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Improving drainage conditions of forest roads using the GIS and forest road simulator

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Abstract: In this study a new method of locating culverts is presented with the composition of achieved discharge from hydrological analysis and simulated forest roads in RoadEng 3D simulator to improve drainage condition. Locating culverts was performed on a small scale (1:20 000, using GIS) and large scale (1:2 000, road geometric design simulator). The small-scale study regarding the achieved discharge from streams shows that the installation of some culverts is not necessary. The large-scale study also showed that the geometric design of forest road has a significant effect on locating culverts and its accuracy. To improve drainage conditions 6 culverts and 2 waterfronts taking into account the geometric design of forest road, hydrological conditions and appropriate intervals (155 m) have been proposed. No installation or lack of accuracy to find the best location of culverts may result in the occurrence of creep and landslide, so the cost of destruction would be several times higher than the cost of technical buildings construction.

Keywords: hydrological analysis; locating culverts; waterfront; large and small scale

In construction engineering, engineers in various branches of science simulate constructions in the computer environment. The simulation by presenting the models can assist the operator with a better view in decision-making (Dai et al. 2004; Bertacchi et al. 2007; Yurdakul, Topcu 2011). The simulation of a road is considered unimportant for the construction of forest roads. While a proper forest road network and planning within construction engineering are very important for environment preservation and conservation (Lewis 2000).

Many factors including vegetation (Jordán-López et al. 2008), soil type in the area, topography and microtopography of the hillside across the road, the hydrology of the area including rainfall (Dubé et al. 2004, Akbari Mazdi 2007), discharges of streams, time of runoff concentration (Ghahraman 2009), length and gradient of streams, fish passages (Asce et al. 2002) and geometric design of forest roads (Schiess et al. 2004; Fu et al. 2010) (including road gradient and superelevation, ditch, vertical and horizontal curves) and considering the appropriate intervals for stream crossing culverts (Sarikhani, Majnounian 1994; Brinker 1995; FAO 1998; Environmental Assessment Division 2003) are important in making decisions on the presence or absence of a culvert.

Numerous studies have been done to improve drainage conditions in forest roads like the use of RoadEng software to optimize the best route of forest road and improve drainage conditions (Heralt 2002), the use of Distributed Hydrology Soil Vegetation Model (DHSVM) to determine the effect of forest road network on watershed hydrology (Surfleet et al. 2001), calculation of sediment delivery from different parts of forest roads to find the best location of culverts (Schiess et al. 2004). Also several studies have been done to find the best method of culvert installation and its environmental impacts (Borga 2005). Four general steps for the culvert installation must be considered in forests with small area: (*i*) planning and selecting the lo-

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cation of culvert installation, (*ii*) to convey surface runoff by culvert in its natural route (*iii*) preparation of foundations and (*iv*) installing the culvert. Results of similar investigations were presented by Helvey et al. (1988), Nikoy Siahkal (2001) and Meng (2006). Akbari Mazdi (2007) conducted a study to determine the diameter of drainage pipes and appropriate intervals using the rational method for estimating peak discharges and curve number. Meng (2006) in China by designing ForCulverts as an extension package of ArcView 3.3 software studied the location of culverts regarding the road gradient and hydrology. He concluded that this software can automatically delineate the number of culverts required for forest roads. In this study a new method of locating a culvert was presented with the composition of the achieved discharge from hydrological analysis and simulated forest roads in RoadEng 3D simulator. Therefore, the aim of this study was to evaluate the area in the point of hydrological flow and assess (on a small and large scale) the location of existent culverts, and on the other hand, offer a suitable location for the construction of new culverts to improve the drainage systems of forest roads.

MATERIAL AND METHODS

Study area. This study was conducted in a road of Caspian forest (Brengestanak basin), Iran. The latitude and longitude of Brengestanak basin (Figure 1) are 36°19'08" to 36°23'30" N, 52°51'22" to 52°56'55"E, respectively. Total length of forest roads and density of these roads are 24 km and 10.5 m·ha^{-1}, respectively. There is a low-volume of forestry machinery traffic on these roads. The forest road type is access and unpaved roads. The forest altitude ranges and average annual precipitation are from 320 to 490 meters above sea level and 700 to 900 mm, respectively. There is an earth dam at the bottom of the above-mentioned basin which is important for fish passage. The bedrock is calcareous sandstone, limestone, and lime marl.

Hydrological analysis. The rational method for peak discharge estimation is used for small basins and some cases without hydrometric data. Due to the small watershed of this area as well as lack of hydrometric data this method is suitable for our study (Alizadeh 2006). First, streams crossed by the road were identified by Arcinfo 9.3 software and in order to estimate the peak of discharges, bound-

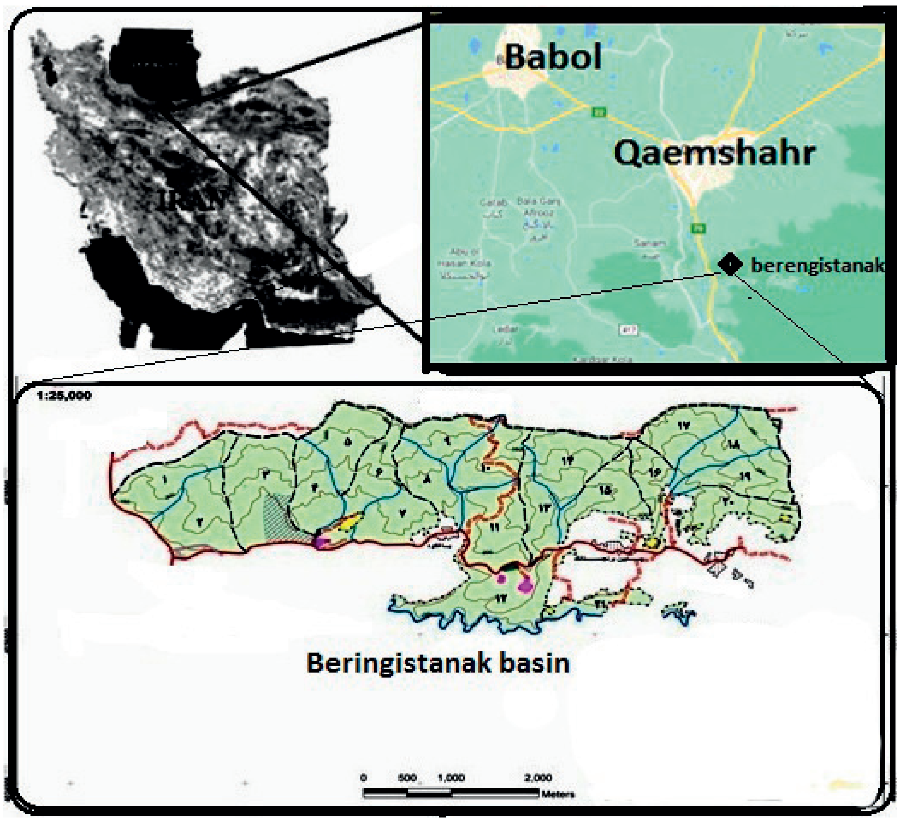

Figure 1. Map of the study area

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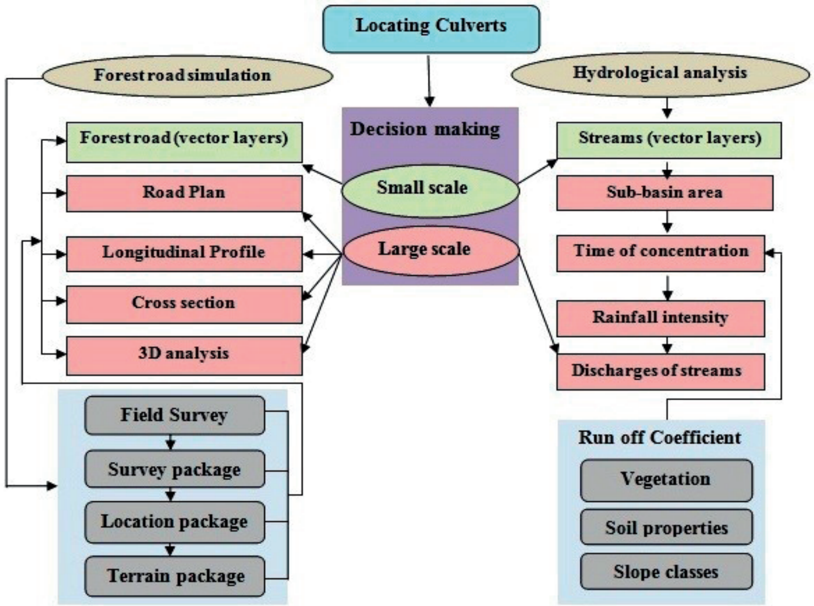

Figure 2. Method of the study

aries were created for a sub-basin and then the area was determined. The time of concentration for each basin was calculated using the following formula regarding the longest branch of the stream and runoff velocity (Alizadeh 2006; Ghahraman 2009). The intensity of rainfall was estimated taking into account the time of concentration for the basin in return intervals of 25 years (Ghahraman 2009). Slope gradient, aspect, vegetation and soil type in the area are some effective factors on drainage network planning. In this study to determine peak of discharges, the runoff velocity was assessed by a nomograph of estimating velocity in relation to the soil and vegetation type - Equation 1–3 (Alizadeh 2006).

$$tc = L/V \quad (1)$$

where:
tc – time of concentration,
L – maximum flow length,
V – runoff velocity.

$$I = a \times t^b \quad (2)$$

where:
I – rainfall intensity (return intervals of 25 years),
a, b – fixed coefficients according to the conditions of the study area (Alizadeh 2006), $a = 350$, $b = -0.4517$;
t – time of concentration.

$$Q = 0.278\ C \times I \times A \quad (3)$$

where:
Q – Peak discharge (m^3/s),
C – rational method runoff coefficient,
I – rainfall intensity in mm/h,
A – sub-basin area.

Road geometric design simulation (3D). In order to locate a culvert on a large scale it is required to identify the existent roads and stream network (Figure 2). Therefore, the vector layer of streams was obtained from the DEM (Digital Elevation Model) of the region in Arcinfo 9.3 software. In the next step, an existent road in the study area was measured by NIVO camera mapping. So, a field survey was done using NIVO mapping camera and geometric specifications of the road such as longitudinal slope and cross-sections. In order to simulate the geometric design of the road, acquired data were entered into the Survey Package (RoadEng software package). Then the geometric design of the existent road was extracted from the Location Package (RoadEng software package). The designed road in Location software was put into Terrain software (RoadEng software package) as a vector layer to be combined with vector layers of streams. To find a location on a small scale, the modelling for each existent culvert was done by using the culvert editor analysis. In order to modify the existing drainage network, the geo-

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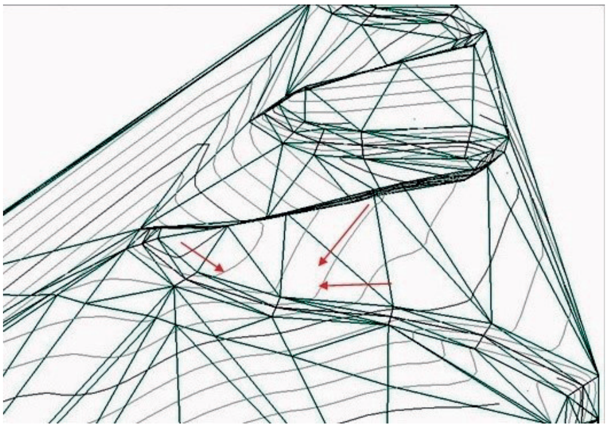

Figure 3. Forest road simulation using the simulator in the location of culvert No. 16

metric design of the road was carefully examined. Some critical points in terms of water accumulation during heavy rainfalls in winter were marked using the GPS (Garmin 62S) and they were identified on the map. By considering appropriate intervals of culverts (Brinker 1995), discharge of the stream network and geometric design of the road, some proposals were offered. The 3D analysis of RoadEng software was used for decision-making (Figure 3) and final decisions were taken based on the longitudinal profile of the road and peak of discharges.

RESULTS AND DISCUSSION

The small-scale study regarding the achieved discharge from the stream network shows that the installation of some culverts is not necessary (culvert No. 5, 13 and 20) because the amount of stream discharge is very low, therefore there was no need to install these culverts. Many studies were conducted using GIS on a small scale (1:20 000) (Nikoy Siahkal 2001; Borga 2005; Akbari Mazdi 2007). In these studies, identifying the culvert diameter was done regardless of microtopography and geometric design of road horizontal and vertical curves. According to the results it can be understood that determining the culvert diameter on a small scale (1:20 000) could not be accurate because the geometric design of the road can cause changes in water flow, thus changing the discharge. The large-scale (1:2 000) study showed that the geometric design of the forest road has a significant effect on locating culverts and its accuracy. Further studies showed that road gradient and water flow cause sediment delivery. Also, the road superelevation (2-4%) may facilitate to convey surface runoff to the ditch (Sarikhani, Majnounian 1994). Unfortunately, in the study area, the superelevation of the road in the location of culvert No. 2 is very bad. Also, on some horizontal curves, the superelevation is in opposite position to the ditch (Figure 4D). Harris et al. (2008) introduced a longitudinal profile as one of the most important factors in decision-making. Using the analysis of microtopography (Figure 3) it can be obtained that we can use waterfronts No. 6 and 8 instead of installing culvert No. 7. Waterfronts can be used instead of culverts at low intervals for reducing the cost with regard to the 2 000 USD cost of installing a culvert with 100 cm diameter.

In order to improve drainage conditions six culverts (culverts No. 2, 3, 9, 15, 17) and two waterfronts (No. 6 and 8) regarding the geometric design of forest road, hydrological conditions and appropriate intervals (average distance 155 m) have been proposed. Standard and proper intervals for culverts on forest roads have been investigated in

Figure 4. Effect of vertical and horizontal curves on locating culverts (A, B); accumulation of water due to the absence of culvert and ditch (C); effect of horizontal curve, superelevation as well as suitable interval between culverts on locating culverts (D); landslide occurrence due to the absence of drainage systems; improper installation of culvert (F)

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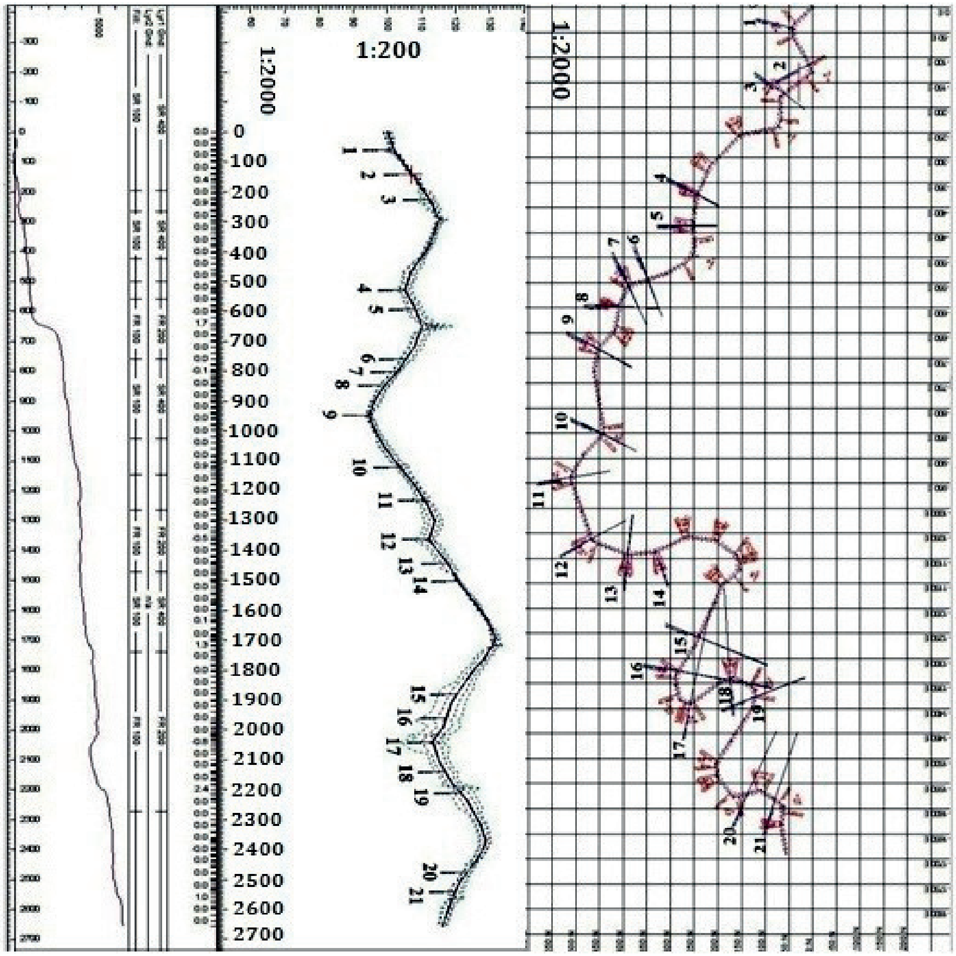

Figure 5. Locating culverts in the longitudinal profile and road plan

several studies. FAO (1998) and the Environmental Assessment Division (2003), taking into account the soil type and road gradient, have assessed the interval of culvert between 50 and 70 m. Akbari Mazdi (2007) by calculating hydrological conditions and determining the peak of discharge estimated the proper interval between 419 and 480 m. According to the results, it is better to determine the optimal interval with respect to issues such as road geometric design (culvert No. 17), hydrology (Figure 4C), upland water volume (culverts No. 14, 19 and 21) and terrain features (Figure 4A–B).

Decisions and recommendations of this study were implemented according to existent conditions. In this study, feasible and accurate determination of culvert location in the longitudinal profile of the road can be obtained when the geometric design of the road is modified and the ditch is reformed in some places. Results of locating culverts for each culvert are shown in the longitudinal profile and road plan (Figure 5). Also, how to make decisions with respect to hydrology and geometric design of the road with all details is presented in Table 1.

CONCLUSION

A positive aspect of this study is the use of efficiency and accuracy of RoadEng simulator in designing the geometric specification of roads. Like in this study the simulation of roads and culverts by RoadEng simulator (3D) could provide a suitable environment for decision-making. The accuracy of image processing software has been more influenced by the input data and DEM accuracy. Planning accuracy is very high in this study because the RoadEng software designed a survey-map package to solve this problem. So using the field data and above-mentioned package, the road would be designed with more accuracy. Therefore, according to the results it can be understood that the 3D simu-

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lator considering microtopography and geometric design of forest road can do this well and the ArcInfo package with low accuracy of DEM (1:20 000) is not offered for locating culverts.

Table 1. Decision-making for each culvert according to the geometric design of forest road and hydrological conditions

General information					Geometric design of road						Hydrological conditions		
Culvert No.	Existent culvert	Suggested culvert	Stream-crossing culvert	Factor in decision making	Superelevation	Vertical curve	Horizontal curve	Culvert interval (before) (m)	Culvert interval (next) (m)	Ditch status	Rainfall intensity ($mm\cdot h^{-1}$)	Time of concentration (s)	Peak of discharge ($m^3\cdot s^{-1}$)
1	+	–	+	H	S	–	+	0	92	U	11.9	2176	2.45
2	–	+	–	G	U	+	–	92	87	U	–	–	–
3	–	+	–	G	S	+	+	87	310	U	–	–	–
4	+	–	–	G	S	+	–	310	74	S	–	–	–
5	+	–	+	N	U	–	–	74	192	S	36.2	152	0.19
6*	–	+	–	N/A	U	+	–	192	38	U	–	–	–
7	+	–	–	G	S	–	–	38	32	S	–	–	–
8*	–	+	–	N/A	U	+	–	32	84	S	–	–	–
9	–	+	–	G	S	+	–	84	210	S	–	–	–
10	+	–	–	G	U	–	+	210	133	S	–	–	–
11	+	–	+	G	S	–	+	133	141	U	–	–	–
12	+	–	–	G	U	+	+	141	94	S	–	–	–
13	+	–	+	N	U	–	+	94	84	S	32.6	192	0.203
14	+	–	+	H	S	–	–	84	45	S	37.9	137	0.156
15	–	+	–	G	U	+	–	45	410	S	–	–	–
16	+	–	–	N	S	–	–	410	82	S	–	–	–
17	–	+	–	G	S	+	+	82	103	S	–	–	–
18	–	+	–	G	S	–	+	103	67	U	–	–	–
19	+	–	+	N	S	–	–	67	270	S	20.2	553	0.2
20	+	–	+	N	U	–	–	270	43	S	45.2	93	0.113
21	+	–	+	H	S	–	–	43	–	S	39.2	127	0.053

the reasons for decision-making (H – hydrological conditions, G – geometric design, N – not necessary, N/A or * – need of a waterfront instead of a culvert); superelevation and Ditch status (S – suitable conditions, U – unsuitable conditions); other symbols (+ positive or existent, – negative or not existent)

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