Anadolu Orman Araştırmaları Dergisi
Anatolian Journal of Forest Research
http://dergipark.org.tr/ajfr

A simple approach on forest roads drainage structures planning using GIS: A case study of Şile-Turkey

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ARTICLE INFO
Received: 19/10/2022
Accepted : 23/12/2022
https://doi.org/10.53516/ajfr.1191385
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Abstract **Research Article**

Forest roads provide access to forest resources for conducting several forestry activities such as production, protection, afforestation, management, recreation and firefighting. Both drainage structures and pavement should be completed for forest roads to serve safely and for a long time. This study aimed to determine both cross-sections and types of drainage structures for newly built forest roads, using Geographic Information System (GIS) techniques. ArcGIS Pro software was used for analysis in the study. The total length of the forest road used in the study area was 7920 m, where 31 drainage structures was planned to be built at stream crossings along the road route. Considering the cross-sections of drainage areas along the route, it has been decided to construct a total of 31 drainage structures, including 25 pipes, 5 culverts and 1 bridge. GIS technology produces accurate and fast results in terms of determining cross-sectional areas in drainage structures on forest roads. A simple GIS-based approach reduces the stabilization and drainage problems and construction and maintenance costs in forest road design compared to traditional land evaluation methods. Thanks to its capacity to process big data and simple hydrological empirical calculations, GIS has significant gains in terms of accuracy and time consumption and is included in the planning forest road designs.

Key Words: ArcGIS, drainage structure, pipe, culvert, forest road, Tablot

Orman yolları drenaj yapılarının CBS kullanılarak planlanmasında basit bir yaklaşım: Şile-Türkiye örneği

Öz

Orman yolları üretim, koruma, ağaçlandırma, yönetim işleri, rekreasyon ve yangınla mücadele gibi tüm ormancılık çalışmalarının yapılabilmesini sağlayan yapılardır. Drenaj yapıları ve üst yapı orman yollarının uzun süreli ve güvenli bir şekilde hizmet etmesini sağlamaktadır. Bu çalışmada CBS teknolojisi kullanılarak yeni inşa edilen bir orman yolu üzerindeki drenaj yapılarının kesit alanları ve yerlerinin tespiti yapılmıştır. Çalışmadaki orman yolunun toplam uzunluğu 7920 m olup, yol güzergahı boyunca 31 adet drenaj yapısının yapılacağı planlanmıştır. Yol güzergahı boyunca planlanan 31 drenaj yapısından 25 adedi büz, 5 adedi menfez ve 1 adedi ise köprüdür. GIS teknolojisi kullanılarak drenaj yapılarının kesit alanlarına karar verilmesi hızlı ve doğru olmaktadır. Basit bir GIS tabanlı yaklaşım drenaj yapılarının belirlenmesinde geleneksel yöntemlere göre planlama ve inşa maliyetlerini azaltmaktadır. CBS, büyük veri işleme kapasitesi ve basit hidrolojik ampirik hesaplamalar sayesinde doğruluk ve zaman tüketimi açısından önemli kazanımlar elde etmekte ve orman yolu tasarımlarının planlanmasında kendine yer bulmaktadır.

Anahtar Kelimeler: ArcGIS, drenaj yapısı, büz, menfez, orman yolu, Tablot

Citing this article:
İnan and Öztürk., 2022. A simple approach on forest roads drainage structures planning using GIS: A case study of Şile-Turkey. Anatolian Journal of Forest Research, 8(2), 104-110.

1. Introduction

A complete and timely fulfillment of forestry works is significant for both economy and nature events. Because it is important to deliver forest products from forest to market as soon as possible, using most convenient and economic techniques are very important (Öztürk and İnan, 2010). For this, it is necessary to reach every forest area through planned forest road networks. In particular, appropriate functional plans are made according to the functions of forest roads (production forest, national park, etc.), whereby both density and spacing of forest roads are determined properly (Şentürk et al., 2007). Forest roads are affected by basin waters at ditches and stream crossings, destructing both infrastructure and pavement materials of forest roads (Bayoglu and Hasdemir, 1991). In case the road surface is constantly wet due to precipitation waters, large deformations occur on the road surface during the passage of heavy trucks, especially after production works. In addition, the water coming from cutting slopes, flowing from the road surface and continuing to flow down the embankment slope also cause great damage to the road, whereby the embankment slope may be damaged by erosion over time. Drainage structures can protect forest roads against all these negative effects of rainwaters.

Drainage structures include all facilities such as pipes, culverts, drainage ditches and water bars built along the route to cross forest roads without interruption, protect the road from harmful effects of rain and snow waters, prevent excavation and fill slope depressions, and to ensure regular and continuous transportation in both summer and winter (Erdaş, 1997). Construction and maintenance of forest roads can affect the environmental impact of natural events. Therefore, the planning stages of drainage structures or protective structures are important for protecting the environment and forests. Drainage structures without proper dimension and position can easily become clogged with sediment or wood materials (Merrill and Casaday, 2001). Due to the environmental impact on basins the sediment flow increases in forest areas (Luce and Beverley, 2001). In this case, drainage structures lose their functions in a short time due to clogging (Öztürk and Hasdemir, 2021). For determining the cross-section types and dimensions of the pipes, culverts and bridges to be built in places where the road routes cut the riverbeds has great importance for the safety of these facilities and the road (Çalıskan et al., 2003). In addition, determining the type and size of hydraulic engineering structures and construction of these structures in suitable places considering terrain and road conditions are of great importance in the success of drainage facilities (Schwab, 1994). Drainage structures to be built at stream crossing points on forest roads should not affect the natural flow of streams. This flow channel should also allow to transfer the waters of periodic rains to the opposite side of the road without any problems (Öztürk and Hasdemir, 2021).

In this study, after determining the locations of drainage structures on the forest road, geographic information systems (GIS) were used to determine the dimensions of drainage structures. For this purpose, the locations of drainage structures on the forest road were determined using the approach specified in the methodology section and then checked using field studies. These locations points were evaluated as Poor points and the basins were delineated. Then, the cross-sectional areas of drainage structures and the types of drainage structures were determined using empirical formulas. The General Directorate of Forestry (GDF) conducted a study on the same road, based on expert opinion, to determine the drainage structures in 2021. In this study, the locations and types of culverts recommended by GDF were compared with those determined by GIS.

2. Material and Methods

2.1 Description of the study area and data

This study was conducted on a newly constructed forest road coded 430 within Yeşilvadi Forest Sub-Directorate affiliated to Şile Forestry Operations Directorate. The total forested and deforested area of the Yeşilvadi is 14424.5 ha and 1541.0 ha, respectively. The Forest Sub-Directorate is located between 41º 08' 41" – 40º 59' 50'' North Latitudes and 29º 22' 38" – 29º 34' 30" East Longitudes (Figure 1). The altitude of the region varies between 60 m and 298 m. The research area has a clay- sandy soil structure. The area has covered with dense vegetation, and it is main stand type dominated by Oak (*Quercus robur* L.). Average rainfall in the area is 88.3 mm per year (Anonymous, 2021).

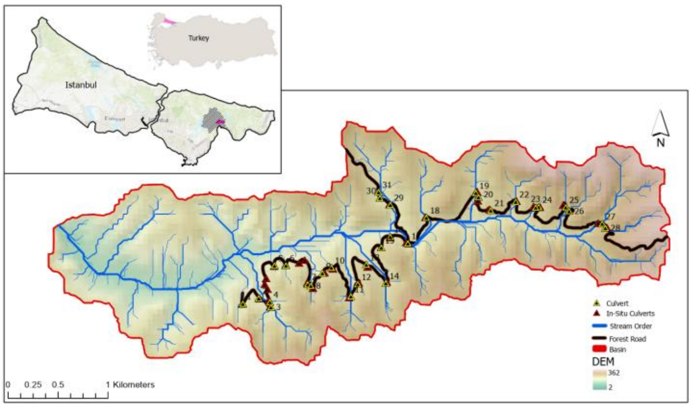

Fig. 1. Maps of study area (Yeşilvadi Forest Sub-directorate)

The 7+920 km length forest road was built between June-July 2021 and has a slope ranging from 2% to 10%. The slopes vary between 25-40% on the area where the forest road is located. The width of the road was 5 m. A Caterpillar bulldozer was used in the construction of this road, making a total of 12851 m^3 of excavation. The drainage structures and pavement of the road will be completed in 2023.

2.2 GIS data and on-site road measurement

The flow direction and flow accumulation in the watershed were used to generate drainage basins of the research area with the help of the Digital Elevation Model (DEM), and the highest flow rate was considered sufficient for the design of culverts. DEM layers with 1m grid spacing and 1/1000 in scale used in the study were obtained from Istanbul Metropolitan Municipality (IMM). The DEM layers were taken from IMM produced with 2013 LIDAR data. In the measurements, the accuracy analysis of DEM layers set was carried out using DGPS data set with a root mean square error (RMSE) of ± 2.3 cm. The accuracy of DEM for the research area was approximately 10 cm horizontally and 5 cm vertically.

2.3 Methodology

In this study, to determine the cross-sections of the drainage structures built on the road, firstly, watershed areas were determinate using GIS technics in the area. Then, by using several empirical formulas, the amount and collection times of precipitation coming from these sub-watersheds were determined. As a result, the cross-sections and types of drainage structures were gathered. Figure 2 shows the workflow in the study.

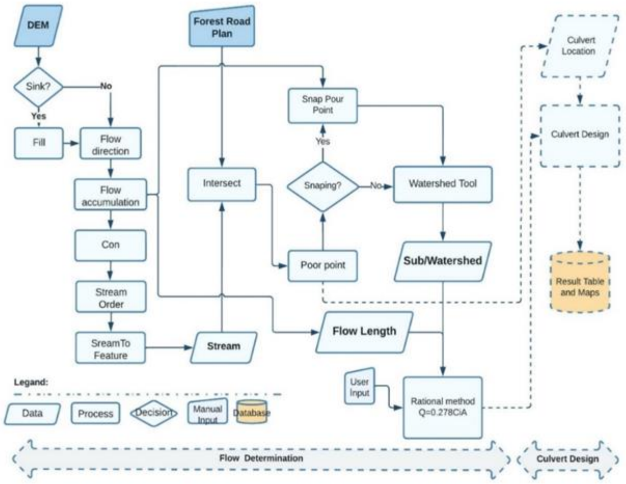

Fig. 2. Process workflow: Watershed delineation and culvert design in GIS

2.4 Watershed delineation

Watersheds boundaries can be determined analyzing digital terrain model using GIS techniques. Due to the automated interpolation and rasterization processes used during the general development of DEM data, this data contains "sinks" and "spikes" which are defective pixels with low or high height values. In GIS-based hydrological assessments, firstly these depression areas should be removed. ArcGIS Pro "*Fill*" tool theorically corrects many sinks errors while producing a depressionless hydrological DEM (Figure 3/A). Depressionless DEM data is used as input to the "*Flow Direction*" tool to calculate the flow direction data on a cell-by-cell basis. The flow direction was calculated using the D8 algorithm: the out-flow of each cell is in the direction of the neighboring cell with the maximum downward slope angle (Schäuble, et al., 2008). Thus, all cells except the plains have a flow direction and the points with minimum height are considered as the outlets of the DEM. From the flow direction raster (Figure 3/B), the ArcGIS Pro "*Flow Accumulation"* tool calculates accumulated flow as the accumulated weight of all cells flowing into each downslope cell in the output raster. The flow direction raster also serves as input to the ArcGIS Pro "*Flow Length"* tool, from which the length of flow paths upstream or downstream of a given point can be calculated (Esri 2005; Tarboton et al., 1991, Inan et al., 2021). This is useful for calculating the travel time of water through a watershed. In the study, the locations of possible culverts were determined by intersecting the forest road line with the river channel. These locations were taken as the pour points of watersheds and then evaluated with the flow direction map to describe watershed boundaries, using ArcMap Pro "*Watershed"* tool.

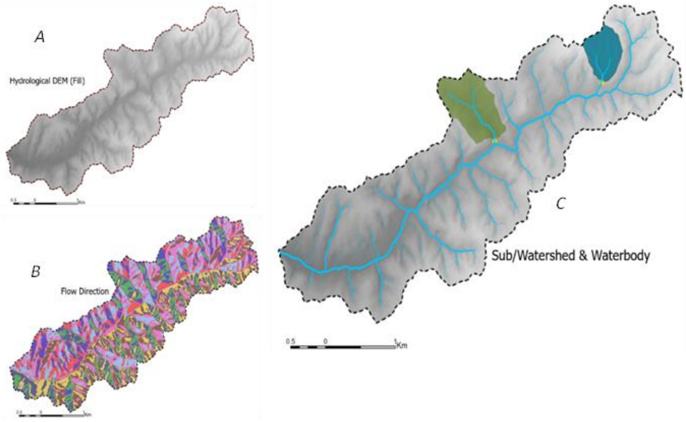

Fig. 3. Progression of watershed delineation: (A) Fill, (B) Flow direction, and (C) Delineated sub/watershed

The location of a culvert can only be ignored if it does not coincide with the river channel. However, this culvert location (as a Pour point) and flow accumulation output raster are both inputs to the ArcGIS Pro "*Snap*" Pour Point tool, which snaps the culvert to the cell of greatest flow accumulation the culvert location lands on a GIS based stream flow path. A flow accumulation raster, together with a snapped culvert location, is sufficient to define a boundary of a watershed that feeds a culvert. The ArcGIS Pro "*Watershed"* tool is operated to define the sub-watershed boundary, area and perimeter (Figure 3/C).

2.5 Culvert design

For forest roads, the empirical formula called Rational Method is used to determine the flow rate of water passing through culverts and pipes. This formula allows for a direct mathematical assessment of the effect of peak flow level, drainage area size, precipitation rate, watershed length and slope on flow (Rothwell, 1978). This method is used for small watersheds, where precipitation is assumed to fall with constant intensity and homogeneity in all basins. It can be said as limitation, this method ignores soil moisture and temperature. Despite this limitation, because of easy use potential, it is widely used (Mahdavi, 2009). The equation of Rational Method is given below (Eq.1);

$$Q = C.I.A/3600 \quad \text{(Eq.1)}$$

Q stand for maximum peak discharge with return period equal with storm return period (m^3 /s), C is coefficient that depends on slope, vegetation, land use, soil and return period and it is variable between 0-1 (Table 1), I is rainfall intensity (mm/h) and A is area (km^2).

Water collection time refers to the time taken in minutes until raindrops reach drainage structure that is planned to be constructed in surface flow from the farthest point of precipitation basin (Yayla, 2018). The precipitation collection times in the sub-watershed examined along the road route in the research area were found by using the following formula (Eq.2).

Table 1. C Coefficient definition (Öztürk and Hasdemir, 2021)

Plant Cover Type	Flow coefficient (C)
Watertight surfaces	0.90-0.95
Vertical and bare surfaces	0.80-0.90
Wavy and bare surfaces	0.60-0.80
Flat and bare surfaces	0.50-0.70
Broad-leaved forests	0.35-0.60
Coniferous forests	0.25-0.50
Farm areas	0.10-0.30

$$Te = 0.0078 \left(\frac{L^{1/2}.3{,}2808}{H^{1/2}}\right)^{0{,}770} \quad \text{(Eq.2)}$$

Where L: The distance between the discharge point and the farthest precipitation point to this point (m), H: The elevation difference between these two points (m).

The collection time consists of the sum of above-ground flow time and specific channel flow duration. It is very important to determine the type and dimensions of a hydraulic structure that can allow waters to pass under the road without damaging which the river can bring during the biggest flow in a certain period (25-50-100-year recurrence intervals). While determining the cross-sections of bridges and culverts, the solid materials (stones, logs, branches, etc.) to be carried by the stream should also be considered. Talbot Formula, the first approximation method used for sizing drainage facilities, is applied according to metric measurements (Menemencioğlu et al., 2013). Talbot Formula (Eq.3) is given below;

$$S = 5{,}791.C.\sqrt[4]{A^3} \quad \text{(Eq.3)}$$

Where S: Cross-sectional area of drainage structure (m^2), C: Talbot's coefficient (Table 2), A: Watershed area (km^2).

Table 2. Talbot's Coefficient (C) definition

Ave. Slope (%)	Plant canopy ratio (%)	Plant cover type	Talbot's coefficient (C)
10-20 (Flat)	100	Vegetation	0.2
10-30 (Flat)	100	Broad-leaved	0.3
10-30 (Flat)	100	Coniferous	0.4
30-50 (Rough)	100	Broad-leaved / Coniferous	0.5
30-50 (Rough)	0-70	Broad-leaved / Coniferous	0.6
40-60 (Rough)	0-40	Vegetation	0.7
> 60 (Steep)	100	Forest cover	0.8
> 60 (Too steep)	0	Bare land	0.9

Talbots' coefficient (C) should be determined very accurately as it directly affects the result in transactions. After determining the cross-sections of drainage structures via this formula, the type of drainage facility should be selected using flow calculations. Several factors such as topographic condition of the precipitation watershed, ground structure of the land, and vegetation should be considered when using this formula.

3. Results

The newly planned road that is within the borders of Yeşilvadi Forestry Sub-Directorate is coded as 430. The total length of this road is 7920 m. A total of 31 crossing points have been identified where the road intersects the stream along the road route through field studies. First of all, the boundaries of the watershed in these areas where the stream and the road intersect were determined. Depending on these boundaries, the area sizes of the watersheds were found. Several studies have been conducted to determine the cross-sections of the drainage structures to be constructed at these 31 points. Tablot's first approximation method was used to calculate these cross-sections. Tablot's formula was used to determine the drainage structures that should be used in the area and were most suitable for the stream crossing points (Table 3). Tablot's coefficient (C) was considered 0.5 in the research area. The area has a rough terrain and is covered with broad leaved trees.

Menemencioglu et al., (2013) conducted a similar study in the Black Sea region of Turkey, considering the basin as a whole. They determined a total of 164 sub-basin areas decided to construct a total of 4 bridges, 138 culverts and 22 pipes on all forest roads within these basins. Another study was conducted in Istanbul Bahçeköy Directorate of Forestry to examine the suitability of drainage structures built on forest roads and determined that 5 of the 7 culverts built along the road route were not suitable for the area. These drainage structures, which were not suitable as cross-sections, were filled with sediment in a short time and lost their functions (Öztürk 2020). Çalıskan et al., conducted a study for determining locations of drainage structures along the forest road route using GIS and GPS (Çalıskan et al., 2004). By using GIS, it is possible to determine the locations of the drainage structures to be built on forest roads, the basin areas, and the amount of precipitation that may come from the basin areas quickly and precisely. Combining field studies and GIS technology enables the planning of environmentally important drainage structures with high accuracy. The standardization for drainage systems is one of the most important technical developments in forest road construction (Vasileios et al., 2020).

The GDF has planned the location and type of drainage structures on this road in line with field studies and observations. In this plan, a total of 34 drainage structures were determined to be needed along the road route, including 26 pipes (Ø 80 cm plastic pipes) and 8 culverts. According to our study, which we have done with GIS technology and field studies, there is a need for 31 drainage structures along the same road route, including 25 pipes (18 plastic pipes and 7 steel pipes), 5 box culverts and 1 bridge. Steel culverts are used because of the filling in places with large dimensions of (Ø 120 and 150 cm). A total of 5 plastic pipes (Ø 80 cm) were recommended by both studies, one conducted by the GDF and our study by GIS approach. Although the GDF suggested Ø 80 cm pipes at nine same points, our study determined Ø 60 cm pipes to be sufficient for these areas. Although the GDF suggested Ø 80 cm pipes at five same points, our study found Ø 120 and 150 cm steel pipes to be required for these areas (Table 4).

Table 3. General characteristics of the drainage areas on the road route

No	Area	Drainage structures elevation	Max. Elevation	Stream Length (L)	Wtr.Total Length	Average Wtr.Slope	Q (Flow 100 yr.)	Prescription Collect Time
	km²	m	m	m	m	%	m³/h	min
W1	0.04	161	201	178	194	8.3	0.30	4.16
W2	0.01	151	193	42	77	45.5	0.07	2.54
W3	0.38	159	233	911	928	1.8	2.58	6.11
W4	0.43	154	235	962	980	1.8	2.91	5.92
W5	0.01	156	192	69	91	24.2	0.09	3.05
W6	0.0	155	209	214	241	11.2	0.31	3.82
W7	0.01	173	213	75	98	23.5	0.06	2.96
W8	0.07	173	232	192	225	14.7	0.44	3.49
W9	0.01	177	207	53	77	31.3	0.06	3.16
W10	0.01	178	203	51	72	29.2	0.05	3.44
W11	0.19	176	218	431	441	2.3	1.29	6.08
W12	0.02	174	216	157	170	7.7	0.16	3.77
W13	0.01	171	190	87	95	8.4	0.05	4.73
W14	0.14	172	219	383	398	3.8	0.95	5.37
W15	0.01	175	213	42	68	38.5	0.06	2.54
W16	0.01	169	210	70	94	25.6	0.04	2.85
W17	3.25	159	249	2577	2583	0.2	22.03	8.98
W18	0.24	169	210	572	583	1.9	1.63	7.10
W19	0.25	174	230	538	548	1.8	1.69	5.63
W20	0.02	176	207	152	167	9.0	0.12	4.56
W21	0.01	180	198	56	65	13.8	0.05	4.05
W22	0.14	181	254	392	404	3.0	0.95	4.06
W23	0.07	186	253	218	246	11.4	0.47	3.35
W24	0.06	186	253	218	246	11.4	0.39	3.35
W25	0.09	197	252	349	365	4.4	0.60	4.65
W26	0.13	198	259	401	414	3.1	0.88	4.63
W27	0.37	194	252	670	687	2.5	2.51	6.16
W28	0.15	196	251	564	572	1.4	1.02	5.81
W29	0.43	160	213	732	754	2.9	2.91	6.84
W30	0.02	169	203	58	81	28.4	0.13	2.99
W31	0.01	171	211	72	104	30.8	0.13	2.54

Table 4. Drainage structures planned according to the determined cross-sectional areas

No	Watershed Area	Cross Sectional Area	C Coefficient	Planning Drainage Structure Types by GIS Methods	Recommended Drainage Structures by Forest General Directorate
	km²	m²			
W1	0.044	0.28	0.5	Ø 80 cm plastic pipe	Ø 80 cm plastic pipe
W2	0.01	0.09	0.5	Ø 60 cm plastic pipe	Ø 80 cm plastic pipe
W3	0.38	1.40	0.5	Ø 150 cm steel pipe	Ø 80 cm plastic pipe
W4	0.43	1.54	0.5	Ø 150 cm steel pipe	Ø 80 cm plastic pipe
W5	0.013	0.11	0.5	Ø 60 cm plastic pipe	Ø 80 cm plastic pipe
W6	0.046	0.29	0.5	Ø 80 cm plastic pipe	Ø 80 cm plastic pipe
W7	0.009	0.08	0.5	Ø 60 cm plastic pipe	Ø 80 cm plastic pipe
W8	0.065	0.37	0.5	Ø 80 cm plastic pipe	Ø 80 cm plastic pipe
W9	0.009	0.08	0.5	Ø 60 cm plastic pipe	Ø 80 cm plastic pipe
W10	0.007	0.07	0.5	Ø 60 cm plastic pipe	Ø 80 cm plastic pipe
W11	0.19	0.83	0.5	Ø 120 cm steel pipe	Ø 80 cm plastic pipe
W12	0.023	0.17	0.5	Ø 60 cm plastic pipe	1.0 x 1.5 box culvert
W13	0.007	0.07	0.5	Ø 60 cm plastic pipe	Ø 80 cm plastic pipe
W14	0.14	0.66	0.5	Ø 120 cm steel pipe	Ø 80 cm plastic pipe
W15	0.009	0.08	0.5	Ø 60 cm plastic pipe	Ø 80 cm plastic pipe
W16	0.006	0.06	0.5	Ø 60 cm plastic pipe	Ø 80 cm plastic pipe
W17	3.25	7.01	0.5	Bridge	Ø 80 cm plastic pipe
W18	0.24	0.99	0.5	1.2 x 1.2 box culvert	1.5 x 1.5 box culvert
W19	0.25	1.02	0.5	1.2 x 1.2 box culvert	1.0 x 1.5 box culvert
W20	0.017	0.14	0.5	Ø 60 cm plastic pipe	1.0 x 1.5 box culvert
W21	0.007	0.07	0.5	Ø 60 cm plastic pipe	Ø 80 cm plastic pipe
W22	0.14	0.66	0.5	Ø 120 cm steel pipe	Ø 80 cm plastic pipe
W23	0.07	0.39	0.5	Ø 80 cm plastic pipe	Ø 80 cm plastic pipe
W24	0.057	0.34	0.5	Ø 80 cm plastic pipe	Ø 80 cm plastic pipe
W25	0.088	0.47	0.5	Ø 80 cm plastic pipe	1.0 x 1.0 box culvert
W26	0.13	0.63	0.5	Ø 120 cm steel pipe	-
W27	0.37	1.37	0.5	1.5 x 1.5 box culvert	1.0 x 1.0 box culvert
W28	0.15	0.70	0.5	Ø 120 cm steel pipe	1.0 x 1.0 box culvert
W29	0.43	1.54	0.5	1.5 x 1.5 box culvert	1.0 x 1.0 box culvert
W30	0.019	0.15	0.5	Ø 60 cm plastic pipe	-
W31	0.01	1.02	0.5	1.2 x 1.2 box culvert	Ø 80 cm plastic pipe

Box culverts were proposed in both studies, although the sizes were different in basins W23, W24, W32 and W34. In the W22 basin, the cross-sectional area was found to be very large (7.01 m^2) by GIS calculations, so it was decided to build a bridge in this area. The GDF calculated that pipe would be sufficient at this point. Çalıskan (2003) was determined as cross sections for drainage structures that are less than 1 m^2 was classified as circular cross section pipe or small culvert, between 1 and 2 m^2 as basket handled pipe, between 2 and 8 m^2 as large culvert and larger than 8 m^2 as bridge.

The positioning and construction for drainage structures on forest road is a very important subject. Especially, drainage structures should not change streambed inside stream cross. The changed streambed will enhance to environmental damages. The drainage structures should be positioning on forest road with 30º angle that water in ditches is pass. The sediment stock at the inlet or outlet of culverts are to be less to situation. The environmental impacts can be minimum with correct approach.

4. Conclusions

This study has indicated that GIS technologies, based on the methodology performed in DEM to obtain suitable layers and knowledge such as areas of watershed, road-stream crossing, slope analysis etc. are needed to determine the types and places of drainage structures on forest roads. The results of this study showed available and proper appreciation of the drainage structures in substantial short time for watersheds. The destructive effect of water on forest roads will be minimized by determining the location and types of drainage structures using GIS technology. Since the forest roads will not be affected much by the water coming from the streams, they will be able to serve for a longer period of time. Forest roads are the most important foundation for sustainable forestry operations in worldwide. Besides, these forest roads can prevent forest fires that is important for Turkey. The drainage structures and pavement on forest roads are very important for long-term use of forest roads. Therefore, it will be more precise to determine the dimensions of drainage structures using GIS technology. A GIS can handle more than one project and database and enable foresters to create a GIS database for all road structures and another forestry operations. Planning errors in drainage structures bring negative effects in terms of environmental damage, cost and occupational safety.

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