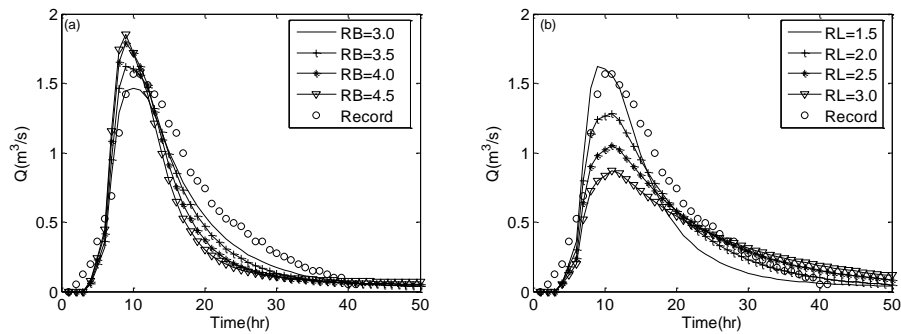
Fig. 3. Effect of R_B and R_L on DRH of the Kasilian catchment   271

272   The values of bifurcation coefficient 3, 3.5, 4, and 4.5 with 0.5 units increment were considered

273   for the Kasilian catchment, and the number of streams and the values of input parameters into

274   GIUH model were computed and inserted to the model. The effect of R_B on shape of hydrograph

275   and peak of the runoff is seen in Fig. (3a).The results of the model are compared with those of

276   recorded runoff hydrographs.

277   To determine the effect of different values of R_B on the peak of runoff, the following equation of

278   relative sensitivity was used:

279    $$S_r = \frac{O_2 - O_1}{P_2 - P_1}(\overline{P}/\overline{O}) \qquad (17)$$

280   where O and P represent particular model outputs and parameters, respectively. So, S_r gives the

281   percentage change in O for a 1% change in P. $\overline{P}$ is given by $(P_1+P_2)/2$ and $\overline{O}$ is given by

282    $(O_1+O_2)/2$. Results confirmed that the least computational error in peak discharge relative to the

283   observed peak discharge was shown by $R_B=3.5$ with 3.5%. The actual R_B for the Kasilian

284   catchment is also 3.5. The mean relative sensitivity of R_B derived from Eq. (17) is 0.56.

285   Fig. (3b) shows the effect of R_L on DRH of the Kasilian catchment. The values of this ratio were

286   taken as 1, 1.5, 2, and 2.5 with a 0.5 increment. According to the results, $R_L=1.5$ has given the

287   least error in peak discharge with 3.6% value. The actual R_L of the catchment is 1.46, and the

288   mean relative sensitivity of R_L amounts to 0.92. The larger the value of R_L, the higher peak error.

289   The runoff is affected more by length ratio relative to bifurcation ratio, a fact seen also in Fig.

290   (3). The next section of the paper was dedicated to the effects of area ratio on the peak of runoff.

291   The values of area ratio were regarded to be between 3 and 6 with 1 unit increment values.
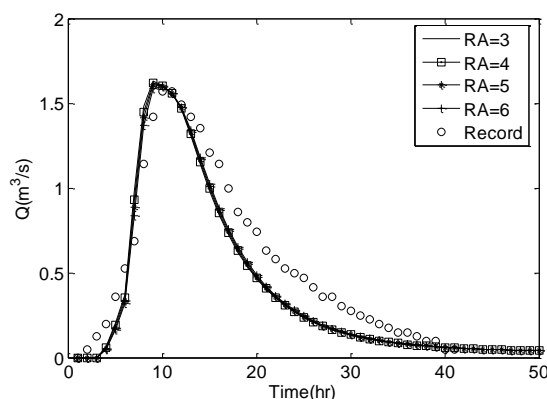
292   Figure (4) depicts the effect of area ratio on DRH.

293

Fig.4. Effect of area ratio on DRH of the Kasilian catchment   294

295   As indicated by the results, the area ratio has had a slight effect on the runoff peak, so that

296   alterations of this ratio do not noticeably influence the shape of hydrograph and flood peak.

297   Fig. (5a) shows how R_S affects DRH for the values 0.1, 0.4, 0.7, and 1 with a 0.3 increment.
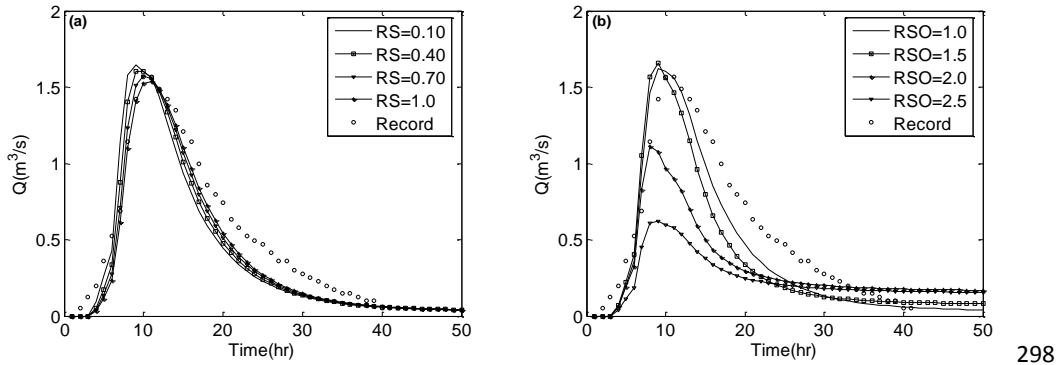
14

Fig. 5. Effect of R_S and R_{SO} on DRH of the Kasilian catchment

The least error is 0.47 which corresponds to the ratio (0.7) while the actual slope ratio of the Kasilian catchment is 0.38. Also, the mean relative sensitivity ratio is 0.042. The results indicate that this parameter has little effect on runoff peak, too.

Figure (5b) shows the influence of R_{SO} on DRH for values of 1, 1.5, 2, and 2.5 with increment as 0.5. The least error relates to the ratio 1 which is 3.54%, whilst that of Kasilian catchment would be 1.1, and the mean relative sensitivity ratio 1.33. According to the results, the parameter R_{SO} has remarkable effect on runoff peak.

According to the overall results, the relative sensitivity ratio of R_B, R_L, R_A, R_S, and R_{SO} is 0.56, 0.92, 0.01, 0.042, and 1.33 respectively. The most effect concerns, correspondingly to the overland slope ratio, length ratio, bifurcation ratio, slope ratio, and area ratio.

To calculate the value of $P_{x_i x_j}$ in Eq. (1) the following equation is used:

$$P_{x_i x_j} = N_{i,j} / N_i \tag{18}$$

where $N_{i,j}$ is number of ith order stream contributing the flow to jth order stream; N_i is the number of ith order channel. The value of N_i is computable by the bifurcation ratio, but to obtain the parameter $N_{i,j}$ the following equation is suggested:

$$N_{i,j} = 2N_i \exp(-0.64 j) \tag{19}$$

15

318 which is obtained through nonlinear regression of the stream network data based on

319 geomorphologic parameters of the Kasilian and the Gagas catchments. In the catchments

320 possessing DEM one needs to delineate stream network and order them by GIS software,

321 however, calculation of $N_{i,j}$ should be done manually and rendered by GIS operator which is a

322 time-consuming and difficult task.

323 **7. Verification**

324 In the previous sections, equations were proffered for computation of stream-order-law ratios

325 based on GP in nine different catchments in the world. For verification of the results of the

326 regression equations the GP of three catchments Gagas, Heng-Chi, and Kasilian were applied.

327 Table (2) lists the GP as well as stream-order-law ratios of the three selected catchments using

328 Eqs. (12) to (16). The table (2) also provides the observed values of stream ratios and their
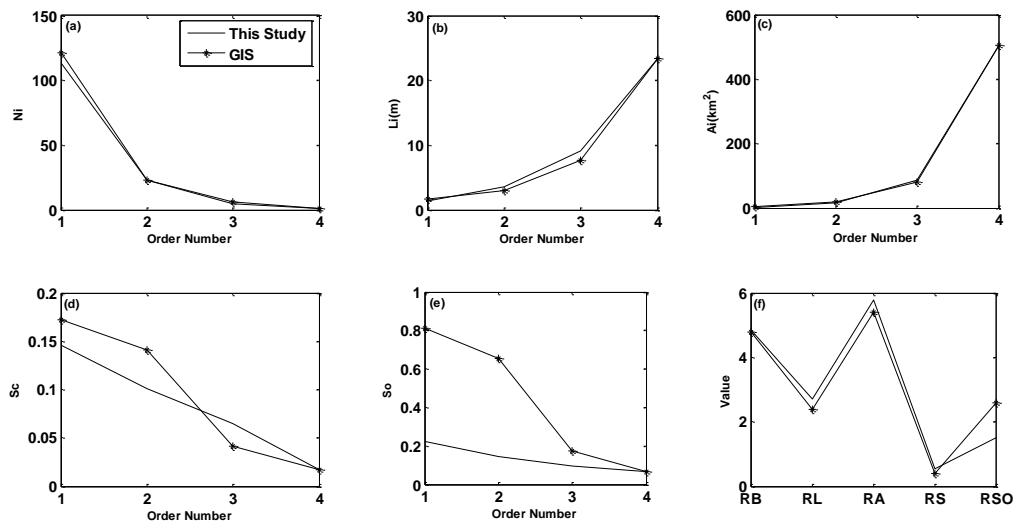
329 computational errors.

330

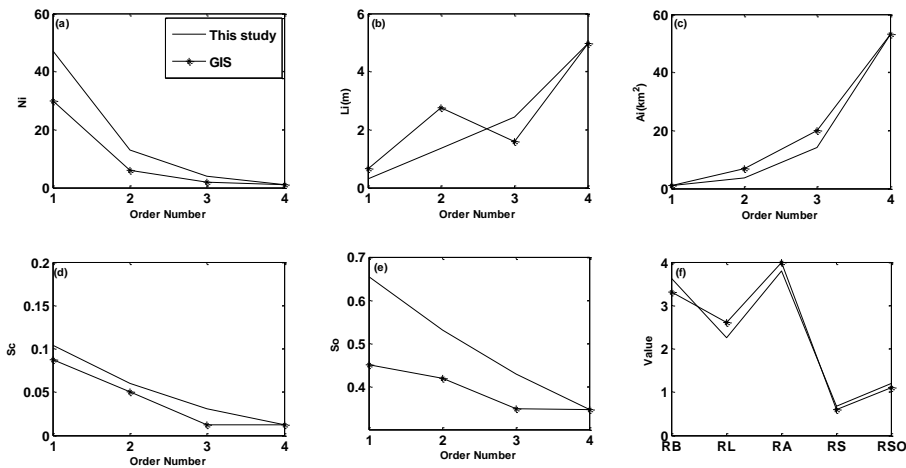331 Fig. 6. Verification of GP in Gagas catchment

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Table 2 Calculated GP of the Gagas, Heng-Chi, and Kasilian catchments   335

Catchment Name	Geomorphologic parameters										
	Order	N_i	$\overline{L_i}$	$\overline{A_i}$	$\overline{S_c}$	$\overline{S_o}$	R_B	R_L	R_A	R_S	R_{SO}
1. Gagas	1	113	1.38	2.6	0.146	0.222	4.84	2.72	5.78	0.53	1.5
	2	23	3.54	15.1	0.101	0.147					
	3	5	9.10	87.5	0.065	0.098					
	4	1	23.40	506.0	0.017	0.065					
GIS Results							4.80	2.40	5.40	0.40	2.60
%Error							0.40	13.7	7.6	21.0	41.4
2. Heng-Chi	1	47	0.32	1.0	0.104	0.654	3.61	2.26	3.80	0.68	1.2
	2	13	1.34	3.7	0.060	0.530					
	3	4	2.43	14.0	0.031	0.429					
	4	1	4.97	53.2	0.012	0.347					
GIS Results							3.30	2.60	4	0.60	1.10
%Error							9.4	13.7	5.0	13.3	9.1
3. Kasilian	1	49	0.49	1.1	0.109	0.563	3.65	2.09	3.92	0.72	1.3
	2	13	1.03	4.4	0.073	0.436					
	3	4	2.19	17.3	0.038	0.337					
	4	1	4.65	67.8	0.008	0.261					
GIS Results							3.5	1.5	4.3	0.4	1.1
%Error							4.3	43.2	8.8	89.5	18.2

336   Figs 6, 8 depict the GIS based and computational GP concerning the three case study

337   catchments.
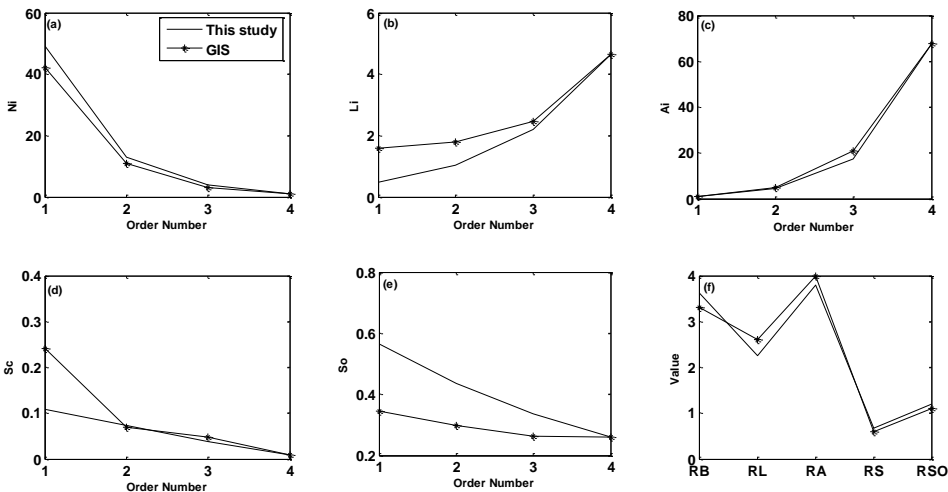

338

339   Fig.7. Verification of GP in Heng-Chi catchment

340

341   Fig.8. Verification of GP in Kasilain catchment

342   The mean errors of regression equations in estimation of R_B, R_L, R_A, R_S, and R_{SO} in the three

343   selected catchments are, respectively, 4.7%, 23.5%, 7.1%, 41.3%, and 22.9%.

344   The greatest errors of the model emerged in estimation of, respectively, R_S, R_L, R_{SO}, R_A, and R_B.

345   As observed in Fig. (5a), the stream slope ratio has a slight affect on runoff, so its error could be

346   ignored. Regarding high sensitivity of the length and overland slope ratios their errors range

347   from 23 to 24 percent and it is recommended that the joint effects of all the ratios on DRH of the

348   selected catchments be considered.

349   In the previous sections, the influences of GP on runoff were pondered separately, and the GP of

350   the three catchments were estimated via the regression equations. To study accuracy of the

351   estimations more deeply it is better to estimate the DRH using GIUH model. For this purpose,

352   taking the information about excess rainfall hyetograph and recorded runoff of the Kasilian and

353   the Heng-Chi catchments into consideration, we turn to verification of the predicted runoff for

354   the two catchments.

355   The model GIUH was employed in two cases, one in which geomorphologic parameters are GIS

356   based and the other where empirical regression equations (GIS-unsupported) are concerned for

18

357 the Kasilian and the Heng-Chi catchments. The results of the model in each case were compared

358 with those of observed runoff recorded. Since the observed runoff and rainfall data of Gagas

359 catchment were not available, this catchment was dispensed in verification phase. Figure 9

360 shows the results of GIUH model for DRH estimation in Kasilian catchment for two events on

361 10th May 1992 and 4th May1993. Also, Fig. (10) illustrates those in Heng-Chi catchment for two
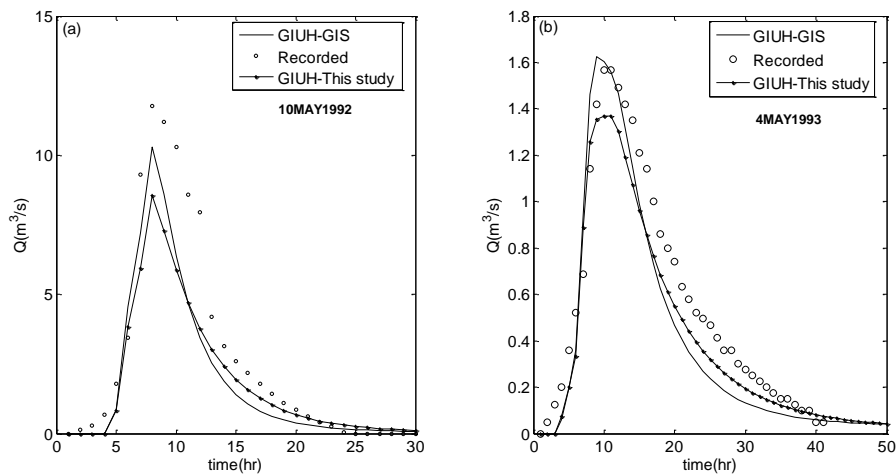
362 events July 1996 and October 2000.

363

Fig.9. Estimation of Kasilian DRH by GIUH model   364

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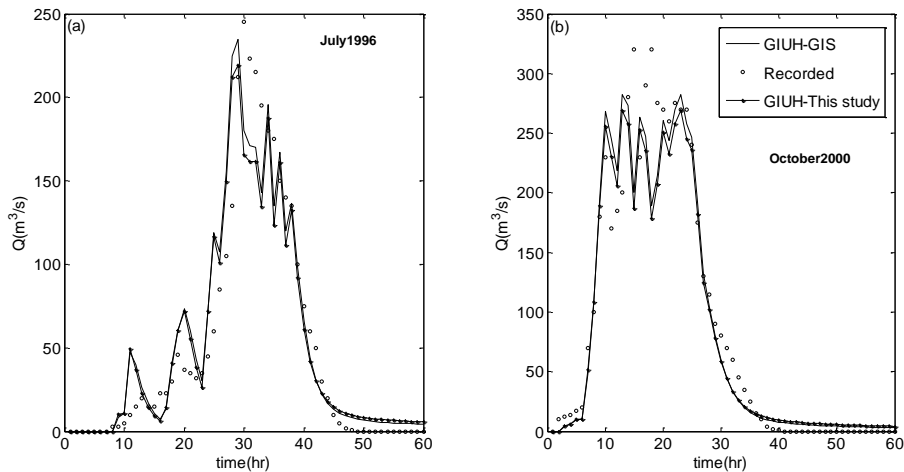
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Fig.10. Estimation of Heng-Chi DRH by GIUH model   366

To validate the fitness of the model for the Kasilian and Heng-Chi catchments, three common statistical measures were used, the coefficient of efficiency (*CE*), Root mean square error (*RMSE*), and Relative error in peak (*REP*).

Estimation of these three parameters is carried out by the following equations:

$$CE = 1 - \frac{\sum_{t=1}^{n}[Q_r - Q_s]^2}{\sum_{t=1}^{n}[Q_r - \overline{Q_r}]^2} \qquad (20)$$

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(Q_r - Q_s)^2\right]^{0.5} \qquad (21)$$

$$REP = 100 \times [Q_{p_s} - Q_{p_r}]/Q_{p_r} \qquad (22)$$

where Q_r is the recorded discharge at time t; Q_s is the simulated discharge at time t; $\overline{Q_r}$ is the mean recorded discharge during the storm event; n is the number of discharge records during the storm event; Q_{p_s} is the peak discharge of the simulated hydrograph and Q_{p_r} is the recorded peak discharge.

Table (3) gives the values of *REP*, *CE*, and *RMSE* calculated for the two selected catchments in GIS-supported and GIS-unsupported (this study) cases.

Table 3. Validation result of the GIUH model   381

July1996	*REP*%	*CE*	*RMSE*
GIS	4.18	0.87	24.54
This study	10.62	0.86	25.44
October 2000			
GIS	11.81	0.93	31.22
This study	15.99	0.92	32.25
10 May 1992			
GIS	12.68	0.81	1.13
This study	27.33	0.76	1.26
4 May 1993			

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GIS	3.5	0.87	0.10
This study	12.6	0.91	0.10

382

383 It is concluded that the computational error values of runoff peak (*REP%*) that could be inferred

384 (in this study) for the four rainfall-runoff events are, on average, 10% more than the error

385 resulting from actual information (GIS support). As seen in Figs (9) and (10), the results of the

386 GIUH model in the two cases concerning GIS and empirical equations are very close to each

387 other. *CE* and *RMSE* are near-valued as well. The mean *CE* of the model was computed for the

388 four events as 0.87 which is a satisfactory value.

389 **8. Summary and conclusion**

390 In this research, experimental equations were presented to work out geomorphologic parameters

391 of watersheds of less than 600 km^2 area. These equations are offered in accordance with the

392 nonlinear regression method fitted to the geomorphologic parameters of nine different

393 catchments of the world. The equations were taken under verification in three other selected

394 catchments, and their results were compared with those calculated from GIS. Finally, direct

395 runoff hydrograph was estimated by GIUH with regard to the geomorphologic data computed for

396 the three catchments, and then compared to the observed values. Sensitivity of bifurcation ratio,

397 length ratio, area ratio, stream slope ratio, and overland slope ratio to runoff of Kasilian

398 catchment were investigated. It is shown that the relative sensitivity of R_B, R_L, R_A, R_S, and R_{SO}

399 was 0.56, 0.01, 0.92, 0.042, and 1.33, respectively. The greatest effect was related to,

400 respectively, the overland slope ratio, length ratio, and bifurcation ratio, and the least effect was

401 related to area ratio, and streams slope ratio.

402 The geomorphologic parameters of three catchments Gagas, Heng-Chi, and Kasilian were

403 determined based on the experimental equations given in this research, and compared with their

404 actual results. The average errors of the model in estimation of R_B, R_L, R_A, R_S, and R_{SO} in the

405 three case study catchments were 4.7%, 23.5%, 7.1%. 41.3%, and 22.9%, respectively.

406 Lastly, the estimated geomorphologic parameters was input into the GIUH model and the values

407 of direct runoff hydrograph of two catchments Kasilian and Heng-Chi were calculated and

408 compared with those of observed runoff. According to the results, the computational error values

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409   of runoff peak (*REP*%) for the four rainfall-runoff events are, on average, 10% more than the

410   error resulting from actual information (GIS-Supported). The results of the GIUH model in the

411   two cases concerning GIS and without GIS are very close to each other. *CE* and *RMSE* in the

412   two cases are near-valued as well. The mean coefficient of efficiency of the model was computed

413   for the four events as equal to 0.87.

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