

## Review

# Impacts of Watersheds' Landscape and climate descriptors on surface runoff in mountainous region

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**Abstract:** Watershed's landscape features and climate variables have a significant influence on the mountainous catchment's hydrological response. This literature review synthesizes recent kinds of literature investigating associations between surface runoff and catchment's landscape features, and the potential controls of climate variables, with an emphasis on mountainous regions. Such factors are significant controls on surface runoff through their influence on the rate of infiltration capacity, antecedent soil moisture conditions, and underlying bedrock structure. The literature review indicates that there are considerable issues that remain to be resolved in advance a concrete understanding of the influence of catchment's characteristics on surface runoff response.

**Keywords:** Runoff runoff; Mountainous region; Watershed; Landscape; Climate; Management

## 1. Introduction

**"Mountainous region plays a crucial role in the supply of freshwater to humankind, in both mountains and lowlands." [1]**

In a mountainous region, a scientific understanding of catchment processes and surface runoff is very essential to effective water policy, development, and management. Urbanization and population evolutions over time are associated with highly increasing demands on accessible freshwater for different purposes like human consumption, industry, agriculture, and environmental regulation [2]. In this region, surface runoff generation and its relationship with climate-landscape features have considerable influence on phenomena like soil erosion, land degradation, desertification, and flooding that impose significant impacts on a community [3]. Confirming save concentrations of pollutants associated with agricultural activities such as fertilizer doses and pesticides, chemicals that are used to kill pests and weeds, requires accurate estimation of surface runoff volume or depth since highly polluted overland flow may be drained into streamflow [4–6], and these factors transport negative implications for stream biota and human consumption if it is beyond the limits of WHO [7,8].

In the mountainous area, soil erosion phenomena due to surface runoff are highly-prone (e.g.[9]), and this erosion resulted in both 'on-site' and 'off-site' problems. On-site problems like a significant loss of agricultural soil fertility on the upper part of the watershed at a rapid rate, resulting in a great loss of natural resources and agricultural yields [10]. Contrary to this, spring development in the mountainous regions can be successfully applied if a watershed is conserved and protected from the unwise use of human beings [1]. Off-site problems such as sedimentation which affects the life span of the reservoir as well as streamflow due to loss of its storage, [11,12], and water quality [13,14]. [15]

investigated that, about 10 out of the 15 reservoirs in Jamaica were significantly silted. Supplement to this, the environmental impacts of sedimentation such as loss of aquatic habitat, decreases in fishery resources, and loss of wetlands [16,17]. Accordingly, a stronger knowledge on the surface runoff is well fundamental in different issues such as non-point contaminant pollutions [18], and in the water scarcity regions like arid and semi-arid mountainous regions, even in a humid mountainous region, areas where water shortages are not communal, the overland flow may be regarded as an additional water resource source [19].

Even if the necessity for a better understanding of surface runoff response to external factors has been known for many years, most previous reviews have tended to emphasize flood response to increased human pressures on the catchment's landscape [20,21], and some researches focus on investigating the baseflow response to catchments' landscape and climate variables [22,23]. In this regard, the literature review is inadequate concerning researches exploring mountain area surface runoff response to biophysical natural factors like geology, relief, forest, climate, soil, and human influences on watershed's landscape.

The purpose of this review was to synthesize investigation from various water resources disciplines, to provide an organized summary of the current state of research knowledge regarding the influences of watershed characteristics and anthropogenic influences on surface runoff, and to address the potential impacts of climate variables and their changes on surface runoff in a mountainous region. Water resource management involves a stronger understanding of surface runoff processes, and a secondary objective of this review is to identify key research questions as a gap that remains unanswered.

This review stresses literature covering geomorphic and anthropogenic effects including climate on surface runoff in mountainous regions of the world. The introductory part covers a basic discussion of primary controls on surface runoff as well as its impacts on human beings, and environmental services. Next, a section on geomorphic controls on overflow processes covers the influences of basin geology, surface topography, and soils. This section is followed by an overview of the anthropogenic effect on surface runoff, with emphases on deforestations, agricultural activities, and urban expansion, because of the large body of research on those topics. Next to this, a summary of current research evaluating and predicting surface runoff response to climate variables and their change is presented. Finally, the review concludes with a discussion of key research topics, the results of which would fill large gaps in our understanding of watershed hydrology and surface runoff.

## 2. Surface Runoff Overview

As a result of either the rainfall rate exceeds the infiltration rate or soil water holding capacity exceeded, water runs off along the land surface and/or hillslopes as overland flow or surface runoff (Horton, 1933 & 1938 cited in [24]). Infiltration excess overland flow (Figure 1a) is common under tropical dry initial conditions and on hillslopes with a paved surface like urban and compacted soil as a result of overgrazed areas, and in semi-arid and arid regions with a less vegetated area [24,25]. Conversely, when the soil excessively saturates, no more water is infiltrated, and as a result saturation excess overland flow (Figure 1b) or surface runoff over the mountainous gentle slope occurs (Dunne and Leopold, 1978 cited in [26]).

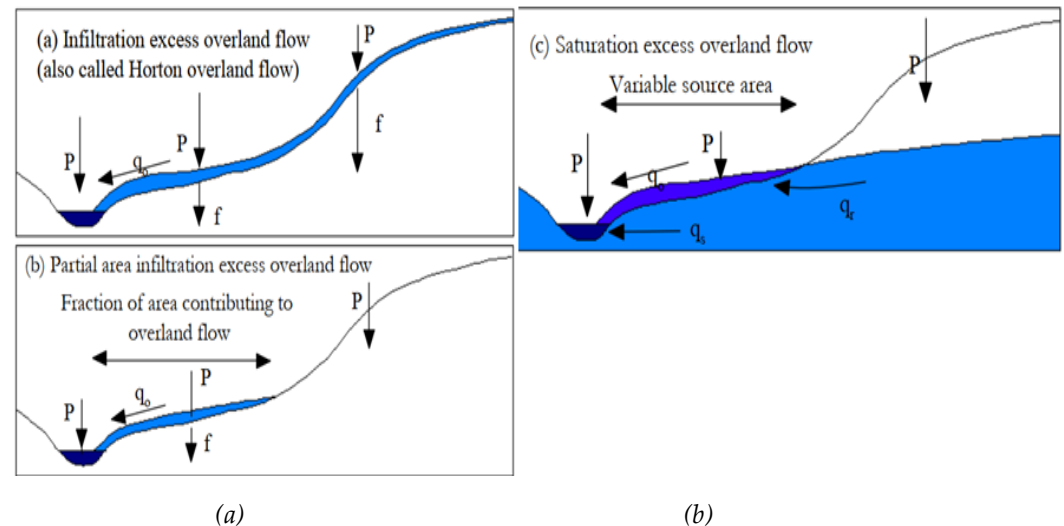


Figure 1. Infiltration excess overland flow (a), and Saturation excess surface runoff (b) (source: [26]).

The saturation excess overland flow is more common in a mountainous region under temperate and/or humid climate conditions with frequent, low precipitation intensity, and occurs when the soil is saturated and unable to absorb more water [26].

Figure 2 summarizes the fundamental processes involved in runoff generation, indicating the interaction between infiltration excess, saturation excess, and subsurface flow pathways. Several rainfall-runoff models are organized around a representation similar to Figure 2 involving the partition of surface water input into infiltration or overland flow, either due to infiltration excess or saturation excess.

Factors that encourage infiltration, percolation, and higher evapotranspiration (ET) will decrease surface runoff, while factors associated with anthropogenic activities like urbanization and logging will increase surface runoff.

Overland flow is influenced by a wide range of features [27–30] like:

- Geomorphology of the catchment's landscape;
- Spatially distributed watershed's soil characteristics;
- Land use land cover change throughout the catchment;
- Catchment's geologic characteristics.

Most of the physiographic features may be changed with anthropogenic effect on the catchments' landscape, and it therefore very essential to understand not only the associations between catchments' landscape characteristics and surface runoff in a mountainous region but also how direct anthropogenic watershed impacts and climate change affects these physiographic characteristics.

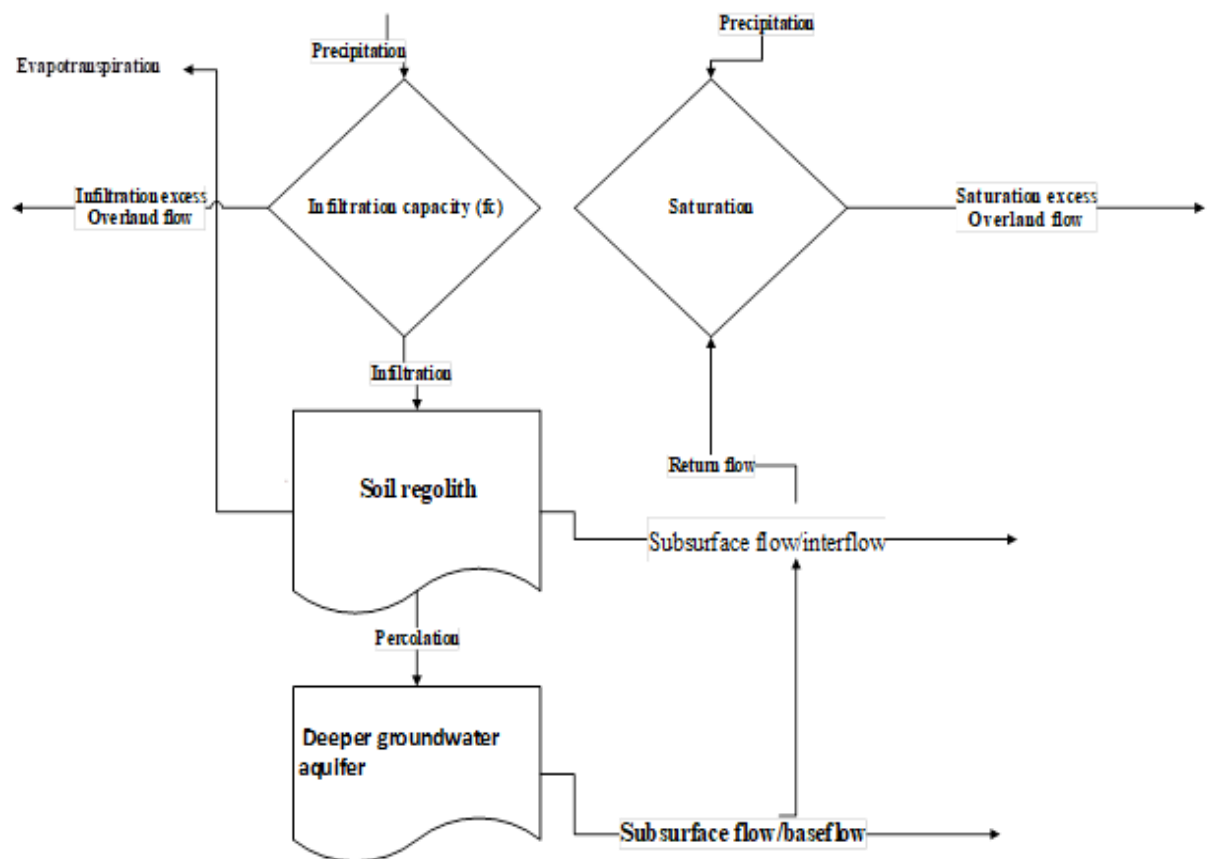


Figure 2. Conceptual hydrological model Pathways of watershed inputs, storage and losses, and their roles involved in different runoff generation processes.

### 3. Geomorphic Controls on Surface Runoff

In a mountainous region, surface topography contributes a significant role in geomorphological and hydrological processes [1,30], specifically, surface topography plays a significant control in surface runoff either directly, or indirectly [31]. Topographic slopes control the rate at which surface runoff moves downslope, thus determining whether an overland flow is drained into the stream channel network or retained in the soil [32]. In explaining the role of topography, several topographic indices (TIs) have been established and used to support understanding hydrological processes (e.g. surface runoff peak, baseflow, and low flow), and to explain the distinction between catchments [30]; [33]. Even though the influence of topography in controlling numerous flow magnitudes has been extensively studied [33], the numerical association between specific TIs and various flow variables (e.g. overland flow, baseflow and/or low flow, and peak flow) is not well understood [30].

[34] tried to classified Topographic indices (TIs) into two groups, that is, primary and secondary indices). Primary indices (e.g., slope, elevation, drainage density, and aspect) are usually directly measured from a digital elevation model (DEM), whereas secondary indices were calculated of primary indices that are used to describe the role of topography in geomorphological, biological, and hydrological processes. For example, the

topographic wetness index (TWI) is defined as  $\ln(\alpha/\tan\beta)$ , where  $\alpha$  is the upward slope contributing area per unit contour length, and  $\beta$  is the slope angle at that specific area [30].

According to [35], steep hillslopes in mountainous catchments were highly susceptible to surface runoff, which resulted in high sediment yields. [21], took a study on Dire Dawa City, Ethiopia on flood risk analysis, and they found that Dire Dawa City was circumscribed by various chained mountainous area like Dengago, Kersa, Kulubi, and Meta Mountains, as a result, a huge surface runoff drained from those mountainous regions and inundated the city.

Table 1. . summary of topographic features and their correlations hydrologic response (source: [36]; [37]).

Topographical attributes	Description	Correlations
Altitudes	Height above reference point	Indicator of climate features (temperature, precipitation), vegetation, and soil patterns.
Slope	Is the rate of change in elevation of the land surface.	Indicator of soil depth, wildland fire spread, the direction of overland flow and flow velocity, and subsurface flow velocity.
Aspect	Compass direction (azimuth) of the steepest slope	Solar irradiance, vegetation patterns, evapotranspiration, ecosystem differentiation
Hillslope's length	Length between foot and peak	Amount of sediment supply for erosion
Topographic Wetness index (TWI)	is defined as $\ln(\alpha/\tan\beta)$ , where $\alpha$ is the upward slope contributing area per unit contour length, and $\beta$ is the slope angle at that specific area.	This shows the spatial distribution of zones of surface saturation and soil water content.
Basin relief (BREL)	Is measured as the difference between the maximum and minimum watershed elevations	Is an indicator of the gravitational potential energy of the water being drained from the system
Drainage density (DDEN)	Is measured by dividing the total length of channels of the watershed by its total drainage area.	A dense stream network or a sparse stream network throughout a watershed

Even if several hydrological studies mostly focus on primary TIs and a few secondary TIs; those primary TIs have limited descriptive influence as they largely fail to describe the variation in hydrological processes [30]. This review article has highlighted GIS-based assessments of the controls of surface topographic features on a hydrological response like surface runoff (Table 1). To this end, it is very important to note that recent done and ongoing research shows that variation in GIS-based processed digital elevation model (DEM) resolution (e.g. 1km, 90m and 30m resolution) can have a significant effect on rain-fall-runoff hydrological analysis, and more scientific-based investigation requests to be conducted to associate DEM-based topographic features with the overland flow at multiple resolutions [38].

#### **4. Soils Characteristics**

Soil properties and their rate of formation are highly dependent on underlying bed-rock geology [39], and topographic position, which affects the hydrologic response of a catchment like precipitation infiltration capacity, percolation, overland flow, subsurface flow, and soil moisture storage. Variation in soil texture and/or soil profile along the hillslope of mountainous catchment plays a significant role in the rate of surface runoff [40]. Additionally, surface runoff is extremely affected by spatial and/or temporal variability of soil initial moisture retention, which may be predominantly controlled by surface and/or subsurface topography [41], and in part soil texture, which affects the saturated hydraulic conductivity of the surface soil ( $K_s$ ) [40,41].

Consequently, in a mountainous region, the associations between soil initial moisture retention and hillslope position are expected to exist, with very small particle size, denser soils, and low slope gradients merging their effects to encourage soil moisture holding, and most probably saturation-excess surface runoff occurs. On the contrary, steep upper hillslopes, soils are likely characterized by coarser, less developed, and thinner as soil accumulation is strongly limited due to strong both wind and water erosion [42], thereby more rapidly transmitting surface runoff water, as the result infiltration excess runoff most commonly happens [43];[44,45] (Figure 3). According to [46], landslides due to soil saturation and perched groundwater dynamics can cause flash floods and mudflows when severe rainstorms occur on steep hillslopes with shallow soils. From this Point of view, separating the influence of soil characteristics from topography in a mountainous region on a hydrological response, specifically on surface runoff is yet a challenging task, which needs further research.

#### **5. Human Being Land Uses Control on Surface Runoff**

In a mountainous region, extensive land-use changes, and soil disturbance go together with most forms of land-cover change [47], and such influences are usually sufficient to modify the timing and quantity of surface runoff [48,49]. Furthermore, the anthropogenic impact may involve direct removal of forests (deforestation) through cutting and/or wildfire, and urbanization [47]. This sub-section synthesized different literature review on anthropogenic controls such as forest removal and/or plantation, urbanization, and agricultural activities on surface runoff.



5.1. Vegetations

In the forested mountainous region, vegetation type and cover have spatial and temporal variation, and as a consequence, this vegetation variance might have significant control on runoff generation and transfer mechanism [32,33], and specifically in a forested humid region, Horton overland flow generation is rare [50]. On the contrary, in arid and semi-arid mountainous regions with deforested and/or scarce vegetated catchments, Horton surface runoff generation is the most dominant processes (Figure 3). [35] took a study on Lake Hayq catchment, South Wollo mountainous region, Ethiopia to detect land-use/land-cover change over 50yrs using multitemporal remote sensing and geospatial data, and they found that farmlands and shrublands were increased, whereas the bushlands, grasslands, forestlands, and Lake surface area were reduced over the past 50yrs, resulted in accelerating soil erosion in the basin, and sediment accumulation into the lake. However, the study didn't consider the rest landscape descriptors like soil characteristics, underlying bedrock geology, and topography of the Lake Hayq catchment. [51] took research on East Africa Region, and estimated that due to forest loss annual discharge and surface runoff increases by  $16\pm5.5\%$  and  $45\pm14\%$  respectively.

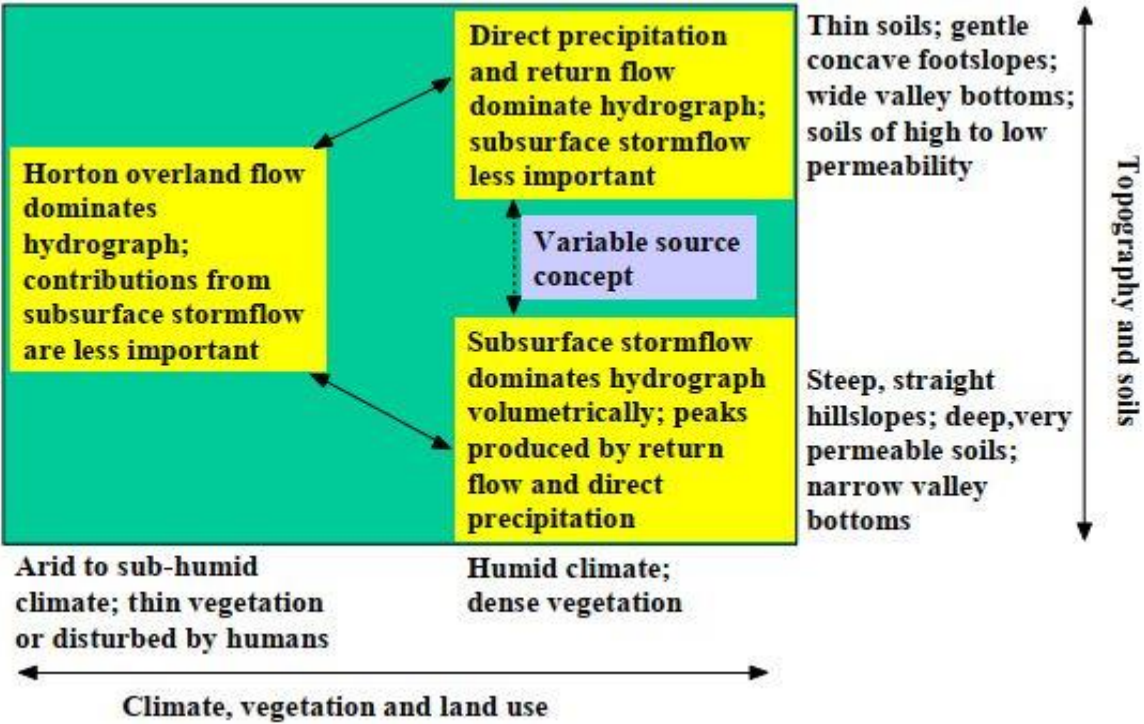


Figure 3. Major controls on runoff processes( source:[26]).

[52] conducted a study at Soil Conservation Research Project (SCR) places in the Ethiopian uplands to assess the impacts of land use/land cover changes, and results found that the forest and grassland plots revealed very low surface runoff coefficients, however, farmlands and degraded lands exhibited very high surface runoff coefficients which resulted in generated high runoff volumes during high stream flows (rainy season). Forest cover in the Mid-Atlantic Mountainous Region/catchments prevents landslides and overland flow, and associated erosion and sedimentation from occurring on steep hillslopes

[32]. [53], were simulated and estimated the surface runoff increases by 5.7% as a result of deforestation in Suiá-Miçu River basin, Brazil, and the same result was performed and confirmed in 27 catchments in South East Asia due to forest cover loss [54].

## 5.2. Urbanization

Following urbanization, impervious surface coverage, compacted soils, and channelization increased, as a result, surface runoff volume and/or rate was accelerated due to low infiltration capacity of impervious surface land [23,55,56]. Impervious surface coverage (e.g. road networks, parking lots, rooftops, etc.) in mountainous urban dominated catchments extremely surpasses that of catchments with other land use types, which has an enormous effect on urban hydrology [23,57,58]. For instance, many studies investigated that urban-generated surface runoff carries contaminants including heavy metals, major nutrients like sodium, nitrate, and phosphorus, and other residues from open dumping and roads [59], and complex pollutants like microbial pollutants [60,61], synthetic chemicals [62,63], pesticides [64,65], and pharmaceuticals [66,67]. According to [57]; increasing impervious surface coverage and soil compaction following urbanization would be linked with corresponding decreases in recharge in the urban system, as a result, a negative effect on baseflow quantity and quality. Furthermore, a series of studies found that compacted urban soils can preclude or slow natural processes like infiltration and throughflow, resulting in increased surface runoff [68,69].

## 5.3. Agricultural Activities

Overland flow response of a mountainous catchment is highly influenced by several land-use descriptors, and among them, agricultural activities are the one [57,70]. Low valley areas of mountainous regions are relatively flat and suitable for agriculture, and in connection with this unwise manipulating various agricultural activities resulted in a loss of fertile soil due to surface runoff. [71] investigated that along hillslope, agricultural fields have generally lower canopy density than the natural vegetation, which makes them more vulnerable to surface runoff and nutrient flushing. Farmland plowing in particular breaks up and make softer the structure of soils and serves as a major contributor to surface runoff-based soil erosion [14], and overland flow-based severe soil erosion which leads to excessive sediment export to streaming and/or reservoirs results in disturbances of life in water bodies as well as reduced duration/life of reservoirs and affects the quality of the environmental services [72]. According to [33] investigation, surface runoff in agricultural fields reduced infiltration rate and decreased baseflow.

## 6. Geology

Weathering is a process of change and fragmentation of rocks by various natural events like physical, biological, and chemical processes [73]. In a mountainous region, a catchment's spatial characteristics of the geological structure and underlying bedrock



permeability are principal control on surface runoff processes [74]. In catchments' landscape underlain by permeable, non-crystalline or highly fractured bedrock, infiltration capacity of underlying bedrock is highly significant and more easily transmit water to deep subsurface storage that is not connected to surface stream network [33], as a result, the probability of surface runoff to occur may be extremely less. Contrary, regions underlain by impermeable, crystalline, or massive bedrock have very limited recharge and low infiltration capacity, as a result, most of the precipitation that falls on the ground may occur as a direct runoff/surface runoff, and run rapidly off the hillslopes [75]; [33]. Previous work publicized significant controls of catchment geology on runoff generation (Abe et al. 2020; Iwasaki, Katsuyama, and Tani 2020; Onda et al. 2001), and low flow [33].

## 7. Climate

Global and regional climate components, and their change caused by a human being and natural events bring influences on catchment's hydrological processes specifically on surface runoff processes [79]. For instance, [80] confirmed that global average temperature was projected to remain steady as a result of constantly increasing atmospheric greenhouse gas concentrations, resulting in a significant influence on runoff generation [81]. [82] studied selected five catchments, which were located in southwest China using a partial least squares regression (PLSR) model to detect the dominant climatic variables driving extremes on annual surface runoff, and results indicated that annual total wet day precipitation (PT), rainy days (RDs), heavy precipitation amounts (R25), heavy precipitation days (RD25), rainstorm days (RD50), and rainstorm amount (R50) are dominant deriving factors of annual surface runoff.

The expected global climate changes that will touch the mainstream of the world may involve some combination of temperature increase and either precipitation increase or decrease, as a result, overland flow response to climate change will depend on the magnitude and direction of changes in both precipitation and temperature [83,84]. A further substantial difficulty to understand the influences of climate variables, and their change on overland flow is that experimental researches assessing surface runoff response to changing climate variables naturally are unable to clearly demarcate from coexisting land-use change during the period of assessment because of uncertain interactions of factors driving these changes [51], and a better understanding of the controls of climate changes on surface runoff is indispensable for mitigation of natural hazards like flooding [82].

## 8. Conclusions

From the beginning, knowing just how catchment's landscape structures and climate variables will affect surface runoff processes, in the framework of catchment geomorphology, will support watershed managers and environmentalists in the protection and conservation of mountainous catchment, which is the headwater of all streams. For instance,

in the mountainous region, accelerated runoff increases the impact of soil erosion, which affects the life of downstream reservoirs due to sedimentation [85], reduces soil fertility [86,87], and the capacity of soil water storage [88], and this may lead to reduced vegetation cover and productivity, forcing people to intensify land use land cover change.

The close linkage between climate variables like precipitation and catchment's hydrological response such as annual surface runoff was determined by partial least square regression (PLSR) approach, and consequently can provide useful and quantitative information that enables decision-makers to make better decisions concerning water resources management [82].

This review has revealed that watershed's topography and geology influences surface runoff response by affecting the soil water holding capacity properties, overland flow generation mechanism, and infiltration and/or percolation rate within a watershed. The influence of topography variables like slope, aspect, and drainage density is predominantly significant. However, whether those factors are themselves strong drivers of surface runoff [90], or whether those main factors correlate to the other aquifer properties that more directly control surface flow.

This literature review has also identified that mountainous watershed's landscape descriptors like an intensification of land-use from natural forests to agricultural activities may increase the probability of surface runoff increases, resulted in reduced lowlands stream water quality [13], and flooding is more apt to occur [21]. While this review of the literature tried to show some highlights of variables influences on mountainous region's surface runoff, more research is needed to understand quantitatively the dominance of those each factor such as geological, soil conditions, morphology, land use land cover, and climate which can have a considerable influence on various flow magnitudes like surface runoff. To this end, across different spatial scales (e.g., plot scale, hillslope, and sub-catchment scale) variability impacts on surface runoff need future more research.

## References

- [1] Messerli B, Meybeck M, Viviroli D and Du H H 2007 global significance Mountains of the world , water towers for humanity : Typology , mapping , and global significance
- [2] FAO 2011 *Highlands and Drylands Highlands and Drylands*

- 
- [3] Campus C 2010 Climate change and geomorphological hazards 2461–79
  - [4] Ongley E D 1996 Control of water pollution from agriculture
  - [5] Javier Mateo-Sagasta, Sara Marjani Zadeh and H T 2017 Water pollution from agriculture: a global review
  - [6] Khan M N, Mobin M, Abbas Z K and Alamri S A 2017 *Fertilizers and Their Contaminants in Soils , Surface and Groundwater* (Elsevier Inc.)
  - [7] UNEP GEMS/Water Programme 2008 Water Quality for Ecosystem and Human Health
  - [8] Karaouzas I, Theodoropoulos C, Vardakas L and Kalogianni E 2018 A review of the effects of pollution and water scarcity on the stream biota of an intermittent Mediterranean basin A review of the effects of pollution and water scarcity on the stream biota of an intermittent Mediterranean basin
  - [9] Aimin Y, Hao W, Kewang T and Ge S 2002 Soil Erosion Characteristics and Control Measures in China
  - [10] Breneman V 2001 I MPACT OF S OIL E ROSION ON C ROP Y IELDS **72**
  - [11] Haregeweyn N, Tsunekawa A, Tsubo M and Meshesha D T 2011 Derege Meshesha & Bedru Babulo
  - [12] A M G, Gabriel S, Hodson M and Wellington D 2015 Sedimentation impacts on reservoir as a result of land use on a selected catchment in Zimbabwe
  - [13] Chen J and Lu J 2014 Effects of Land Use , Topography and Socio-Economic Factors on River Water Quality in a Mountainous Watershed with Intensive Agricultural Production in East China **9** 1–12
  - [14] Issaka S and Ashraf M A 2017 Impact of soil erosion and degradation on water quality : a review *Geol. Ecol. Landscapes* **9508** 1–11
  - [15] Buckalew J, James M, Lisa S and Reed P 1998 Water Resources Assessment of Ecuador *Water Resour. Assess. Ecuador* 83
  - [16] Cooper M 2010 Advanced Bash-Scripting Guide An in-depth exploration of the art of shell scripting Table of Contents Okt 2005 Abrufbar uber <http://www.tldp.org/LDP/absguide/pdf> Zugriff 1112 2005 **2274** 2267–74
  - [17] Ongley E D and Division I 2011 Produced by : Natural Resources Management and Environment Title : Control of water pollution from agriculture ... Español More details Table of Contents *Control* 3–5
  - [18] Lúcia R, Nobre G, Caliman A, Rodrigues C, Carvalho F De, Guérin J, Catombé C, Barbosa L, Martins E, Dettogni R, Megali A, Kelly P, Vanni M J and Silva L 2020 Science of the Total Environment Precipitation , landscape properties and land use interactively affect water quality of tropical freshwaters **716**
  - [19] Viviroli D and Weingartner R 2004 The hydrological significance of mountains : from regional to global scale **8** 1016–29
  - [20] Rogger M, Agnoletti M, Alaoui A, Bathurst J C, Bodner G, Borga M, Chaplot V, Gallart F, Glatzel G, Hall J,

- Holden J, Holko L, Horn R, Kiss A, Quinton J N, Leitingen G, Lennartz B, Parajka J, Peth S, Robinson M, Salinas J L, Santoro A, Szolgay J, Tron S and Viglione A 2016 *Water Resources Research* 5209–19
- [21] Erena S H and Worku H 2018 Flood risk analysis : causes and landscape based mitigation strategies in Dire Dawa city , Ethiopia **8**
- [22] Segura C, Noone D, Warren D, Jones J A, Tenny J and Ganio L M 2019 Climate, Landforms, and Geology Affect Baseflow Sources in a Mountain Catchment *Water Resour. Res.* **55** 5238–54
- [23] Price K 2011 Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: A review *Prog. Phys. Geogr.* **35** 465–92
- [24] Baiamonte G and Agnese C 2010 AN ANALYTICAL SOLUTION OF KINEMATIC WAVE EQUATIONS FOR OVERLAND FLOW UNDER GREEN-AMPT INFILTRATION 41–8
- [25] Hallema D W, Moussa R, Sun G and McNulty S G 2016 Surface storm flow prediction on hillslopes based on topography and hydrologic connectivity *Ecol. Process.*
- [26] Tarboton D G 2003 R Ainfall -R Unoff P Rocesses *Utah State Univ.*
- [27] Serrano-Muela M P, Lana-Renault N, Nadal-Romero E, Regüés D, Latron J, Martí-Bono C and García-Ruiz J 2008 Forests and their hydrological effects in mediterranean mountains: The case of the Central Spanish Pyrenees *Mt. Res. Dev.* **28** 279–85
- [28] Nippgen F, McGlynn B L, Marshall L A and Emanuel R E 2011 Landscape structure and climate influences on hydrologic response **47** 1–17
- [29] Dwarakish G S and Ganasri B P 2015 Impact of land use change on hydrological systems : A review of current modeling approaches Impact of land use change on hydrological systems : A review of current modeling approaches *Cogent Geosci.* **1**
- [30] Li Q, Wei X, Yang X, Giles-hansen K, Zhang M and Liu W 2018 Topography significantly influencing low flows in snow-dominated watersheds 1947–56
- [31] Vivoni E, Bras R L and Ivanov V Y 2007 Controls on runoff generation and scale-dependence in a distributed hydrologic model
- [32] Mohamoud Y 2004 Comparison of Hydrologic Responses at Different Watershed Scales
- [33] Price K 2011 Effects of watershed topography , soils , land use , and climate on baseflow hydrology in humid regions : A review
- [34] Moore I D, Burch G J and Mackenzie D H 1988 Topographic Effects on the Distribution of Surface Soil Water and the Location of Ephemeral Gullies. *Trans. Am. Soc. Agric. Eng.* **31** 1098–107
- [35] Yesuf H M, Assen M, Melesse A M and Alamirew T 2015 Detecting land use / land cover changes in the Lake Hayq ( Ethiopia ) drainage basin , 1957 – 2007 1–18

- 
- [36] Ambroise B, Freer J and Beven K 1996 Application of a generalized TOPMODEL to the small Ringelbach catchment, Vosges, France *Water Resour. Res.* **32** 2147–59
- [37] Li L, DiBiase R A, Del Vecchio J, Marcon V, Hoagland B, Xiao D, Wayman C, Tang Q, He Y, Silverhart P, Szink I, Forsythe B, Williams J Z, Shapich D, Mount G J, Kaye J, Guo L, Lin H, Eissenstat D, Dere A, Brubaker K, Kaye M, Davis K J, Russo T and Brantley S L 2018 The Effect of Lithology and Agriculture at the Susquehanna Shale Hills Critical Zone Observatory *Vadose Zo. J.* **17** 180063
- [38] Zhang H, Li Z, Saifullah M, Li Q and Li X 2016 Impact of DEM Resolution and Spatial Scale : Analysis of Influence Factors and Parameters on Physically Based Distributed Model **2016**
- [39] Rains M C, Dahlgren R A, Fogg G E, Harter T and Williamson R J 2008 Geological control of physical and chemical hydrology in California vernal pools *Wetlands* **28** 347–62
- [40] Yeakley J A, Swank W T, Swift L W, Hornberger G M and Shugart H H 1998 Soil moisture gradients and controls on a southern Appalachian hillslope from drought through recharge *Hydrol. Earth Syst. Sci.* **2** 41–9
- [41] Del Toro-Guerrero F J, Vivoni E R, Kretzschmar T, Runquist S H B and Vázquez-González R 2018 Variations in soil water content, infiltration and potential recharge at three sites in a Mediterranean mountainous region of Baja California, Mexico *Water (Switzerland)* **10** 7–9
- [42] Ariele Singer 2007 *The Soils of Israel*
- [43] Huang P, Li Z, Yao C, Li Q and Yan M 2016 Spatial Combination Modeling Framework of Saturation-Excess and Infiltration-Excess Runoff for Semihumid Watersheds *Adv. Meteorol.* **2016**
- [44] Schneiderman E M, Parlange J and Steenhuis T S 2013 A s e e m **56** 681–95
- [45] Reli S N, Yusoff I M, Lateh H and Ujang M U 2016 A Review of Infiltration Excess Overland Flow (IEOF): Terms, Models and Environmental Impact *J. Adv. Humanit.* **4** 490–502
- [46] Pelletier J D and Orem C A 2014 How do sediment yields from post-wildfire debris-laden flows depend on terrain slope, soil burn severity class, and drainage basin area? Insights from airborne-LiDAR change detection *Earth Surf. Process. Landforms* **39** 1822–32
- [47] Falcucci A, Maiorano L and Boitani L 2007 Changes in land-use/land-cover patterns in Italy and their implications for biodiversity conservation *Landsc. Ecol.* **22** 617–31
- [48] Zhao L and Hou R 2019 Human causes of soil loss in rural karst environments: a case study of Guizhou, China *Sci. Rep.* **9** 1–11
- [49] Kanińska R 2016 Agriculture and Its Impact on Land - Use , Environment , and Ecosystem Services 3–26
- [50] Holko L, Kostka Z and Šanda M 2011 Assessment of frequency and areal extent of overland flow generation in a forested mountain catchment *Soil Water Res.* **6** 43–53
- [51] Guzha A C, Rufino M C, Okoth S, Jacobs S and Nóbrega R L B 2018 Impacts of land use and land cover change

on surface runoff, discharge and low flows: Evidence from East Africa *J. Hydrol. Reg. Stud.* **15** 49–67

- [52] Hurni H, Tato K and Zeleke G 2005 The implications of changes in population, land use, and land management for surface runoff in the Upper Nile Basin Area of Ethiopia *Mt. Res. Dev.* **25** 147–54
- [53] Maeda E E, Formaggio R A, Shimabukuro Y E and Kaleita A L 2009 Impacts of agricultural expansion on surface runoff: A case study of a River basin in the Brazilian Legal Amazon *Int. J. Geoinformatics* **5** 33–41
- [54] Valentin C, Agus F, Alamban R, Boosaner A, Bricquet J P, Chaplot V, de Guzman T, de Rouw A, Janeau J L, Orange D, Phachomphonh K, Do Duy Phai, Podwojewski P, Ribolzi O, Silvera N, Subagyo K, Thiébaux J P, Tran Duc Toan and Vadari T 2008 Runoff and sediment losses from 27 upland catchments in Southeast Asia: Impact of rapid land use changes and conservation practices *Agric. Ecosyst. Environ.* **128** 225–38
- [55] Chandler Morse 2001 The Response of First and Second Order Streams
- [56] Galster J C, Pazzaglia F J, Hargreaves B R, Morris D P, Peters S C and Weisman R N 2006 Effects of urbanization on watershed hydrology: The scaling of discharge with drainage area *Geology* **34** 713–6
- [57] Landers M N, Ankorn P D and McFadden K W 2007 Watershed Effects on Streamflow Quantity and Quality in Six Watersheds of Gwinnett County , Georgia
- [58] McGriff E C 1972 The Effects of Urbanization on Water Quality *J. Environ. Qual.* **1** 86–8
- [59] Yong S T Y and Chen W 2002 Modeling the relationship between land use and surface water quality *J. Environ. Manage.* **66** 377–93
- [60] Tetzlaff D and Birkel C 2010 Hydrological connectivity and microbiological fluxes in montane catchments: The role of seasonality and climatic variability *Hydrol. Process.* **24** 1231–5
- [61] McGrane S J, Tetzlaff D and Soulsby C 2014 Application of a linear regression model to assess the influence of urbanised areas and grazing pastures on the microbiological quality of rural streams *Environ. Monit. Assess.* **186** 7141–55
- [62] Sullivan P J, Clark J J J, Agardy F J and Rosenfeld P F 2007 Synthetic Chemical Contaminants in Air *Toxic Leg.* **97** 161–75
- [63] Heim T H and Dietrich A M 2007 Sensory aspects and water quality impacts of chlorinated and chloraminated drinking water in contact with HDPE and cPVC pipe *Water Res.* **41** 757–64
- [64] Varca L M 2012 Pesticide residues in surface waters of Pagsanjan-Lumban catchment of Laguna de Bay, Philippines *Agric. Water Manag.* **106** 35–41
- [65] Anderson T A, Salice C J, Erickson R A, McMurry S T, Cox S B and Smith L M 2013 Effects of landuse and precipitation on pesticides and water quality in playa lakes of the southern high plains *Chemosphere* **92** 84–90
- [66] Jones O A, Lester J N and Voulvoulis N 2005 Pharmaceuticals: A threat to drinking water? *Trends Biotechnol.* **23** 163–7



- 
- [67] Burkholder J A, Libra B, Weyer P, Heathcote S, Kolpin D, Thorne P S and Wichman M 2007 Impacts of waste from concentrated animal feeding operations on water quality *Environ. Health Perspect.* **115** 308–12
- [68] Gregory J H, Dukes M D, Jones P H and Miller G L 2006 Effect of urban soil compaction on infiltration rate *J. Soil Water Conserv.* **61** 117–24
- [69] Richard G, Cousin I, Sillon J F, Bruand A and Guérif J 2001 Effect of compaction on the porosity of a silty soil: Influence on unsaturated hydraulic properties *Eur. J. Soil Sci.* **52** 49–58
- [70] García-Ruiz J M and Lana-Renault N 2011 Hydrological and erosive consequences of farmland abandonment in Europe, with special reference to the Mediterranean region - A review *Agric. Ecosyst. Environ.* **140** 317–38
- [71] Hallema D W, Moussa R, Sun G and McNulty S G 2016 Surface storm flow prediction on hillslopes based on topography and hydrologic connectivity *Ecol. Process.* 1–13
- [72] Kondolf G M, Gao Y, Annandale G W, Morris G L, Jiang E, Zhang J, Cao Y, Carling P, Fu K, Guo Q, Hotchkiss R, Peteuil C, Sumi T, Wang H-W, Wang Z, Wei Z, Wu B, Wu C and Yang C T 2014 Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents *Earth's Futur.* **2** 256–80
- [73] Peter A. Troch<sup>1</sup>, Tim Lahmers<sup>2</sup>, Antonio Meira<sup>1</sup>, Rajarshi Mukherjee<sup>1</sup> J W P and Tirthankar Roy<sup>1</sup> and R V-P 2015 Catchment coevolution: A useful framework for improving predictions of hydrological change? 4903–22
- [74] Pfister L, Martínez-Carreras N, Hissler C, Klaus J, Carrer G E, Stewart M K and McDonnell J J 2017 Bedrock geology controls on catchment storage, mixing, and release: A comparative analysis of 16 nested catchments *Hydrol. Process.* **31** 1828–45
- [75] Mohamoud Y 2004 Comparison of hydrologic responses at different watershed scales 1–81
- [76] Iwasaki K, Katsuyama M and Tani M 2020 Factors affecting dominant peak-flow runoff-generation mechanisms among five neighbouring granitic headwater catchments *Hydrol. Process.* **34** 1154–66
- [77] Abe Y, Uchiyama Y, Saito M, Ohira M and Yokoyama T 2020 Effects of bedrock groundwater dynamics on runoff generation: A case study on granodiorite headwater catchments, western Tanzawa Mountains, Japan *Hydrol. Res. Lett.* **14** 62–7
- [78] Onda Y, Komatsu Y, Tsujimura M and Fujihara J I 2001 The role of subsurface runoff through bedrock on storm flow generation *Hydrol. Process.* **15** 1693–706
- [79] MARGRETH KEILER, JASPER KNIGHT A S H 2010 Climate change and geomorphological hazards 2461–79
- [80] IPCC 2007 *C l i m a t e C h a n g e 2 0 0 7 : I m p a c t s , A d a p t a t i o n a n d V u l n e r a b i l i t y . C o n t r i b u t i o n o f W o r k i n g G r o u p I I t o t h e F o u r t h A s s e s s m e n t R e p o r t o f t h e I n t e r g o v e r n m e n t a l P a n e l o n C l i m a t e C h a n g e*, M.L. Parry, O.F. Canziani, J.P. Palutikof,
- [81] Yin J, Gentine P, Zhou S, Sullivan S C, Wang R, Zhang Y and Guo S 2018 Large increase in global storm runoff extremes driven by climate and anthropogenic changes *Nat. Commun.* **9**

- 
- [82] Li Z, Xu X, Xu C, Liu M, Wang K and Yu B 2017 Annual runoff is highly linked to precipitation extremes in Karst catchments of Southwest China *J. Hydrometeorol.* **18** 2745–59
- [83] IPCC 2012 *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*
- [84] Mirza M 2006 Mainstreaming climate change for extreme weather events & management of disasters: An engineering challenge 2006 *IEEE EIC Clim. Chang. Technol. Conf. EICCCC 2006*
- [85] Dutta S 2016 Soil erosion, sediment yield and sedimentation of reservoir: a review *Model. Earth Syst. Environ.* **2** 1–18
- [86] Ritter J and Eng P 2011 Soil Erosion - Causes and Effects Soil Erosion - Causes and Effects *Control* 1–4
- [87] Chalise D, Kumar L and Kristiansen P 2019 Land Degradation by Soil Erosion in Nepal: A Review *Soil Syst.* **3** 12
- [88] FAO 2015 *Understanding mountain soils Understanding Mountain Soils A contribution from mountain areas to the*
- [89] ZHENWEI LI, XIANLI XU, CHAOHAO XU, MEIXIAN LIU K W and B Y 2017 Annual Runoff is Highly Linked to Precipitation Extremes in Karst Catchments of Southwest China
- [90] Ries F, Schmidt S, Sauter M and Lange J 2017 Journal of Hydrology : Regional Studies Controls on runoff generation along a steep climatic gradient in the Eastern Mediterranean *Biochem. Pharmacol.* **9** 18–33