HYDROLOGICAL PROCESSES
Hydrol. Process. **29**, 1772–1782 (2015)
Published online 20 August 2014 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.10301

Effects of forest roads on the hydrological response of a small-scale mountain watershed in Greece

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Abstract:

The effects of land use changes on the ecology and hydrology of natural watersheds have long been debated. However, less attention has been given to the hydrological effects of forest roads. Although less studied, several researchers have claimed that streamflow changes related to forest roads can cause a persistent and pervasive effect on hillslope hydrology and the functioning of the channel system. The main potential direct effects of forest roads on natural watersheds hydrologic response are runoff production on roads surfaces due to reduced infiltration rates, interruption of subsurface flow by road cutslopes and rapid transfer of the produced runoff to the stream network through roadside ditches. The aforementioned effects may significantly modify the total volume and timing of the hillslope flow to the stream network. This study uses detailed field data, spatial data, hydro-meteorological records, as well as numerical simulation to investigate the effects of forest roads on the hydrological response of a small-scale mountain experimental watershed, which is situated in the east side of Penteli Mountain, Attica, Greece. The results of this study highlight the possible effects of forest roads on the watersheds hydrological response that may significantly influence direct runoff depths and peak flow rates. It is demonstrated that these effects can be very important in permeable watersheds and that more emphasis should be given on the impact of roads on the watersheds hydrological response. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS forest roads; hydrological response; runoff; experimental watershed; runoff routing; spatially distributed unit hydrograph; HYDRUS

Received 11 February 2014; Accepted 22 July 2014

INTRODUCTION

The effects of land use changes on the ecology and hydrology of natural watersheds have long been investigated (e.g. La Marche and Lettenmaier, 2001; Brown *et al*., 2005; Chu *et al*., 2010; Sung and Li, 2010; Soulis *et al*., 2012; Julian and Gardner, 2014; Schottler *et al*., 2014). Especially in recent years, the combined effect of land use and climate change has attracted even more attention (e.g. Hejazi and Moglen, 2008; Wang *et al*., 2013; Zhang *et al*., 2014). Among other changes, the construction of forest roads may play a significant role in altering hydrologic response and accelerating soil erosion in previously undeveloped areas (Ziegler and Giambelluca, 1997). Forest roads are constructed to increase access in order to allow forest management and utilization and may also be used in firefighting or act as firebreaks. Recently, forest roads are also built to allow the construction and operation of renewable energy projects in remote areas. However, forest roads may alter hydrologic patterns, increase erosion and cause ecosystems discontinuity, as well as increase the risk of forest fires initiation, illegal waste dumping and timber harvesting. Despite the potential impact of building roads and the long history of research in this topic, important gaps in current understanding of their hydrological effects are still present (Luce, 2002; Ziegler *et al*., 2004; Cuo *et al*., 2008). A key characteristic of roads hydrological impact is the extensive uncertainty caused by differences in their behaviour as a function of climate, soil and topography. As it is stated by Luce (2002) 'current models and literature addressing road hydrology are based on the hydrology of a few sites, and a more general conceptualization is needed'. Therefore, further studies in areas where this issue has attracted limited attention up to now may contribute to this effort.

Despite their normally small areal extent as compared with the total area of natural watersheds, road surfaces may significantly affect the watersheds hydrological response (Ziegler and Giambelluca, 1997; Woldie *et al*., 2009). Several studies have shown that streamflow changes related to forest roads in some cases could be

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more important than those related to other factors, such as vegetation destruction, because unlike vegetation destruction, which recovers overtime, forest roads could have a more persistent and pervasive effect on hillslope hydrology and the functioning of the channel system (Jones and Grant, 1996; La Marche and Lettenmaier, 2001). Road construction has been associated with a number of effects on hydrologic and geomorphic processes, including increased direct runoff volumes and peak flow rates, increased soil erosion and consequent impact on stream sedimentation and channel morphology, possible landslide risk and potential effects on water quality and ecosystem functioning (Reid and Dunne, 1984; Montgomery, 1994; Jones and Grant, 1996; Wemple *et al*., 1996; Ziegler *et al*., 2000; MacDonald *et al*., 2001; Wemple *et al*., 2001; Takken *et al*., 2008; Foltz *et al*., 2009).

The main direct mechanisms through which roads may alter hydrologic response are the following: (1) Development of overland flow on the highly compacted or impermeable road surfaces due to the reduced infiltration rates (Ziegler and Giambelluca, 1997; Takken *et al*., 2008). (2) Interception of subsurface flow by road cutslopes, which is then rerouted via the faster overland flow mechanism (Jones and Grant, 1996; Wemple and Jones, 2003). (3) Rapid routing of both subsurface flow and surface runoff through roadside ditches and culverts directly to the streams (Jones and Grant, 1996; Wemple *et al*., 1996; Croke and Mockler, 2001; Takken *et al*., 2008; Buchanan *et al*., 2013). (4) Development of erosion gullies along the roads or at the outlet of culverts that act similarly to ditches in capturing and rerouting surface water (Wemple *et al*., 1996; Croke and Mockler, 2001; La Marche and Lettenmaier, 2001). (5) Ditches, channels, culverts and gullies act as an extension of the natural stream network effectively increasing stream network density (Jones and Grant, 1996; Wemple *et al*., 1996; Croke and Mockler, 2001; La Marche and Lettenmaier, 2001; Buchanan *et al*., 2013). However, the contribution of the previously described mechanisms may vary depending on the specific characteristics of each watershed (e.g. dominant runoff generation mechanism, channel and subcatchment configurations), and the overall impact of forest roads on streamflow response may range from significant to even negligible (La Marche and Lettenmaier, 2001). Land cover, soil type, antecedent soil moisture conditions, total storm precipitation and rainfall intensity are some of the main parameters that have been examined towards this direction (Cuo *et al*., 2008; Woldie *et al*., 2009).

Despite the evidence that road-related impact often outweigh those of other landcover changes, conservation efforts in many parts of the world have historically focused on agriculture or forest management, often ignoring road effects (Ziegler *et al*., 2004; Cuo *et al*., 2008). Roads design may significantly affect their hydrological impact. For example, simple changes in road design that would reduce drainage concentration could minimize road-related adverse impact on slope stability and downslope stream channels (Montgomery, 1994; Wemple *et al*., 1996).

Simulation models are important tools in the study of forest road impacts on hydrologic response and can provide a better insight in the involved mechanisms. As an example Dutton *et al*. (2005) and Mirus *et al*. (2007) employed a transient, heterogeneous and variably saturated subsurface finite-difference flow model to simulate the effect of a forest road on near-surface hydrologic response. Other researchers used hydrological models to investigate the effects of forest roads on hydrological response at a catchment scale (e.g. La Marche and Lettenmaier, 2001; Cuo *et al*., 2008; Bowling and Lettenmaier, 2013).

Mediterranean arid and semi-arid areas, and especially Greece, are characteristic examples of regions where the hydrologic effects of forest roads have attracted limited attention up to now. This study uses detailed field data, spatial data and hydro-meteorological records, as well as Geographical Information Systems (GIS) techniques and numerical simulations to investigate the effects of forest roads on the hydrological response of a small-scale mountain experimental watershed, which is situated in the east side of Penteli Mountain, Attica, Greece. The watershed has a mixed vegetation cover; it is dominated by coarse soils with generally high hydraulic conductivities, and it has a dense network of forest roads. These conditions are generally related to significant forest road impacts on hydrological response.

MATERIALS AND METHODS

Study area

The study area is the small-scale experimental watershed of Lykorrema stream (7.84 km^2), located in the east side of Penteli Mountain, Attica, Greece (Coordinates: UL 23°53′33′E-38°04′13″N; LR 23°56′00″E-38°02′28″N) (Figure 1). The region is characterized by a Mediterranean semi-arid climate with mild, wet winters and hot, and dry summers. Precipitation occurs mostly in the autumn–spring period. The average annual precipitation for the 6 years studied (2004–2005 to 2009–2010) is 690 mm. The hydrographic network of the watershed is particularly dense, including fifth-order streams according to the Strahler (1952) method.

The Lykorrema watershed presents a relatively sharp relief, with elevations ranging between 280 and 950 m. Its average slope is as high as 36%. Geologically, the watershed is characterized by schist's formations covering 96% of the area, while the rest is covered with marbles. A soil survey in

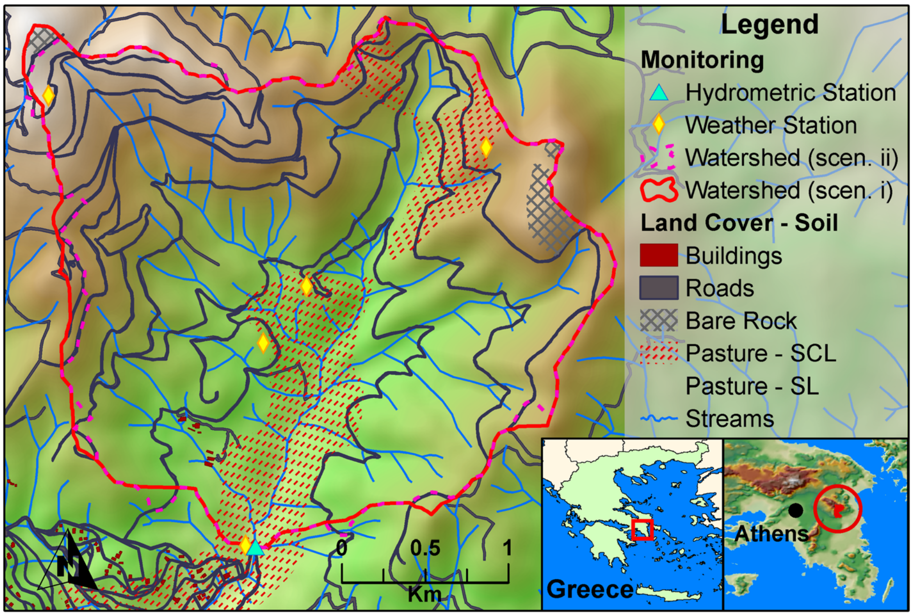

Figure 1. Map of Lykorrema stream experimental watershed

the area showed that the watershed is dominated by coarse soils with high hydraulic conductivities and a smaller part is covered with medium textured soils presenting relatively high hydraulic conductivities. A detailed land cover classification based on remote sensing techniques carried out in 2009 showed that the watershed had a mixed vegetation cover consisting of pasture, shrublands, a pine forest at the first stage of development and a few scattered tufts of trees. There was also a dense network of forest roads, while a small part of the watershed was covered by bare rock (Figure 1 and Table I). The total length of the road network of the watershed was estimated equal to 40.15 km. The aquifers system developed within the intensely fractured bedrock contributes significantly to the base flow of the watershed, which is continuous throughout the year. Generally, there is not an immediate response of base flow rate to the storm events. During wet years, the base flow rate increases continuously till late spring, whereas in dry years base flow rate decreases slowly throughout the year. The Base Flow Index (BFI – the long-term proportion of base flow on total stream flow) of the watershed is 0.79. Schneider *et al.* (2007) correlated the BFI values to hydrological soil characteristics and Longobardi and Villani (2008) correlated high BFI values to high watershed permeability. Consequently, the highly observed BFI values are in agreement with the aforementioned referred studies, because the studied watershed is dominated by coarse soils with high hydraulic conductivities.

Table I. Summary of watershed's soil land cover complexes and percentages of surface runoff produced in each soil land cover complex for the events studied

Soil–land cover complex	Area (km^2)	Area (%)	Surface runoff* (%)
SL – Pasture	6.049	77.18	0
SCL – Pasture	1.393	17.76	0–36
Roads	0.267	3.40	41–65
Stream channels	0.002	0.03	
Buildings	0.004	0.05	22–35
Rock	0.128	1.58	

SL, Sandy Loam; SCL, Sandy Clay Loam.
*Percentage of surface runoff coming from the corresponding soil–land cover complex.

The study area is equipped with a dense hydro-meteorological network, which is operational since September 2004. The network consists of five rain-gauges, one hydrometric station at the outlet of the watershed, one full meteorological station, including a soil moisture sensors array, and four temperature-relative humidity recorders (Figure 1). The Lykorrema experimental watershed is operated by the Agricultural University of Athens. Detailed description of the hydrology, climate and physiography of Lykorrema experimental watershed and of the available geographical and hydro-meteorological databases are provided by Soulis *et al.* (2009) and Soulis and Valiantzas (2012, 2013).

Runoff volume

At a first stage of analysis, a numerical simulation model predicting surface runoff volume was applied with the aim to investigate the impact of forest roads on the direct runoff volume produced. On the basis of the detailed soil survey and land cover classification carried out in the area (Figure 1 and Table I), the watershed was categorized in four main soil–land cover complexes, namely Sandy Loam (SL) – Pasture, Sandy Clay Loam (SCL) – Pasture, roads and other impermeable surfaces.

For the purpose of this application, it was assumed that the watershed is characterized by an infiltration-excess (Hortonian) surface runoff generation mechanism, which results from the saturation of the top soil 'saturation from above'. This assumption is justified because the region, in which the watershed under study is located (Attica, Greece), is characterized by semi-arid climate conditions, ground water level is very deep, and antecedent moisture conditions are dry in most studied events (Soulis *et al.*, 2009). As Dingman (2002) reported, 'the Hortonian surface runoff is an important response mechanism in semi-arid to arid regions'. This assumption is also supported by the results of the numerical simulations of representative soil profiles (described in the succeeding text) and soil moisture recordings carried out at the meteorological station located in the Pasture – SCL complex indicating that the bottom part of the soil profile is not saturated in the studied events (it should be noted that soil moisture readings are local and may not represent the entire area of the soil–land cover complex, but they provide an important indication). On the basis of the earlier indications, it can be assumed that saturation from the succeeding text is not a dominant runoff generation mechanism in this case.

In this approach, the total amount of water, which infiltrates in the SL – Pasture and SCL – Pasture soil–land cover complexes and which is therefore lost by surface runoff was simulated by means of the HYDRUS-1D code (Simunek *et al.*, 1998). In numerical runs, the observed 10-min rainfall records of the storm events producing significant direct runoff that occurred from September 2004 to August 2008 (30 events) were used as inputs in order to predict the corresponding amount of surface runoff produced from each storm event and each soil type of the watershed. A storm event was considered significant when the value of peak flow rate in the hydrograph was greater than $0.15\,m^3/s$. Accordingly, the spatially distributed rainfall excess was calculated at every point of the studied watershed, and then it was routed to the watershed's outlet using the spatially distributed unit hydrograph (SDUH) method as it is described in the 'Runoff Routing' section.

In HYDRUS-1D code, one-dimensional water flow in a homogeneous, rigid and variably saturated porous medium is described using Richards' equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial K(\psi)}{\partial z}\left[\left(\frac{\partial \psi}{\partial z}\right) - 1\right] \tag{1}$$

where θ is the volumetric water content ($L^3\,L^{-3}$), t is the time (T), z is the vertical coordinate (positive downwards) (L), ψ is the pressure head (L) and K is the hydraulic conductivity ($L\,T^{-1}$). The HYDRUS-1D code is generally considered robust, accurate and numerically reliable.

A simplified uniform soil profile was simulated for the first two soil–land cover complexes. The depth of the soil profile is assumed to be equal to 1 m. Test simulations with shallower or deeper soil profiles indicated that reasonable variations in soil depth do not influence significantly the results, at least as related to direct runoff. To solve Equation (1), the upper and lower boundary conditions and the initial conditions need to be specified. In this study, the upper boundary condition was defined as an atmospheric condition where potential water fluxes across the soil surface correspond to the 10-min recorded precipitation storm events. It was assumed that no ponding occurs at the soil surface, and that all excess water is removed instantaneously by surface runoff. Evapotranspiration was not considered in the simulation runs, which is acceptable during storm events. At the lower boundary of the 1 m uniform soil profile, a zero pressure head gradient was defined, i.e. free-draining soil profile. The free drainage boundary conditions were chosen for the bottom of the soil profile because there are permeable geological formations in most of the area, and the aquifer was found in deep depths. An initially dry soil profile is supposed for all the events analysed, while the simulation for the events belonging to medium or wet antecedent moisture conditions starts 5 days earlier to take into account the antecedent precipitation.

The soil profile was discretized into 500 soil compartments to enhance the numerical stability and the accuracy of the solution. The initial conditions were given in terms of pressure heads and were all set at 1 m. In addition to the initial and boundary conditions, the water retention characteristics, $\theta(\psi)$, and the hydraulic conductivity curve, $K(\theta)$ or $K(\psi)$, must be specified to solve Equation (1). In this study, the empirical closed-form analytical model of van Genuchten (1980) was used to describe, respectively, the water retention characteristic $\theta(\psi)$ and the $K(\theta)$ relationship. The parameters of the van Genuchten (1980) model, α, n, θ_s and θ_r for each soil type, were evaluated using the Rosetta Lite Version 1.1 (Schaap *et al.*, 2001). The saturated hydraulic conductivity value K_s, for each soil type, was evaluated by measurements taken during the soil survey. Table II presents the values of the aforementioned parameters for the two soil profiles.

Table II. Soils hydraulic properties

Soil type	α (1/m)	n (–)	θ_s ($m^3\,m^{-3}$)	θ_r ($m^3\,m^{-3}$)	K_s ($cm\,h^{-1}$)
SL	2.7	1.45	0.39	0.039	24
SCL	2.1	1.33	0.38	0.063	1.6

SL, Sandy Loam; SCL, Sandy Clay Loam.

In the case of the other impermeable surfaces, it was assumed that surface runoff volume was equal to the corresponding rainfall volume. Finally, direct runoff volume coming from the roads surface, $runoff_{roads}$, was estimated with a linear runoff response formula of the form:

$$runoff_{roads} = C \cdot P \tag{2}$$

where C is a runoff coefficient and P is the precipitation depth.

Accordingly, it was possible to estimate the total direct runoff volume, $runoff_{total}$, of the watershed for each event as the sum of the direct runoff volume generated by each soil–land cover complex.

$$runoff_{total} = runoff_{SL} + runoff_{SCL} + runoff_{otherimperm.} + runoff_{roads} \tag{3}$$

where $runoff_{SL}$, $runoff_{SCL}$ and $runoff_{otherimperm.}$ are the direct runoff volumes coming from SL – Pasture, SCL – Pasture, and other impermeable surfaces soil–land cover complexes correspondingly.

The direct runoff volume coming from roads surface and the associated parameter, C, were calibrated and validated using the measured precipitation and direct runoff volume data corresponding to the 30 studied events based on Equations (2) and (3). For this purpose, the studied events were sorted according to the measured direct runoff volume and then separated in two even groups covering all the range of measured direct runoff volumes (Figure 2). The first group (odd rank events of the sorted list) was used for the calibration and the second group (even rank events of the sorted list) for the validation of parameter C. More details on the numerical simulation model and the characteristics of the events analysed are presented by Soulis *et al*. (2009).

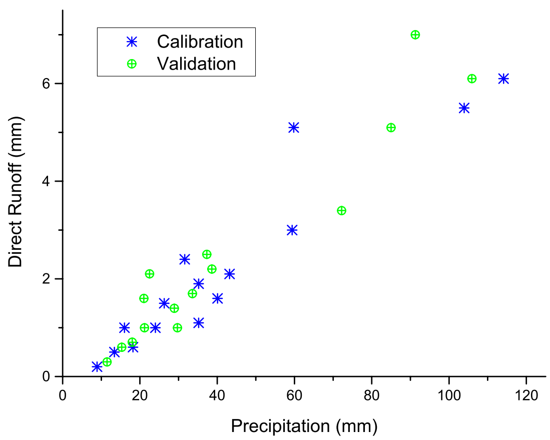

Figure 2. Measured direct runoff depth plotted as a function of precipitation depth for the 30 events used for the calibration and the validation of the model

Geomorphological characteristics

In the current analysis, a detailed (5 × 5 m) digital terrain model (DTM) and a detailed map of the roads network were used in order to investigate the effect of the road network on the geomorphological characteristics of the watershed. The DTM was generated using the corresponding 1/5000 scale topographic diagrams of the Hellenic Military Geographical Service. The road network and its characteristics were mapped using orthophotos and field survey data.

Two scenarios were examined as follows: (i) neglecting road effects and (ii) considering road effects. In the first scenario, the original DTM was used. The original DTM was generated on the basis of the contours, and the elevation points shown on the topographic diagrams. Consequently, the original DTM does not comprise the effect of roads on runoff flow. In the second scenario, the original DTM was modified to reflect the effect of roads on runoff routing, and thus to represent more correctly the actual conditions. Therefore, the road network was 'burnt' on the DTM, i.e. the elevation of DTM grid cells associated with roads was lowered (Duke *et al*., 2006; Callow *et al*., 2007) as it can be seen in Figures 3 and 4(a). In this way, overland flow is collected by road cutslopes, and it is then rerouted through roadside ditches and directly delivered to the nearest culvert or stream crossing, in order to represent more correctly the actual conditions. For the two DTMs corresponding to the two scenarios, the usual GIS terrain analysis for hydrological applications was followed, which includes DTM processing for depressions removal, computation of flow direction and flow accumu-

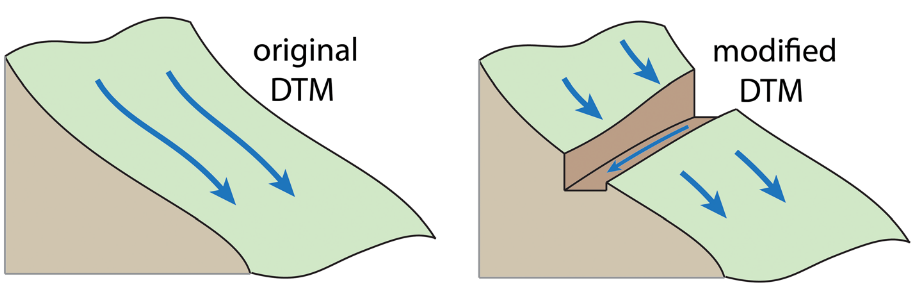

Figure 3. DTM modification to reflect the effect of roads on runoff routing

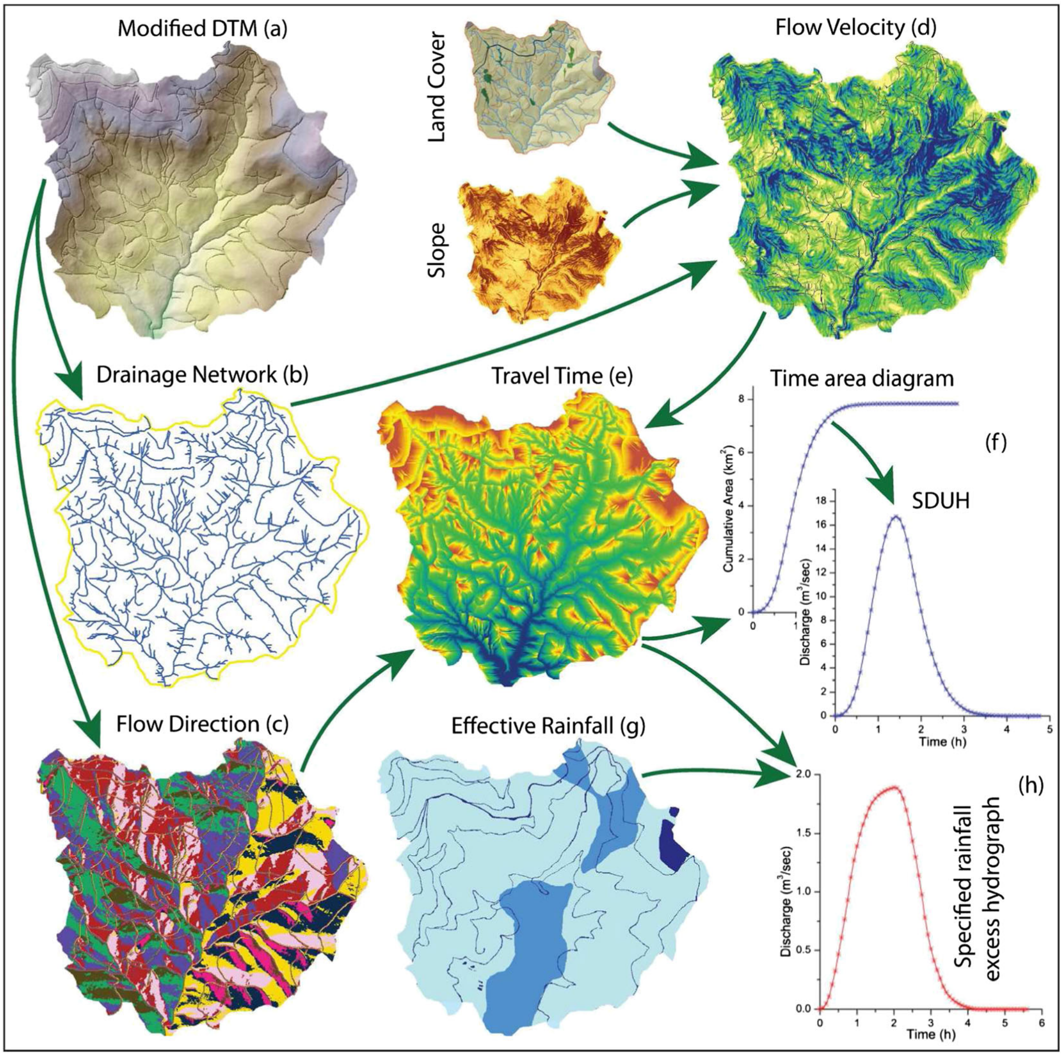

Figure 4. Graphical representation of the required steps for the determination of the SDUH using GIS

lation, delineation of watersheds and analysis of the drainage network (Soulis, 2013). Then the following parameters concerning the physical characteristics of the watershed were calculated: area, perimeter, slope and altitude statistics, circularity ratio and elongation ratio. The drainage network was also analysed through the calculation of the drainage network length, drainage density, average length of overland flow and of the Horton's laws for both scenarios (Bárdossy and Schmidt, 2002; Moussa, 2009).

Runoff routing

The effect of roads on the timing of runoff response was investigated by means of the SDUH. The SDUH is a unit hydrograph derived from a spatially distributed excess rainfall. It is computed from the time–area diagram of a watershed, compiled by analyzing the corresponding DTM. The time–area diagram is a graph of cumulative watershed area whose time of travel is less or equal to a given value, and it is calculated using a simple flow routing algorithm in a GIS computing runoff travel time through the hillslopes and the channel network of the watershed based on the velocity field, i.e. the velocity of flow on each grid cell (Muzic, 1996). The SDUH allows for spatially variable runoff routing parameters and effective rainfall to be used in the runoff routing process. The SDUH is derived from the watershed's time–area diagram according to the method described by Maidment (1993).

The methodology used in this study for the determination of the SDUH is illustrated in Figure 4. In this figure, scenario ii (considering roads effect) is illustrated as an example; however, the same methodology was applied in both scenarios. More specifically, the required steps for the implementation of this methodology are the following:

1. On the basis of the original DTM and the modified DTM considering road effects, as it was described in

the previous section, the flow direction grids and the drainage networks are derived for scenarios i and ii, respectively [Figures 4(a), (b) and (c)].
2. On the basis of the land cover, the slope, and the drainage network grids corresponding to each scenario, the flow velocity grids for scenarios i and ii, respectively, are generated [Figure 4(d)].
3. The two travel time grids are then derived using the flow direction and the flow velocity grids corresponding to scenarios i and ii [Figure 4(e)].
4. Following the aforementioned steps, the time–area diagrams for both scenarios are derived from the travel time grids, and the corresponding SDUHs are then estimated based on the time–area diagrams [Figure 4 (f)]. These SDUHs can be used for the calculation of specific storms' hydrographs according to the unit hydrograph theory.
5. In case the hydrograph of spatially variable effective rainfall is required, the flow velocity grid is overlaid with the effective rainfall grid [Figure 4(g)] in order to derive the time–area diagram and the hydrograph of the specified rainfall excess [Figure 4(h)].

In conclusion, using this methodology, the effect of roads on runoff routing and especially the interception of surface flow by road cutslopes and its routing through roadside ditches to the nearest culvert or stream crossing are directly considered. In the case that subsurface flow provides an important contribution to direct runoff, the same method may also consider subsurface flow interception by adapting the flow velocities of the corresponding parts of the hillslopes.

In the current analysis, the time–area diagrams for the two scenarios examined were calculated for isochrone intervals equal to 5 min. According to the SDUH method, constant values of flow velocities for both overland flow and channel flow were used. The flow velocities were adjusted according to the land cover category, the stream order and the slope [Figure 4(d)]. The flow velocity values used were obtained from the study of Dervos *et al*. (2006), who applied the SDUH runoff routing method in the same watershed. The validity of these flow velocities values was tested by comparing the concentration times resulting from the time–area curves with concentration times estimated from observed hydrographs. For these reasons, the hydrographs of the studied events were examined, and 5 of them corresponding to, as much as possible, isolated and uniform rainfall events were selected.

The 1-h SDUHs for both scenarios were calculated assuming that 1 cm of rainfall excess was uniformly distributed on the watershed's surface. The produced time–area diagrams and the SDUHs illustrated the effect of roads on the timing of runoff response. Finally, to investigate the combined effect of roads on both runoff volume and timing, a test event was studied using the previously described runoff volume numerical simulation model and the SDUHs. For this purpose, the test event was simulated with the numerical simulation model in order to calculate the spatially distributed rainfall excess for each scenario. The calculated rainfall excess was then routed to the watershed's outlet using the previously described methodology.

RESULTS AND DISCUSSION

As it was described in the 'Materials and Methods' section, the direct runoff volume model was calibrated and validated using the measured precipitation and direct runoff volume data for the events studied. The value of the associated parameter, *C*, was estimated equal to 0.95. The root mean square error of calibration (RMSE) was equal to 0.39 mm, and the coefficient of determination R^2 was equal to 95.3%. The RMSE of validation was equal to 0.49 mm, and the coefficient of determination R^2 was equal to 93.9% suggesting that the model can satisfactory predict direct runoff volumes at least for the studied watershed and the studied period. The comparison between the predicted direct runoff volumes and those measured for both the calibration and the validation phases is presented in Figure 5. Generally, there is a good agreement between the measured and the simulated runoff values.

As it can be seen in Table I, roads cover about 3.4% of the watersheds surface. However, according to the simulation model results, the direct runoff volume coming from the roads surfaces ranged between 41% and 65% with an average value of 62% for the events studied. The

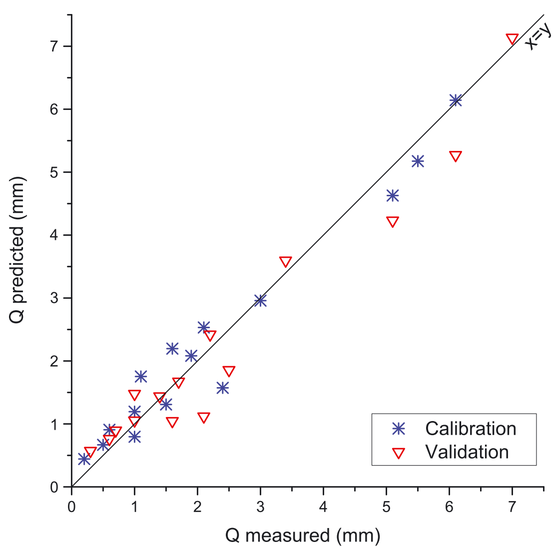

Figure 5. Comparison between the predicted and the measured direct runoff volumes for both the calibration and the validation phases

direct runoff depth coming from the remaining soil–land cover complexes ranged between 22% and 35% for the other impermeable surfaces (bare rock, buildings and stream channels), 0% and 36% for SCL – Pasture, while the SL – Pasture complex did not produce any direct runoff for the events studied (Table I). This can be attributed to the combination of very permeable soils covering the larger area of the watershed with the almost impermeable surface of the roads. As it can be seen in Table II, the saturated hydraulic conductivity K_s of the SL soil is very high, and as a result, it was much higher than the maximum 10-min rainfall intensity in all the events simulated, resulting in zero direct runoff (the maximum 10-min rainfall intensity for the events studied was measured equal to 9.4 cm h^{-1}). This is in agreement with the statement of Dingman (2002) that many natural soils present saturated hydraulic conductivities K_s much higher than the normal rainfall intensities. Furthermore, as it can be seen in Figure 2, the direct runoff response of the watershed is very low. Specifically, the observed direct runoff depths range between 2.2% and 9.3% of the corresponding observed rainfall depths (5.2% on average). Therefore, the large percentages of direct runoff volumes coming from the roads surfaces and the other impermeable surfaces can be justified. It is also worth noting that the percentage of roads contribution was lower in events characterized by very high rainfall intensities. In these events, the areas covered by SCL – Pasture produced significant amounts of direct runoff as well. The aforementioned behaviour is also in agreement with the very high BFI value of the watershed as it is described in the ‘Study Area’ section. A similar behaviour has been observed by other researchers (e.g. Wemple *et al*., 1996; Ziegler and Giambelluca, 1997; Cuo *et al*., 2008).

The geomorphological characteristics calculated for the two scenarios examined are presented in Table III. Roads affect geomorphic processes mainly by capturing and rerouting overland flow, acting as an extension of the natural stream network (Figure 3). Therefore, as it can be seen in Table III and in Figure 6, the total drainage network length and the drainage density are almost doubled, while the average length of overland flow is significantly decreased, when the effect of roads is considered (scenario ii). Horton’s laws values are generally higher in the second scenario demonstrating the effect of roads on drainage network density. However, the observed variation is low, indicating that the basic geomorphic factors governing the drainage network

Table III. Watershed geomorphological characteristics for the two scenarios examined

	Scenario			Scenario	
Watershed characteristics	i	ii	Drainage network	i	ii
Perimeter (km)	12.2	13.09	Total stream length (km)	49.07	92.75
Area (km^2)	7.84	7.70	Drainage Density: D_A (m^{-1})	0.006	0.012
Circularity ratio (Ec)	0.66	0.57	Average length of overland flow (m)	79.36	41.66
Compactness ratio (Ec’)	1.23	1.32	Bifurcation ratio: R_B	4.44	5.26
Elongation ratio (E_L)	0.65	0.49	Law of stream lengths: R_L	2.12	2.66

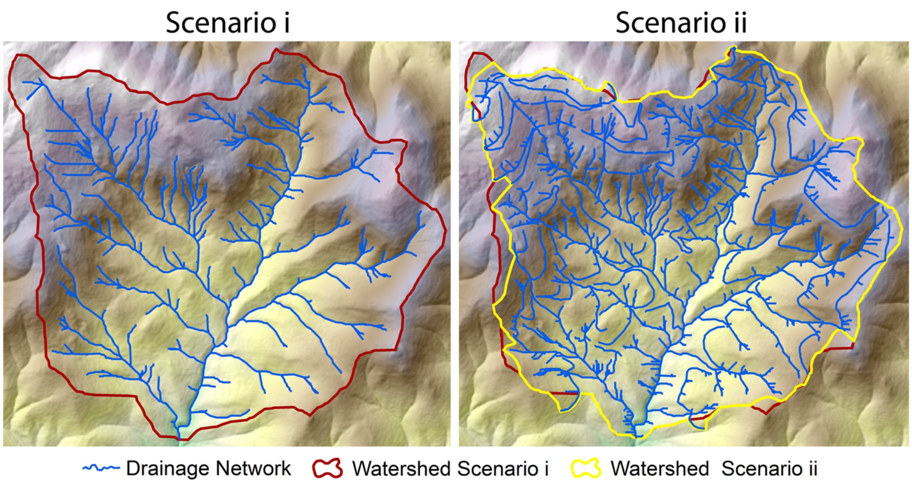

Figure 6. Effects of roads on the water divide and the drainage network

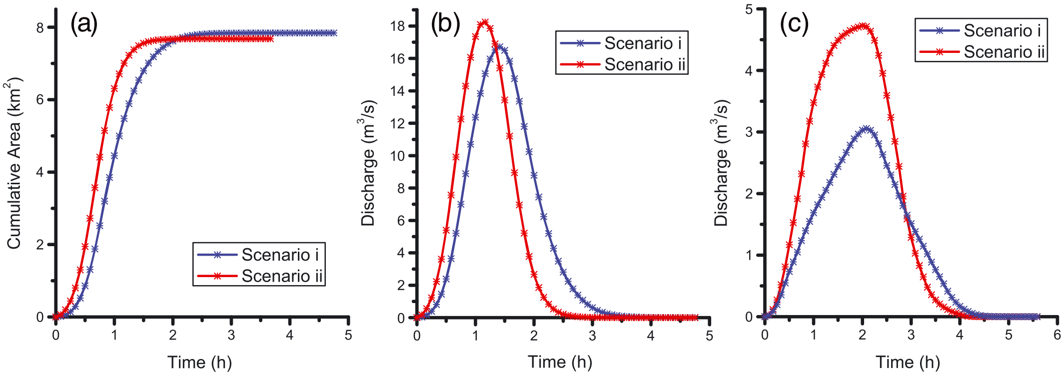

Figure 7. Time–area diagrams (a), spatially distributed unit hydrograph (b) and direct runoff hydrograph (c), for the two scenarios examined

composition are similar in both scenarios. It is also interesting that roads affect the basic geometrical characteristics of the watershed as well, although their impact is limited. It should be noted that usually in the GIS terrain analysis procedures for hydrological applications, the effect of roads on the estimated geomorphological characteristics is not taken into account, despite their influence on some characteristics as previously described.

The time–area diagrams for the two scenarios examined are presented in Figure 7(a). The concentration times resulting from the time–area curves were 225 min and 170 min for scenarios i and ii, respectively. As it can be seen, the concentration time in the case where the effect of roads is taken into account is much shorter than when it is neglected. The concentration times estimated by the observed hydrographs ranged between 140 and 240 min with an average of 184 min and a standard deviation of 39 min. These values are comparable with the ones estimated by the time–area curve for the case of scenario ii, which corresponds to the existing conditions. Therefore, the selected flow velocity values are supposed acceptable for use in this application, considering the limitations and the uncertainty associated with the estimation of concentration times based on observed hydrographs as well as the fact that SDUH is a simplified runoff routing method based on constant flow velocities values.

In the same figure, the effect of roads on the timing of runoff response is presented. As it can be observed, the time–area curve corresponding to the second scenario is sharper, implying significantly faster runoff routing when roads are taken into account. As an example, the cumulative watershed area whose time of travel is less than 1 h covers 94% of the watershed's area in the case where the effect of roads is considered (scenario ii) but only 56% when it is neglected (scenario i). The same observations can be made in Figure 7(b), where the 1 h-SDUHs for the two scenarios examined are illustrated. It can be clearly seen that the rising limb of the hydrograph is steeper, the time to peak is lower, and the peak flow rate is higher in the case where the effect of roads is taken into account (scenario ii). As it is also stated by Wemple *et al.* (1996), road segments linked to the channel network increase flow routing efficiency and hence provide a plausible mechanism for observed increases in peak flows.

Finally, the combined effect of roads on both runoff volume and timing is illustrated in Figure 7(c). In this figure, the direct runoff hydrographs corresponding to a 2-h rainfall event with an average rainfall intensity of 25 mm/h, for the two scenarios examined are presented. The estimated total direct runoff depth was equal to 3.45 and 5.1 mm for the first and second scenarios, respectively. As it can be seen, the combined effect of roads on both the runoff volume and the runoff routing efficiency may significantly increase the observed peak discharge values. However, in this case, the effect of roads on the time to peak is not as profound as in the case of the SDUH. This observation can be attributed to special characteristics of the studied watershed. More specifically, as it can be seen in Figure 1, the less permeable areas of the watershed (main runoff producing areas) are mainly concentrated at the lower parts of the watershed and nearer to the drainage network.

CONCLUSIONS

Using detailed field data, spatial data, hydro-meteorological records, as well as GIS techniques and numerical simulations, it was found that roads significantly increase the produced direct runoff volume of the studied watershed. However, the percentage increment is generally lower in events characterized by very high rainfall intensities. It was also found that roads affect the geomorphological characteristics of the studied watershed, and especially those related to the drainage network. Furthermore, it was shown that the effects of roads on the drainage network increase flow routing efficiency, thus leading to profound increase in peak flows. Here, it should be noted that in the current analysis only the infiltration-excess surface runoff generation mechanism was considered. In cases that subsurface flow and its interception by roads cutslopes are considered, even more considerable effects on the hydrograph shape are expected.

The aforementioned results highlight the need to put focus on the impact of roads on the watersheds hydrological response and especially in the case of permeable watersheds. It was also found that considerable errors may be caused by neglecting roads effects on the usually applied GIS terrain analysis procedures for hydrological applications. Furthermore, the use of HYDRUS-1D model in combination with the simple SDUH method as an alternative tool in studies investigating the hydrological effects of roads was presented. Further steps in this direction could be the testing of similar approaches under various conditions favouring different direct runoff generation mechanisms or testing the combination of SDUH with two or three-dimensional vadose zone hydrology simulation models that could provide more insight at the soil water dynamics at the hillslope scale.

Finally, the results obtained can be very important considering the rising number of renewable energy projects, which are currently built in rural areas and require the construction of new roads. However, road impact is associated with large uncertainty and greatly depends on the special conditions of each watershed; therefore, further research using more detailed data at the hillslope scale and research in new inadequately studied regions is still needed to investigate road impact under various conditions and to propose improvements in roads design.

ACKNOWLEDGEMENTS

The authors wish to sincerely thank the editor and the two anonymous reviewers for their constructive comments and suggestions, allowing us to improve the final version of the paper.

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