Available online at www.sciencedirect.com

ScienceDirect

Building and Environment 43 (2008) 687–695

BUILDING AND ENVIRONMENT

www.elsevier.com/locate/buildenv

Estimating sediment yield from a forest road network by using a sediment prediction model and GIS techniques

Abdullah E. Akay*, Orhan Erdas, Mahmut Reis, Alaaddin Yuksel

Department of Forest Engineering, Faculty of Forestry, Kahramanmaras Sutcu Imam University, 46100 Kahramanmaras, Turkey

Received 4 May 2006; received in revised form 17 January 2007; accepted 26 January 2007

Abstract

In forest lands, the stream channels receive the highest amount of sediment during road construction activities due to removal of vegetation cover from road surface, cut-slope, fill-slope, and ditch areas. Sediment delivered from a road section to streams causes serious damages on water resources and aquatic life. Performing revegetation in cut-slope and fill-slope reduce sediment yield from a road section; however, road surface and ditch continue to deliver considerable amount of sediment to the streams. Therefore, accurate prediction of sediment yield from existing road network can be very critical. In order to estimate average sediment yield, several sediment prediction models have been developed based on empirical relationships between various road erosion factors. In this study, average annual sediment yield from a road network to streams in a forest watershed was estimated by using the methodology of a GIS-based sediment prediction model, the SEDMODL model. GIS techniques were used to provide required data layers such as topography, streams, roads, geology, and average precipitation. The results indicated that the SEDMODL model integrated with GIS techniques can assist road managers to estimate total sediment yield quickly and effectively. Besides, critical road sections with high sediment yield potential can be identified and the efficiencies of various sediment control measures can be evaluated for these sections.

Keywords: Forest road network; Erosion factors; Sediment model; GIS

1. Introduction

A road network in forest lands provides easy access to forest resources for extraction, regeneration, protection, and recreation activities [1]. Traditionally, the planning of low-volume road networks highly depends on economical and social considerations [2]. In recent years, forest road construction and maintenance activities have become controversial, because of increasing public concerns about short- and long-term effects of forest roads on environment and the value that society now places on roadless wilderness [3,4]. In the last decade, considerable increase of traffic volume on forest roads, along with the expansion of the road networks has led to some negative consequences such as unsafe trafficking, air and noise pollution, and flora and fauna degradation [5–7].

Suitable forest road network is crucial for sustainable management of forest resources; however, inadequately constructed and maintained forest roads can cause more environmental impacts than any of these activities [8]. Studies have indicated that forest roads produce the highest amount of sediment yield to streams from forest lands [9–11]. Road construction removes the forest vegetation, disturbs forest floor, and damages soil structure, which dramatically increases the sediment yield [12,13]. Sediment delivered to streams from road sections leads to number of dramatic effects on water quality (i.e. increased water temperature and reduced oxygen) and aquatic life (i.e. siltation of spawning beds and aquatic insect habitat). Therefore, forest road managers should consider not only the total road cost but also environmental impacts caused by the road construction and use [14].

To reduce the potential sediment yield from a road section, cut-slope and fill-slope areas are immediately

*Corresponding author. Tel.: +90 344 223 7923x453; fax: +90 344 221 7244.
E-mail addresses: akay@ksu.edu.tr (A.E. Akay), erdas@ksu.edu.tr (O. Erdas), mreis@ksu.edu.tr (M. Reis), ayuksel@ksu.edu.tr (A. Yuksel).

0360-1323/$ - see front matter
doi:10.1016/j.buildenv.2007.01.047

revegetated following road construction activities. However, road surface and ditch areas still continue to deliver sediment to the streams as long as the road is used. The amount of sediment produced from road surface highly depends on traffic density, road surface type, road dimensions, and road gradient. The ditches receive the sediment yield from the cut-slope areas, depending on road section length, ground slope, and vegetation and rock cover density. Inslope roads with ditch keep the runoff water away from the fill-slope which may cause much smaller sediment yield than road surface and cut-slope areas.

Several sediment prediction models have been developed to help road managers in estimating average sediment from a road network to the streams. The Forest Road Sediment Assessment Methodology (FROSAM) model was developed as a practical approach for estimating sediment yield from forest roads as well as predicting and measuring the capabilities of road improvement methods [15]. In the model, the source areas for sediment yield include road surface, ditches, cut-slope, and fill-slope. The erosion factors considered in the model were cover, gravel, traffic, and percent of sediment delivery.

The Water Erosion Prediction Project (WEPP): Road Interface model was developed to estimate sediment yields, considering the specific conditions for soil, climate, ground cover, road surface, ditch, and topography [16]. The WEPP: Road Interface model assumes that sediment is produced from three overland flow elements including road surface, fill-slope, and a forested buffer area. Sediment yield is predicted based on road gradient, road width, surface type, road design (insloped or outsloped), and traffic density.

The X-DRAIN (Cross Drain Spacing and Sediment Yield Program) model was developed as a stand-alone and network interface to access the sediment yield data generated by the WEPP model for more than 130,000 combinations of topography, soil types, and climates [17]. The user controls over the erosion factors such as climate, soil, side-slope, and stream distance.

The model presented cannot identify the road sections with high sediment yield potential. They do not have capability to evaluate the effects of prevention techniques on total sediment yield from a road network to the streams. In this study, the methodology of a GIS-based sediment prediction model, the SEDMODL (Road Sediment Delivery Model) model was used to estimate average annual sediment yield from a road network to streams in a forest watershed [18]. The formulas used in the model are based on empirical relationships between road erosion factors such as road use, parent material, road surfacing, road surface slope, cut-slope vegetative cover, and distance to streams [11,19–21].

In the SEDMODL model, GIS tools can be used to generate some of the required data such as topography (10 m DEM optimal), streams, roads, and other optional layers (soil, local geology, precipitation, etc.). The accuracy of the GIS data layers directly affects the performance of the model in predicting sediment yield. After estimating average sediment yield from the road network, SEDMODL can assist road managers to locate the road sections with high sediment potential and to evaluate various sediment control measures for these sections. SEDMODL was successfully used in recent forest road design studies to estimate the sediment yield from an optimal forest road alignment [22].

2. Material and methods

2.1. Study area

The study area was the Baskonus Research and Application Forest of Kahramanmaras Sutcu Imam University, which is located approximately 45 km west of the city of Kahramanmaras in the Mediterranean region of Turkey. The research forest is about 458 ha in which 374.5 ha is forest land and 83.5 ha is open areas. The dominant tree species in the forest are *Pinus brutia*, *Pinus nigra*, *Cedrus libani*, and *Abies cilicica*. The average ground elevation and side-slope were 1165 m and 73%, respectively. In the research forest, there are county-maintained roads and secondary forest roads, with the lengths of approximately 7250 and 3155 m, respectively. The stream network in the research forest consists of two types of streams including medium and small types.

2.2. Mathematical formulations

The sediment yield is typically produced from four overland flow components including road surface, cut-slope, fill-slope, and ditch (Fig. 1). Since the road sections in the research forest are insloped with a ditch, surface water stay away from the fill-slope area. Based on the field observations and calculations, sediment yield from a revegetated fill-slope produces very small amount of sediment which can be ignored in the sediment prediction. In the formulation, the sediment yield from road surface and ditch were combined into one unit and called tread sediment. The road tread width includes both running surface width and ditch width. Therefore, total sediment delivered from each road section was predicted based on two components: road tread and cut-slope [18]:

$$\text{Total Sediment(t/year)} = (\text{TS} + \text{CS})A_{\text{f}}, \quad (1)$$

where TS is tread sediment, CS is cut-slope sediment, and A_{f} is road age factor. Tread sediment varies based on road dimensions including length (L_{r}) and width (W) and various erosion factors including geologic erosion rate (GE_{r}), road tread surfacing (S_{f}), traffic (T_{f}), road grade (G_{f}), precipitation (P_{f}), and sediment delivery factors (D_{f}):

$$\text{TS} = L_{\text{r}} W_{\text{r}} \text{GE}_{\text{r}} S_{\text{f}} T_{\text{f}} G_{\text{f}} P_{\text{f}} D_{\text{f}}. \quad (2)$$

Cut-slope sediment is a function of geologic erosion rate, cut-slope factor (CS_{f}), cut-slope height (CS_{h}), road length,

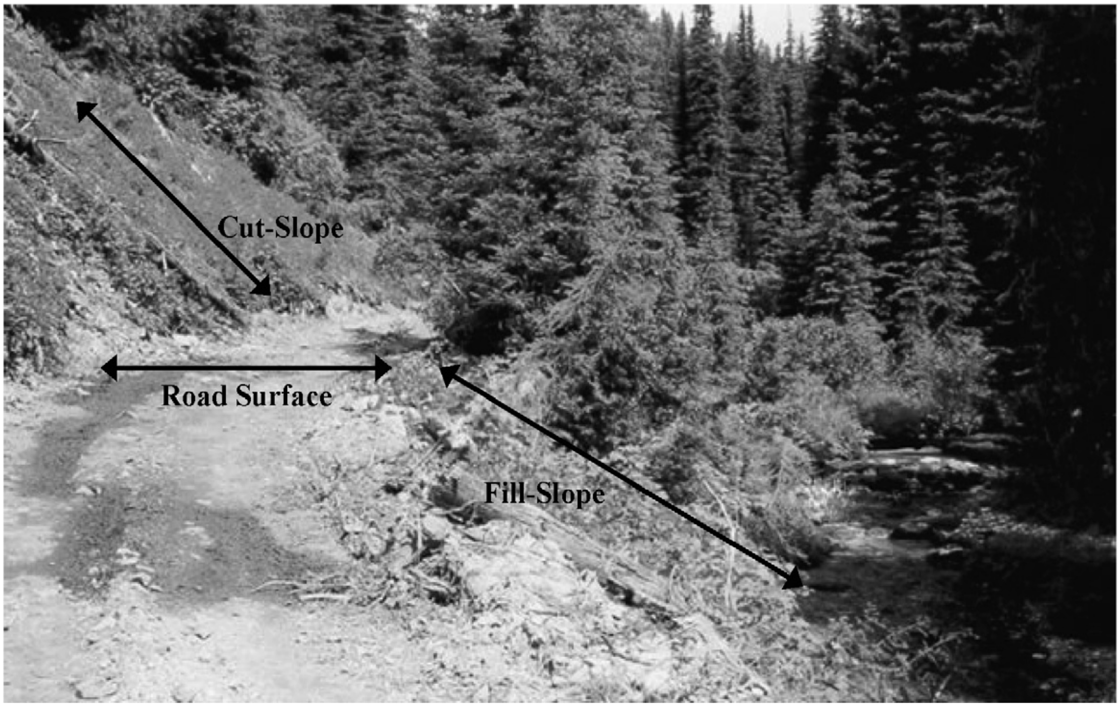

Fig. 1. A sample forest road template.

and sediment delivery factor:

$$CS = GE_r CS_f CS_h L_r D_f. \quad (3)$$

The majority of sediment yield from a new road is produced during the first two years until cut-slope, fill-slope, and ditch areas are properly covered by vegetations. According to the empirical observation, sediment yield is affected by time following construction [23]. The model considered the effects of the road age by multiplying the total sediment by the road age factor. It was assumed that the road age factor within the first year is 10, while it was 2 after two years or more [18].

The values for the erosion factors were obtained from user input values or from model-supplied tables generated based on the previously conducted studies. The following section describes the erosion factors and their associated values used in the equations.

2.2.1. Geological erosion rate

The sediment yield potential from a specific road segment highly depends on sub-soil properties and geology [23,24]. For example, the silt-dominated soils are the most erodible soils, followed by clay-dominated and gravel-dominated soils [25]. The erosion rates for basalt, andesite, granite, and sedimentary rocks are higher for Mesozoic and older rocks [18]. After determining the geologic information of lithology and geologic age, the geological erosion rates for common parent materials were obtained from Table 1. The erosion rates listed in this table were generated based on previously conducted studies [11,19,24,26–28]. In these studies, the local erosion factors such as surfacing, traffic, slope, and precipitation were factored out in determining the values of erosion rates.

2.2.2. Tread surfacing factor

The quality of the road surfacing material directly affects the sediment yield from the road tread surface [29]. After determining the road segments with high sediment yield potential, road managers can choose a better road surfacing type to reduce sediment yield. Based on the previous studies, tread surfacing factors for common road surface types are shown in Table 2 [21,30–32].

2.2.3. Traffic factor

The sediment yield from a road tread surface is also affected by road use, as well as road surface material [19]. The effect of road use on sediment yield is represented by traffic factor. Reid and Dunne [11] reported that traffic factor was to be the single most essential factor influencing sediment generation. There is an opposite relationship between traffic factor and surfacing factor [18]. The most heavily used roads with high traffic factor have high quality surfacing with low surfacing factor, while rarely used roads with low traffic factor have low quality surfacing with high surfacing factor. Therefore, these two factors tend to even each other out in estimating sediment yield from a road segment. Traffic factors for various road classes are indicated in Table 3 where the values are estimated based on previously performed field measurements and road erosion inventories [11,21,28]. To determine average sediment yield from a forest land, the road class should be selected from the table by considering long-term traffic

Table 1
Geologic erosion rates based on lithology and geologic age (in t/ha/year)

Lithology	Geologic age of formation[a]				
	Quaternary	Tertiary	Mesozoic	Paleozoic	Precambrian
Metamorphic	–	37	37	37	37
Schist	–	148	148	148	148
Basalt	37	37	74	74	74
Andesite	37	37	74	74	74
Ash	124	124	124	124	124
Tuff	124	124	74	74	74
Gabbro	–	25	25	25	25
Granite	–	49	74	74	74
Intrusive	–	37	37	37	37
Hard Sediment	–	37	37	74	74
Gravelly Sediment	37	37	–	–	–
Soft Sediment	74	74	–	–	–
Fine-Grained Soft Sediment	148	148	–	–	–

[a]Some of the lithology/ages categories with no occurrence do not have erosion rates (i.e. Soft Sediment and Mesozoic category does not occur).

Table 2
Road tread surfacing factors for various common road surface types

Surface type	Surfacing factor
Asphalt	0.03
Gravel	0.20
Pitrun	0.50
Grassed native	0.50
Native surface	1.00
Native with ruts	2.00

use, including log-truck, residential, recreational, and administrative traffic [18]. To determine sediment yield from a specific timber sale, the road class should be selected by considering the traffic use during that sale.

2.2.4. Road grade factor

A road grade factor was assigned to each road segment based on the road gradient classes. Luce and Black [23] and Reinig et al. [33] suggested road grade factor of 0.2, 1.0, and 2.5 for road grades less than 5%, between 5% and 10%, and more than 10%, respectively. The road grade affects the type and the amount of road surface material to be used in base course. In forest roads, pitrun materials are commonly used on grades less than or equal to 10%, while gravel materials are used on grades more than 10% [34]. Increasing road grade from 5% to over 10% increases the road grade factor from 1 to 2.5 (i.e. 2.5 times), while using gravel materials instead of pitrun material on road grade of more than 10% reduces the surfacing factor from 0.50 to 0.20 (i.e. 2.5 times).

2.2.5. Precipitation factor

The amount of sediment yield potential from a road segment can vary with annual regional precipitation. According to WFPB [15], exceeding the average annual precipitation of 1200 mm can increase the effects of erosion factors on sediment yield estimation about two times. In the methodology of SEDMODL, the precipitation factor was computed based on the average annual precipitation (P_{avr} in mm) in the basin [26]:

$$P_f = \left(\frac{P_{avr}}{1524}\right)^{0.8}. \quad (4)$$

The average annual precipitation can be estimated by using an interpolation method based on a meteorology station with known elevation and average precipitation. In this study, following formula was used to estimate the average annual precipitation in the research forest [35]:

$$P_h = P_0 \pm \frac{54h}{100} \quad (5)$$

where P_h is the estimated average annual precipitation at a study site (mm), P_0 the annual precipitation at the nearest meteorology station (mm), h the elevation difference between meteorology station and study site (m), 54 the increase in annual precipitation for every 100 m increment in elevation.

2.2.6. Delivery factor

Estimating percent of sediment yield from a road segment to a near by stream is the most difficult part in sediment prediction models [15]. The road sections with a long distance to the streams tend to have a low percentage of sediment yield since most of the sediment from the road section traps in the forest land and cannot reach the streams [36]. In the methodology of SEDMODL model, the erosion delivery factor for each road stage was estimated based on the distance from the middle point of the nearest stream to the middle point of the road stage [21]. The model assumed that a road segment at stream crossing directly delivers sediment to streams with a delivery factor of 100%. A road segment within 30 and 60 m of a stream resulted in a delivery factor of 35% and

Table 3
Road traffic factors for various road classes

Road classes	Road descriptions	Traffic factor
Highway	Main highway	120
Main Haul	Heavily used by log truck traffic throughout the year; usually the main access road in a watershed that is being actively logged	120
County Road	Wide, county-maintained road that receives heavy residential and/or log truck use	50
Primary Road	Receives heavy to moderate use by log trucks throughout all or most of the year. Usually roads branching off main haul road that head up tributaries or that access large portions of the watershed	10
Secondary Road	Receives light log truck use during the year. May occasionally be heavily used to access a timber sale. Receives car/pickup or recreational use	2.0
Spur Road	Short road used to access a logging unit. Used to haul logs for a brief time while unit is logged. On the average receives little use	1.0
Abandoned/blocked	Road is blocked by a tank trap, boulders, etc. or is no longer used by traffic	0.1

10%, respectively. These roads were located closely parallel to streams and indirectly deliver sediment to streams. The road segments that were located further than 60 m did not deliver sediment to streams since sediment was infiltrated into the forest floor. A delivery factor for road segments with no sediment delivery to streams was 0. The sediment delivery factors for each segment were determined based on the sediment delivery zones generated by using "buffer" tool in ArcView GIS 3.2 (ESRI, Redlands, CA, USA).

2.2.7. Cut-slope cover factor

The cut-slope cover factor can be defined as the percent of non-erodible cover on road tread, cut-slope, and fill-slope areas [18]. The cut-slope cover factor as percent of vegetative or rock cover on cut-slopes are included into the sediment yield estimations based on the local conditions on the watershed [21]. In order to control road segments with high sediment yield potentials, road managers may consider improving rock cover on the cut-slope areas as a quick prevention method. Improving vegetation cover on these cut-slopes can be also considered as a long-term solution. The cut-slope cover factors are listed in Table 4, depending on percentages of vegetation or rock cover on the cut-slope areas [21].

2.2.8. Cut-slope height

Increasing the cut-slope height increases the amount of sediment yield from cut-slope area to ditch area through soil creep, sheet wash, and slumping [23]. In the SEDMODL model, cut-slope height was determined based on hillside gradient class over the length of a road segment that draines to the stream. Four gradient classes were specified during the field measurements and cut-slope height was assigned for each gradient class based on the average cut-slope heights measured in road erosion inventories [18]. The mean cut-slope heights for gradient classes of 0–15%, 15–30%, 30–60%, and over 60% were estimated as 0.75, 1.5, 3.0, and 7.5 m, respectively. Therefore, the forest lands with steep hillside gradient deliver more sediment yield to the streams than a forest land with a even hillside gradient [36]. The hillside gradient data over the research forest was generated based on 10 m DEM and cut-slope height was determined for each road segment.

Table 4
The cut-slope cover factors as a function of vegetation or rock cover rates

Vegetation or rock cover (%)	Cover factor
100	0.1023
90	0.1500
80	0.2003
70	0.2540
60	0.3116
50	0.3742
40	0.4435
30	0.5222
20	0.6155
10	0.7700
0	1.0000

3. Results and discussion

GIS data layers for road and stream networks were generated based on a 1:25,000 scale topographic map by using Ilwis 3.2 Academic (ITC, Enschede, Netherlands). There were two county-maintained and four secondary forest road sections in the research forest. Each road section consisted of various numbers of road segments. In sediment prediction method, the sediment yield from each road segment was estimated and then cumulative sediment was computed for each road section. The road specifications of the road sections and their associated average annual sediment yields are listed in Table 5. The results indicated that the highest amount of sediment yield to the streams was produced by Section V, followed by Sections II, VI, I, and IV. There was no sediment delivery from Section III since the distance between all the road segments in Section III and the nearest stream was more than 60 m. The average annual sediment delivery from a square meter of the road sections was also computed by factoring out the road dimensions (i.e. length and width). The amount of

Table 5
Specification summary for road sections located in the research forest

Road sections	Road classes	Surface type	Length (m)	Width (m)	Average grade (%)	Sediment (t/year)
I	Secondary	Gravel	893.50	5	14	0.839
II	Secondary	Gravel	866.65	5	17	2.715
III	Secondary	Gravel	443.26	5	12	0.000
IV	Secondary	Gravel	951.43	5	6	0.258
V	County	Asphalt	3195.73	10	7	28.667
VI	County	Asphalt	4053.24	10	12	1.476

sediment yield (t/m^2) to the streams was 0.0037, 0.0199, 0.0004, 0.0636, and 0.0051 for Sections I, II, IV, V, and VI, respectively. Therefore, the highest amount of sediment yield in tons per square meter was also produced by Section V, followed by Sections II, VI, I, and IV.

Geology data coverage for the research forest was generated based on a 1:100,000 scale geologic map of Kahramanmaras. Then, this coverage was used to determine geologic erosion rates for the road segment in t/ha/year. The results indicated that available geologic age and lithology combinations in the research forest were Mesozoic/Hard Sediment, Tertiary/Hard Sediment, and Tertiary/Metamorphic. The estimated annual geologic erosion rate for all of these classes was 37 t/ha (Table 1). Therefore, the geologic erosion rate in tons per square meter (0.0037 t) was the least effective erosion factor on sediment yield from each road segments.

The secondary roads with gravel surfacing had about seven times greater surfacing factor than that of the county roads with asphalt surfacing. However, the traffic factor for the county road was 25 times greater than that of the secondary road. The cumulative effects of surfacing and trafficking on the potential sediment yield from a unit road length were 1.5 (i.e. 0.03×50) and 0.4 (i.e. 0.2×2) for county and secondary roads, respectively. Therefore, trafficking factor was more effective than surfacing factor on sediment yield from the road network in the research forest. Foltz and Burroughs [32] also reported that sediment yield from a low quality surfacing was 4–17 times greater than that of good quality surfacing, while the section with log-truck traffic produced 2–25 times greater sediment yield than the section with no traffic.

The road grade for each road segment was computed by using a 10 m DEM (Fig. 2) which was generated based on a 1:25,000 scale contour map. The average road grade for Sections IV and V was between 5% and 10% while for Sections I, II, and VI it was more than 10%. Therefore, effect of road gradient on the potential sediment yield from a unit road length in Sections I, II, and VI was 2.5 times greater than that in Sections IV and V. This result agreed well with the findings of Luce and Black [23] where increases in road gradient lead to increased sediment yield. Akay and Sessions [22] estimated the average annual sediment yield of an economically optimized road section for two different surfacing scenarios. The results indicated that the sediment yield from a road section with high

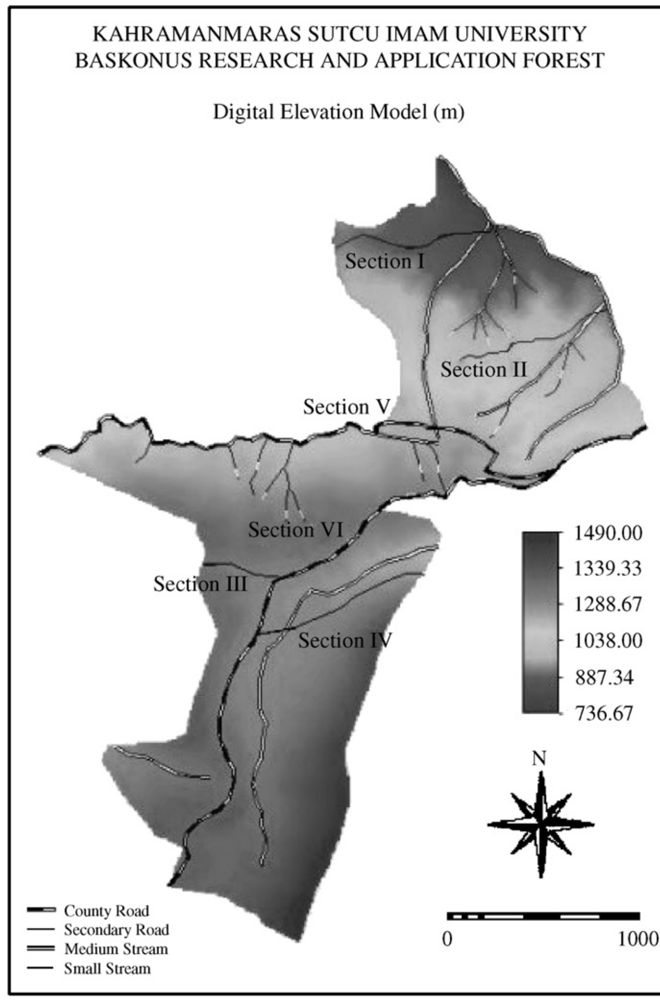

Fig. 2. The DEM (10 m) of the study area indicating road networks and streams.

quality surfacing and steep road gradient (i.e. $>10\%$) in the first scenario was more than the sediment yield from a road section with low quality surfacing and less steep road gradient (i.e. $<10\%$). Therefore, the effect of road grade factor on sediment yield was more than that of surfacing factor.

To determine the precipitation factor for each road segment, a 100 m precipitation map was generated by using interpolation method based on the DEM and meteorology data from the station in Kahramanmaras. The elevation

Table 6
The number of road segments within the road sections with a high sediment delivery potential

Road sections	Number of segments	Direct delivery	Within 0–30 m	Within 30–60 m	No delivery
I	11	2	–	–	9
II	15	1	3	4	7
III	3	–	–	–	3
IV	7	1	–	–	6
V	47	6	2	6	33
VI	47	–	–	3	44

and the average annual precipitation at the meteorology station was about 566 m and 712 mm, respectively. Then, precipitation factor for each road segment was computed (Eq. (4)). The results indicated that the average precipitation factor for road sections varied from 0.64 (Section I) to 0.75 (Section VI) based on the average elevation along the road sections. Therefore, the effect of precipitation factor on sediment yield was not significant in the road network. However, in seasons with intense rainfall events, a considerable amount of sediment yield might occur, especially in the road sections with low quality surfacing. In order to prevent excessive sediment yield due to intense rainfall, the surfacing quality of the roads should be improved [28].

In the road network, the road segments with high sediment delivery factor and segments with no delivery were identified. For each road section, the number of road segments under each sediment delivery category was indicated in Table 6. Only 28 segments out of 130 segments delivered sediment to the stream network in the research forest. In Section V, six segments directly deliver sediment to the streams at stream crossings, while the rest of the segments were closely parallel to the streams and indirectly deliver sediment to the streams. In Section III, the sediment yield from each segment was infiltrated into the forest floor before reaching the streams.

Based on the field measurements, the percentages of vegetation and rock cover on cut-slopes for county-maintained roads and secondary roads were estimated as 80% and 60%, respectively. The associated average cut-slope cover factors were 0.2003 and 0.3116, respectively. Therefore, secondary roads had about 36% less cut-slope cover capacity than that of county-maintained roads. Luce and Black [23] also indicated that reduction in the amount of cut-slope vegetation and rock cover material caused a significant increase in sediment yield.

The cut-slope heights were estimated for each road segment based on the hillside gradient data layer generated based on the DEM. The results indicated that the average cut-slope heights for the road segments that deliver sediment to the streams in Sections I, II, IV, V, and VI were 1.52, 3.43, 0.76, 1.42, and 4.57, respectively. Therefore, the effect of cut-slope height on sediment delivery was very considerable in Sections II and VI. Luce and Black [23] also suggested that high cut-slopes were the most important source of sediment yield from the road segment after two years or more.

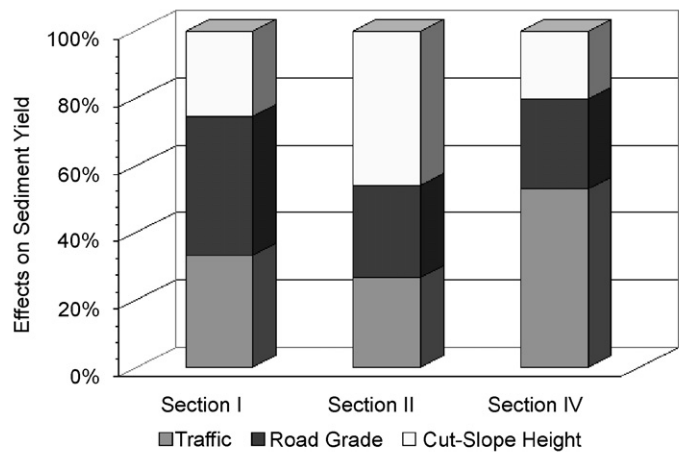

Fig. 3. The effects of traffic, road grade, and cut-slope height on sediment yield in percentage.

The effects of improving tread surfacing material and cut-slope cover capacity in secondary roads were evaluated. It was found that using asphalt surfacing type in secondary roads reduced the annual sediment delivery by about 74%, 63%, and 73% in Sections I, II, and IV, respectively. However, improving cut-slope cover capacity of secondary roads from 60% to 80% reduced the sediment delivery by only 5%, 10%, and 5% in Sections I, II, and IV, respectively. Therefore, the effect of road tread surfacing factor on sediment yield was much higher than that of cut-slope cover factor.

To investigate the most effective erosion factors in sediment yield, the erosion factors whose average values were more than 1.0 in the equations were determined for each road section. In Section I, road grade factor was the most influential factor, followed by traffic factor and cut-slope height. In Section II, the most influential factor was cut-slope height, followed by road grade factor and traffic factor. In Section IV, only traffic factor had a considerable effect on the sediment yield. Fig. 3 indicated the effects of these three factors on sediment yield in percentage. In the county-maintained road sections, traffic factor significantly affected the amount of sediment yield produced from the road segments.

The amount of sediment yield produced from road tread surface and cut-slope area was also evaluated. The results indicated that sediment yield from road tread surfacing was 7, 3, 6, 26, and 14 times more than sediment yield from the cut-slope area in Sections I, II, V, and VI. There was a significant difference between these two sediment sources in Sections V and VI due to the high value of traffic factor (i.e. 50). In Section IV, sediment yield from road tread surface was not high due to low value of road grade factor.

4. Conclusions

The average annual sediment yield from a road network to streams in a forest watershed was estimated based on the methodology of the SEDMODL model, which was relatively easy and flexible in sediment prediction. It is capable of identifying the road segments with high sediment yield potential. The success of various road improvement techniques in reducing sediment yield can be evaluated through a sensitivity analysis of the road erosion factors. Besides, GIS technologies can be easily integrated with the methodology in generating some of the main data layers (such as DEM, streams, roads, soil, local geology, and precipitation), which can assist road managers to quickly and efficiently evaluate the sediment yields in large forest lands. However, there are a number of limitations of the model in predicting sediment yield. The model assumes that all roads are in-slope with ditch. Besides, the model may over-predict sediment yield if the GIS data layers (stream, soil, etc.) are not accurate and road template information (road length, cut-slope, etc.) is not complete.

The results from this study proved that the sediment yield from road sections highly depends on several erosion factors. Even though their effects on sediment yield vary based on the road types (i.e. secondary or county-maintained roads), the most important attributes to consider in predicting sediment yield are road use, gradient, and cut-slope heights. In spite of the fact that these three factors are very effective on sediment yield, their effects can be dramatically reduced or even vanished by sediment delivery factor based on the distance between the road segments and the streams.

The accuracy of these results still needs to be validated in a field study. However, the effects of the erosion factors on the sediment yield were in good agreement with the results derived from the previously conducted observational studies. Therefore, this methodology can be used as a decision support tool in predicting sediment yield and identifying the problematic road segments with high sediment yield potential.

Acknowledgments

This research was supported by the Research Fund of the Kahramanmaras Sutcu Imam University, Kahramanmaras, Turkey. Project Number: 2004/4-16.

References

[1] Demir M, Hasdemir M. Functional planning criterion of forest road network systems according to recent forestry development and suggestion in Turkey. Am J Environ Sci 2005;1(1):22–8.
[2] Demir M. Impacts, management and functional planning criterion of forest road network system in Turkey. Transportation Res Part A 2007;41(2007):56–68.
[3] Cole DN, Landres PB. Threats to wilderness ecosystems: impacts and research needs. Ecol Appl 1996;6:168–84.
[4] Williams T. The unkindest cuts. Audubon (January–February); 1998. p. 24–31.
[5] Jaarsma FC. Rural low-traffic roads (LTRs): the challenge for improvement of traffic safety for all road users. In: Proceedings of the 27th ISATA, dedicated conference on road and vehicle safety, Aachen, Germany; 1994. p. 177–83.
[6] Jaarsma FC, Van Langevelde F. The motor vehicle and the environment: balancing between accessibility and habitat fragmentation. In: Proceedings of the 29th ISATA, dedicated conference on the motor vehicle and the environment, Florence, Italy; 1996. p. 299–306.
[7] Jaarsma FC. Approaches for the planning of rural road network according to sustainable land use planning. Landscape Urban Plan 1997;39:47–54.
[8] Akay AE, Sessions J. Forest operations: roading and transport operations chapter. In: Burley J, Evans J, Youngquist JA, editors. Encyclopedia of forest sciences. Oxford, UK: Elsevier Limited; 2005. p. 2400pp.
[9] Binkley D, Brown TC. Forest practices as nonpoint sources of pollution in North America. Water Res Bull 1993;29(5):729–40.
[10] McClelland DE, Foltz RB, Falter CM, Wilson WD, Cundy T, Schuster RL, et al. Relative effects on a low-volume road system of landslides resulting from episodic storms in Northern Idaho. In: Proceedings of the seventh international conference on low-volume roads, Washington, DC, vol. 2(1652); 1999. p. 235–43.
[11] Reid LM, Dunne T. Sediment production from forest road surfaces. Water Resour Res 1984;20(11):1753–61.
[12] Grace JM. Control of sediment export from the forest road prism. ASAE Annu Meeting 2002;45(4):1–6.
[13] Megahan WF. Erosion over time: a model. US Department of Agriculture Forest Service, Intermountain Res Stn, Ogden, Utah Res Paper INT-156; 1974. 14p.
[14] Akay AE, Boston K, Sessions J. The evolution of computer-aided road design systems. Int J Forest Eng 2005;16(2):73–9.
[15] WFPB. Washington Forest Practices Board Manual: standard methodology for conducting watershed analysis, Version 4.0; 1997.
[16] Elliot WJ, Hall DE, Scheele DL. WEPP interface for predicting forest road runoff, erosion and sediment delivery. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, San Dimas Technology and Development Center; 1999.
[17] Elliot WJ, Hall DE, Graves SR, Scheele DL. The X-DRAIN cross drain spacing and sediment yield program Version 2.00. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, San Dimas Technology and Development Center; 1999.
[18] Boise Cascade Corporation. SEDMODL-Boise Cascade road erosion delivery model. Technical documentation; 1999. 19p.
[19] Bilby RE, Sullivan K, Duncan SH. The generation and fate of road-surface sediment in forested watersheds in southwestern Washington. Forest Sci 1989;35(2):453–68.
[20] Megahan WF, Seyedbagheri KA, Mosko TL, Ketcheson GL. Construction phase sediment budget for forest roads on granitic slopes in Idaho. In: Hadley RF, editor. Drainage basin sediment delivery. International Institute of Hydrologic Science, Publication 159; 1986. p. 31–9.
[21] WDNR. Standard methodology for conducting watershed analysis, Version 3.0. Washington Forest Practices Board; 1995.

[22] Akay AE, Sessions J. Applying the decision support system, TRACER, to forest road design. West J Appl Forestry 2005;20(3): 184–91.

[23] Luce CH, Black TA. Sediment production from forest roads in western Oregon. Water Resour Res 1999;35(8):2561–70.

[24] Ketcheson GL, Megahan WF. Sediment production and downslope sediment transport from forest roads in granitic watersheds. US Department of Agriculture, Forest Service, Intermountain Research Station; 1996.

[25] Burroughs ER, Luce CH, Phillips F. Estimating interrill erodibility of forest soils. Trans. ASAE 1992;35(5):1489–95.

[26] Reid LM. Sediment production from gravel-surfaced forest roads, clearwater basin, Washington. M.S. Thesis, University of Washington; 1981.

[27] Vincent KR. Runoff and erosion from a logging road in response to snowmelt and rainfall. Master's thesis, University of California Berkley; 1985.

[28] Foltz RB. Traffic and no-traffic on an aggregate surfaced road: sediment production differences. Paper presented at food and agriculture organization seminar on environmentally sound forest road and wood transport, Sinaia, Romania; 1996.

[29] Foltz RB. Traffic and no-traffic on an aggregate surfaced road: sediment production-differences, paper presented at Seminar on environmentally sound forest roads and wood transport. Rome, Italy: Food and Agric. Organ.; 1999.

[30] Burroughs ER, King JG. Reduction of soil erosion on forest roads. USDA Forest Service, Intermountain Research Station, Ogden, Utah. General Technical Report INT-264; 1989.

[31] Swift LW. Gravel and grass surfacing reduces soil loss from mountain roads. Forestry Sci 1984;30:657–70.

[32] Foltz RB, Burroughs ER. Sediment production from forest roads with wheel ruts. In: Proceedings of a symposium on watershed planning and analysis, July 9–11, 1989, Durango CO. ASCE; 1990. p. 266–75.

[33] Reinig L, Beveridge RL, Potyondy JP, Hernandez FM. BOISED user's guide and program documentation. USDA Forest Service, Boise National Forest; 1991. 12pp.

[34] Kramer BW. Forest road contracting, construction, and maintenance for small forest woodland owners. Oregon State University, Forest Research Laboratory, Research Contribution 35; 2001. 79pp.

[35] Ozyuvaci N. Meteorology ve Climatology. Istanbul University, Faculty of Forestry Publication No: 460; 1999.

[36] Ouyang D, Bartholic J. Reducing sediment delivery ratio in Saginaw Bay Watershed. In: The 22nd national association of environmental professionals conference proceedings, May 19–23, 1997, Orlando, FL; 1997. p. 659–71.