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Paper title: Assessment of the flood hazard arising from land use change in a forested catchment in northern Iran

Authors: Farhad Hajian [a †], Alan P. Dykes [b *] and Sandra Cavanagh [c]

Author affiliations:
[a] School of Civil Engineering and Construction, Kingston University, Penrhyn Road, Kingston-upon-Thames, KT1 2EE, UK.
f.hajian@yahoo.com
[b] Centre for Engineering, Environment and Society Research, School of Engineering, Kingston University, Penrhyn Road, Kingston-upon-Thames, KT1 2EE, UK.
a.p.dykes@kingston.ac.uk
[c] Centre for Engineering, Environment and Society Research, School of Engineering, Kingston University, Penrhyn Road, Kingston-upon-Thames, KT1 2EE, UK.
s.cavanagh@kingston.ac.uk

[†] Present address: Department of Civil Engineering, Neyshabur Branch, Islamic Azad University, Neyshabur, Iran.

Correspondence: * Corresponding author (A P Dykes). Address and Email shown above.
Tel.: +44 (0)208 417 7018

Abstract: The provinces of northern Iran that border the Caspian Sea are forested and may be prone to increased risks of flooding due to deforestation and other land use changes, in addition to climate change effects. This research investigated changes in runoff from a small forested catchment in northern Iran for several land use change scenarios and the effects of higher rainfall and high antecedent soil moisture. Peak discharges and total runoff volumes from the catchment were estimated using the US Soil Conservation Service ‘Curve Number’ (SCS-CN) method and the SCS dimensionless unit hydrograph. This method was selected for reasons of data availability and operational simplicity for flood managers. A GIS was used to manipulate spatial data for use in the catchment runoff modelling. The results show that runoff is predicted to increase as a result of deforestation, which is dependent on the proportion of the catchment area affected. However, climate change presents a significant flood hazard even in the absence of deforestation. Other land use changes may reduce the peak discharges of all return period floods. Therefore a future ban on timber extraction, combined with agricultural utilisation of rangeland, could prove effective as ‘nature-based’ flood reduction measures throughout northern Iran.

Key words: northern Iran, land use change, deforestation, catchment runoff, flood hazard, flash floods

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Farhad Hajian[†], Alan P. Dykes* and Sandra Cavanagh

Centre for Engineering, Environment and Society Research, School of Engineering, Kingston University, Penrhyn Road, Kingston-upon-Thames, KT1 2EE, UK.

[†] *Present address: Department of Civil Engineering, Neyshabur Branch, Islamic Azad University, Neyshabur, Iran.*
*Corresponding author

Abstract

The provinces of northern Iran that border the Caspian Sea are forested and may be prone to increased risks of flooding due to deforestation and other land use changes, in addition to climate change effects. This research investigated changes in runoff from a small forested catchment in northern Iran for several land use change scenarios and the effects of higher rainfall and high antecedent soil moisture. Peak discharges and total runoff volumes from the catchment were estimated using the US Soil Conservation Service 'Curve Number' (SCS-CN) method and the SCS dimensionless unit hydrograph. This method was selected for reasons of data availability and operational simplicity for flood managers. A GIS was used to manipulate spatial data for use in the catchment runoff modelling. The results show that runoff is predicted to increase as a result of deforestation, which is dependent on the proportion of the catchment area affected. However, climate change presents a significant flood hazard even in the absence of deforestation. Other land use changes may reduce the peak discharges of all return period floods. Therefore a future ban on timber extraction, combined with agricultural utilisation of rangeland, could prove effective as 'nature-based' flood reduction measures throughout northern Iran.

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Introduction

The provinces of Iran that border the southern Caspian Sea are highly susceptible to damaging floods. This region is characterised by a climatic regime entirely different from the surrounding arid and semi-arid environments. Mean annual rainfall increases westwards from around 800 mm to more than 2000 mm, delivered by Siberian air masses that gain moisture as they move south across the Caspian Sea (Rasouli et al. 2012). This generally moist climate supports an area of Hyrcanian forest that is globally recognised for its extremely high biodiversity and good overall ecological quality, and which was added to the UNESCO 'Tentative List' for World Heritage status in 2007 (UNESCO 2018). These high value environments are part of the reason for northern Iran's rapidly developing tourism industry. However, the flood risk is perceived to be sufficiently high that the potential economic gains from increased tourism may not be fully realised if appropriate (e.g. catchment specific) flood reduction strategies are not implemented and seen to be effective. Such strategies may include so-called 'grey infrastructure' (i.e. traditional engineered structures such as dams or bypass channels) or ‘green infrastructure’ (i.e. ‘natural’ flood risk management) including ‘natural water retention measures’ (NWRMs) (Collentine and Futter 2018; Hartmann et al. 2018). Furthermore, the general context of natural population growth, climate change and – historically at least – significant deforestation, together mean that assessments of potential flood magnitudes and probabilities need to be easily made and updated so as to inform local flood risk management strategies.

In Iran, there have been more than 3700 recorded floods during the 50 years up to 2005, of which slightly more than half occurred during the final decade of this period (Hosseini Asl et al. 2008). Over a longer period (1909-2004), floods in Iran caused economic losses in excess of US$3.5 billion (Omidvar and Khodaei 2008). These floods, and associated erosion problems, have previously been attributed to land use change and climate change (Omidvar and Khodaei 2008, Sharifi et al. 2012, Madani and Makki 2005, Saghafian et al. 2006, Saghafian et al. 2008). For example, a devastating flood occurred in 2001 in Golestan Province, northern Iran, causing many casualties (200,000 people were affected) and damage estimated at over $400 million dollars (Sharifi et al. 2012). More recently, on 10-11 August 2017, twelve people were killed by floods following heavy rain in several provinces of northeast Iran including Golestan and Khorasan Razavi, resulting in initial damage estimates of more than $35 million (IRNA 2017; PressTV 2017). In April 2017, floods and landslides in northwest Iran caused widespread damage with at least 35 fatalities (Tehran Times 2017). Notwithstanding the background issue of population growth, there is an increasing urgency to the development of flood reduction strategies to support the developing tourism industry of northern Iran.

Reduction of the flood risk is always a matter of concern for local populations but the responsibility for addressing the issue may lie with different levels of governing authorities or delegated agencies and, increasingly, individual landowners (Morris et al. 2016; Collentine and Futter 2018). However, potential strategies for reducing the flood risk cannot be developed without some reasonable quantitative assessment of that risk, i.e. analysis of ‘the likelihood of a specific event and the severity of the outcome. This process combines both the severity and the probability of all relevant hazard loss scenarios’ (Li 2013, p.239). One of the challenges is to be able to assess the probabilities and magnitudes of future floods in places where relevant data (including community observations: Tellman et al. 2016), resources and expertise may be very limited (e.g. Bajracharya et al. 2017). Several types of flood hazards may arise in different contexts, including coastal flooding, flooding due to unusually high groundwater, surface water flooding (rainwater accumulates faster than it can dissipate), channel capacity exceedance (including downstream floodplain inundation) and infrastructure failure (Morris et al. 2016), and also ‘flash floods’ in tributary catchments. This paper is concerned with flash floods. Although normally of restricted spatial extents and durations of no more than a few hours, their impacts can be locally highly damaging (Caseri et al. 2016; Brookhuis and Hein 2016). Such events may constitute even greater hazards if steep tributary catchment slopes are susceptible to rainfall-triggered landslides that can cause a torrent of water to become a much more devastating debris flow or debris flood (Caballero et al. 2006). The latter issue is not considered in this paper.

Whether the flood risk is increasing over time and if so, why, will affect the range of mitigation options that may be appropriate. Many methods of flood prediction assume that all of the controlling parameters and processes are unchanging over time but this assumption of ‘stationarity’ may no longer be valid in many situations (Ehret et al. 2014). The overarching influence on changing flood hazards is global climate change. Although there is still considerable uncertainty in the future climate predictions generated by the various global climate models (GCMs), a common theme is one of more frequent ‘extreme’ conditions (however defined) (IPCC 2007). For northern Iran, Hajian et al. (2016) found that the most likely effect of climate change is to produce higher rainfall with an increased risk of flooding in spring and a higher probability of flash floods from ‘extreme’ rainfall at any time of year. The other factor that can alter runoff patterns over even shorter timeframes, and which is of comparable significance to climate change according to Ehret et al. (2014), is land use or land cover (LULC) change. Deforestation is a commonly cited example but urbanisation may give rise to more dramatic effects on storm runoff (Chen and Yu 2015), and even changes between different agricultural land use and land management regimes can affect flood characteristics (Pattison and Lane 2011; Bulygina et al. 2013). Flood prediction methods therefore need to be able to represent different scenarios for future climate and/or catchment characteristics relatively routinely in order to facilitate efficient evaluation of future flood hazards and associated risks.

Quantitative assessments of flood risks from catchments with permanent streamflow gauges and corresponding raingauges can be readily obtained from statistical analysis of the rainfall and discharge records (Do et al. 2017). However, flow gauges are much more expensive to establish than raingauges. In some parts of the world there are none, but the Global Runoff Data Centre does contain records from 9,500 stations in 160 countries (GRDC 2017). The need to be able to estimate flow regimes from ungauged catchments for a variety of purposes has given rise to decades of research into catchment hydrological processes and associated development of various techniques for estimating rainfall-runoff relationships. Ever greater computing power, open-source software and more widespread software inter-compatibility (e.g. integration of GIS into hydrological models: McColl and Aggett 2007) have allowed the variety of rainfall-runoff models to increase rapidly in recent years. Many such models are bespoke for particular purposes, such as the framework model for optimising the design of a detention basin flood mitigation scheme developed by Bellu et al. (2016) which combined an empirical-statistical hydrological module with geomorphological and environmental modules in a GIS. On the other hand, some models such as HEC-HMS (USACE-HEC 2000) and SWAT (USDA-ARS 2018) were designed to be widely applicable by having deliberately flexible structures and parameter requirements. Others have become very widely accepted as useful through generally successful application to contexts other than those for which they were originally developed, such as the SCS-CN (Soil Conservation Service – Curve Number) method (USDA 1986).

The choice of which tool to use for assessment of the flood risk from an ungauged catchment may depend on one or more of several factors. These may include, but are not limited to, (i) availability of software (including cost), (ii) availability of data to enable a model to be set up and (calibrated/)validated, and (iii) availability of relevant expertise to undertake the modelling and interpret the outputs appropriately. The choice of model is likely to be strongly determined by the data requirements and the extent to which they can be fulfilled. Types of rainfall-runoff models that can be used for catchment flood risk assessments range between (a) physically-based and empirical/conceptual, (b) lumped and fully distributed, (c) stochastic and deterministic. More recently the ‘empirical’ models can be subdivided into traditional and non-traditional statistical methods and machine learning methods. Examples of the latter include the Streamflow Hydrology Estimate using Machine Learning (SHEM) model that can reconstruct missing data from failed streamflow gauges in real-time using current and historical data from a set of nearby streamflow gauges, in this case for the Boise River catchment in Idaho, USA (Petty and Dhingra 2018), and a distributed Random Forest analysis that used eleven indices, including runoff depth and topographic wetness index, to generate a flood risk map for a 27,000 km^2 drainage basin in southeast China (Wang et al. 2015). An example of a non-traditional statistical method is Li's (2013) use of variable fuzzy sets to improve the accuracy of flood risk probability estimation from small data sets by generating and quantifying uncertainties and imprecisions that are then incorporated into the flood risk assessments. Other variations include approaches such as the WBS-FLAB rule-based expert system for identifying runoff generation within a catchment, which was integrated with other GIS-based geostatistical modules to optimise flood prevention whilst also minimising ecosystem impacts (Richert et al. 2011).

Most models lie on a spectrum between the extremes that define categories (a) to (c) above (Booker and Woods 2014). A recent review of distributed physically-based hydrological modelling (Fatichi et al. 2016) found that despite some significant limitations such as extreme complexity and extensive data requirements, they can constitute the most suitable investigative tool for some types of problems precisely because they can incorporate realistic parameter values and process constraints. However, uncertainty in any component(s) of a physically-based model can cause such a model to perform less well than an empirical model or indeed than the same model corrected using results from an empirical model (e.g. Booker and Woods (2014) testing TopNet in New Zealand). Similarly, Bulygina et al. (2013) compared a 'metamodel' with physically-based hydrological components against other conceptual and statistical methods for the assessment of impacts of land management on runoff in rural Wales (UK) and found that the different model structures and parameter estimations gave rise to a variety of estimates for different output measures such as the magnitude of change. The superior performance in some circumstances of empirical/conceptual and/or 'combination' models (part physically-based but with simplified structures defined by ranges of data values), together with limitations outlined by Fatichi et al. (2016), mean that fully physically-based models are rarely used for investigations of catchment runoff or for operational catchment management purposes.

The simplest 'lumped conceptual' models, requiring calibration of a small number of parameters representing an entire catchment using sufficiently long discharge records, can appear to be very effective at simulating the runoff. However, confidence in model outputs necessarily depends on confidence in the underlying model structure and parameterisation which define the structural identifiability of such models, i.e. ensuring that all parameters uniquely represent different components of the hydrological system (Shin et al. 2015). The generation of multiple acceptable sets of different optimised parameter values that all give rise to acceptable model performance is an example of the problem, which may also affect conceptual lumped elements of semi-distributed 'combination' models.

Notwithstanding the above issues, several well-established semi-distributed and fully distributed combination models are routinely widely used throughout the world. Many of these simulation models, including SWAT (USDA-ARS 2018), APEX and EPIC (TAMU 2018), are the products of the United States

Department of Agriculture (USDA) and use the SCS-CN (Soil Conservation Service – Curve Number) method as the underlying basis of the hydrology algorithms (Garen and Moore 2005). Similar models developed by other groups including HEC-HMS from the US Army Corps of Engineering (USACE) and many bespoke models (e.g. Bulygina et al. 2013) also use the CN method. SWAT, for example, was described by Wang and Kalin (2011, p.268) as a 'distributed, process-based watershed model, but with a significant number of empirical relationships'. It was developed to analyse long term runoff and nutrient losses from agricultural catchments using modest input data comprising soil, land management and elevation information, organised by 'hydrologic response units' (HRU) defined by uniform LULC and soil type (Easton et al. 2008). Easton et al. (2008) modified SWAT by replacing the CN method with a 'variable source area' component based on TOPMODEL (Beven and Kirkby 1979), which did not change runoff predictions but gave more realistic indications for pollution transport. HEC-HMS contains a much wider range of modelling options than SWAT and many similar models, including an option to use the CN method for determining the direct storm runoff from a catchment. Its data requirements are much greater than SWAT, requiring careful optimisation and calibration with the possible risk of structural non-identifiability (Shin et al. 2015), but it has been successfully used in a wide range of global contexts (e.g. northwestern USA – McColl and Aggett 2007; eastern China – Chen et al. 2009; Kenya – Olang and Fürst 2011; eastern India – Sanyal et al. 2014; Greece – Papathanasiou et al. 2015; El Salvador – Tellman et al. 2016; northern Iran – Hajian et al. 2016).

The curve number (CN) is an empirical function of three factors – soil group, plant cover and antecedent soil moisture conditions – that represents the runoff potential of an area of land (McCuen 1998). It is used to estimate 'direct runoff' from rainfall events, and is a tabulated value that combines the effectiveness of land use and 'hydrologic soil group' in generating such runoff (USDA 1986). 'Direct runoff' incorporates overland flow, subsurface stormflow (i.e. excluding base flow) and direct channel precipitation and not simply infiltration excess overland flow as is commonly assumed (Garen and Moore 2005). The low data requirements, simplicity of the method, and more recently its integration with GIS giving it a distributed capability, make the CN method a powerful tool for estimating runoff volumes from catchments (Shadeed and Almasari 2010) and, as a result, possibly the most popular and widely applied runoff models (Ajmal et al. 2015). Caution is needed because the method was developed in, and for, 'humid rain-fed agricultural areas' of the USA, using rainfall and runoff data from catchments with a single soil and (vegetation) cover type (Woodward et al. 2002). However, although its application for water quality and pollution modelling has been found to be highly problematic (Garen and Moore 2005), the CN method has been applied to runoff studies with reasonable success in many other parts of the world (e.g. southern China – Shi et al. 2007; Palestine – Shadeed and Almasri 2010), though sometimes with modification to the 'initial abstraction' parameter (e.g. central E. China – Shi et al. 2009; South Korea – Ajmal et al. 2015). Hawkins (1984, cited in Woodward et al. 2002) noted that the CN method works better for non-forested lands than forested areas, but Woodward et al. (2002) suggest that even CN values derived for degrees of urbanisation seem to work reasonably well.

Land use change in northern Iran

In northern Iran, the risk of increased regional-scale flooding from changing rainfall patterns associated with climate change has been found to be potentially significant in Spring, with flash floods resulting from localised high intensity rainfall events becoming increasingly likely at any time of year (Hajian et al. 2016). The LULC change context is less clear, however. Saghafian et al. (2008) used a lumped event-based configuration of the HEC-HMS model, incorporating the SCS-CN method, to investigate the changes in volume of runoff and peak discharge resulting from different LULCC scenarios in the 4800 km^2 Golestan Catchment following the flooding in 2001. They found that flood peak discharges and, to a lesser degree, total runoff volumes had increased due to adverse LULC change (e.g. deforestation), but that the hydrological responses varied according to subcatchment characteristics (Saghafian et al. 2008). Elsewhere in northern Iran, the nature of any changing risk of (flash) floods due to LULC change in upstream catchments is effectively unknown because there are insufficient studies to indicate any consistent patterns.

In 2015, Iran’s Forest, Range, and Watershed Management Organisation (FRWO) highlighted ongoing losses of Caspian Hyrcanian forest due to logging (legal and illegal) and ‘excessive’ construction such as dams and reservoirs. These losses amounted to more than 7% of the total forest area within the preceding few years (Financial Tribune 2015), with 12,000 km^2 of ‘pristine’ forest and 6,000 km^2 of ‘damaged woodland’ remaining in 2002 (Financial Tribune 2017). However, with annual timber extraction having reduced from 1.5 million m^3 in 1996 to 550,000 m^3 in 2017 (an 8% fall since 2016), a 10-year ban on logging these forests, part of a new Forest Protection Bill, is due to start in 2020 (Financial Tribune 2017). It therefore appears that any adverse runoff effects of forestry activities seem likely to diminish or even stop in the next few years but there remains a flood hazard to be assessed and addressed.

The aim of this paper is to estimate the future change in flood risk arising from LULC in the humid mountainous catchments of northern Iran. In particular, we identify the potential for NWRM or NBS (‘nature based solutions’: Schanze 2017) within the study catchment and, by implication, similar catchments throughout the region. We also consider the validity and utility of the SCS-CN method as a decision-making tool for this region of northern Iran, given the constraints that led to this choice of methodology.

Study Site

The Casilian (or ‘Cassilian’, ‘Kasilian’ or ‘Kassilian’) Catchment was selected for this study because the availability of data is better than for most other catchments in Iran. This catchment is located in northern Iran (Mazandaran Province), on the northern side of the Alborz Mountains south of the Caspian Sea, at 53°18’ to 53°30’E and 35°58’ to 36°07’N (Fig. 1). Around 80% of this 65.7 km^2 area is forested, the remainder being mostly agricultural land (Fig. 2). The southern edge of the catchment is defined by the Mirozad and Golrad mountains (2700 and 3349 metres, respectively) (Fig. 2B) but the elevations of the mountain peaks progressively reduce northwards (downstream) towards the Caspian Sea. Further characteristics of the catchment were reported by Hajian et al. (2016).

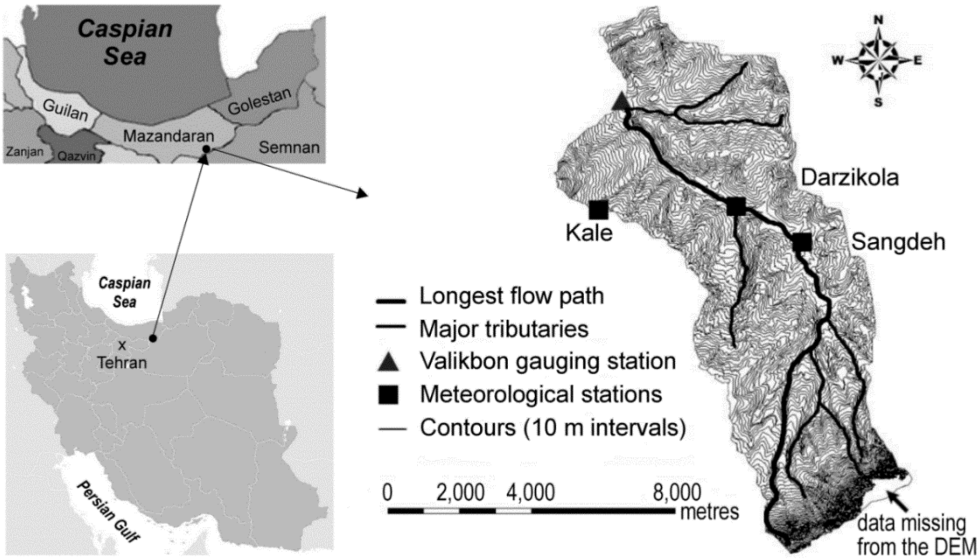

Figure 1. Location of the Casilian Catchment in Mazandaran Province, northern Iran, showing locations of hydrometric monitoring stations within the catchment. Valikbon station defines the outflow from the study catchment. Partly from Hajian et al. (2016) © Taylor & Francis Ltd. (www.tandfonline.com), reproduced with permission.

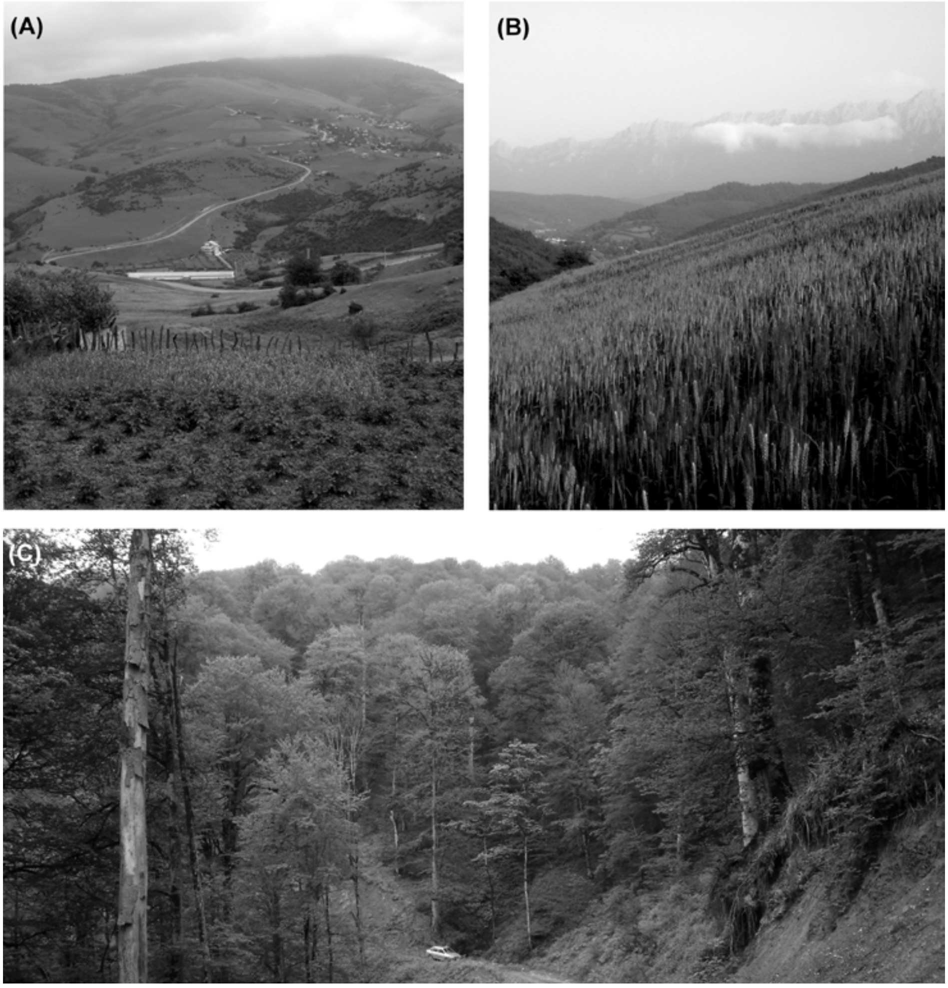

Figure 2. Casilian Catchment, northern Iran: (A) Downstream of Sangdeh, much of the catchment has been deforested in favour of agriculture. (B) Beyond the wheat field, the catchment extends to the top of the mountain range in the upper right of this view. (C) The mid-slopes of the mountain range, below the clouds in (B), are covered with ‘fair’ quality deciduous forest, partly accessible by a sparse network of forestry tracks. All photos by APD, May 2010.

There are several monitoring stations within the Casilian Catchment (Fig. 1). Although the range of recorded data available from them is very limited, it is significantly greater than from most other catchments in northern Iran. Sangdeh meteorological station, located at the upstream end of Sangdeh village, provides daily rainfall and temperature data. Darzikola and Kale stations have only daily rainfall data. There are no rainfall intensity data for the catchment. At Valikbon hydrometric station, which defines the downstream limit of the study area, the discharge from the upper catchment is also manually recorded only once every day. Tamab, Iran's Water Resources Research Organization based in Tehran, provided most of the data for this study. The mean annual rainfall for the catchment was around 756 mm (1977–1996 inclusive) with a mean annual runoff of around 230 mm and a mean discharge from the catchment that varies seasonally between around 0.3 and 0.6 $m^3 s^{-1}$ (Hajian et al. 2016) (Table 1).

Land use/land cover data for the Casilian Catchment were obtained from Mahab Ghodss (a commercial consultancy company, website: www.mahabghodss.com/Default.aspx) in the form of maps of the catchment derived from Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM) satellite images. We selected the LULC map produced from 1990 satellite data as the reference 'initial condition' for the catchment (Fig. 3), with explanations of the LULC categories provided in Table 2 (Mahab Ghodss, pers. comm., 2009-10). The soils of the Casilian Catchment have been classified by the Geological Survey of Iran as shown in Fig. 4 according to standard criteria (Table 3) (USDA 2009). These data comprised GIS layers that provide a semi-distributed basis for the runoff estimates, but the very coarse spatial resolution and the highly simplified categorisation of the information inevitably give rise to some uncertainty in the results obtained.

Methodology

In this study we examined the responses of catchment storm runoff to several land use change scenarios for hypothetical rainfall events (Merianji and Marofi 2007). We also used one of these scenarios to indicate the potential significance of the antecedent soil moisture and the input rainfall characteristics. The general approach of this study was to estimate runoff volumes by integrating the SCS-CN method with spatial catchment data using ARC-GIS and to derive peak discharges using the SCS dimensionless unit hydrograph. All of the specific derivations and calculations follow procedures documented by McCuen (1998).

Rainfall conditions

We required 24-hour rainfall depths corresponding with return periods from 2 to 200 years as the input rainfall events, from which changes in the runoff from the catchment due to LULCC could be estimated. Firstly, the annual maximum 24-hour rainfall values for the 11-year period 23 September 1984 to 22 September 1995 inclusive, were obtained from the three rainfall stations in Casilian Catchment. Different statistical distributions were then fitted to these data using DISTRIB software (Eaglin et al. 1997) with the degree of fit being determined using a chi-square test. In all cases χ^2 <<1 and in some cases was nearly zero.

Table 1. Summary of the runoff regime at Valikbon station in the Casilian Catchment, 1980-1986 inclusive (except Winter: 1980-1985 only), based on a single daily reading at an unspecified time each day. Source: Tamab.

SEASON	DISCHARGE (m^3 s^{-1})	
Autumn	mean 1980-86	0.32
	highest measured peak (1981)	4.17
	mean highest annual measured peak 1980-86	2.55
Winter	mean 1980-85	0.64
	highest measured peak (1984)	6.25
	mean highest annual measured peak 1980-85	3.34
Spring	mean 1980-86	0.64
	highest measured peak (1981)	4.76
	mean highest annual measured peak 1980-86	3.30
Summer	mean 1980-86	0.30
	highest measured peak (1983)	13.87
	mean highest annual measured peak 1980-86	4.06

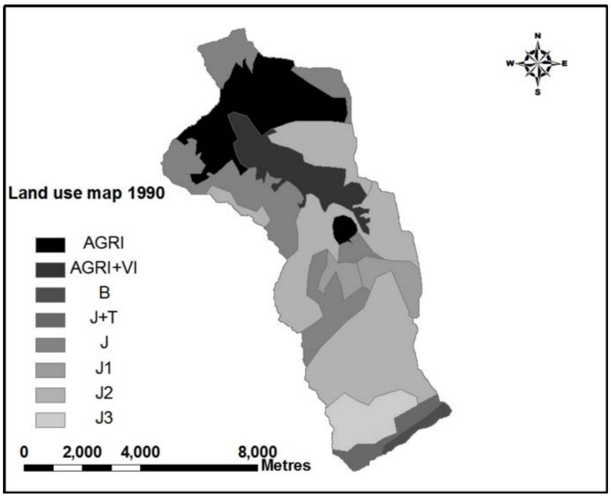

Figure 3. Land use in Casilian Catchment in 1990, based on Landsat Thematic Mapper and Enhanced Thematic Mapper satellite images dated 2000 (Landsat.org undated). The Legend is explained in Table 1. Source: Mahab Ghodss.

Table 2. Explanations of land use categories used for the land use maps of Casilian Catchment. Source: Mahab Ghodss.

Expression	Explanation
AGRI	Agriculture
AGRI + VI	Agricultural land including residential area
B	Bare rock
J + T	Forest including more than 70% bare rock
J	Good forest[1] (J is better than J1)[2]
J1	Good forest[3]
J2	Fair forest (average)[4]
J3	Poor forest[5]

Notes:

[1] Forests are mostly deciduous according to field observations.

[2] The cover quality of the forests was determined by Mahab Ghodss (consulting engineering company in Tehran, Iran) based on ground cover density although the method used is not known.

[3] Good hydrologic condition has more than 70% ground cover density.

[4] Fair hydrologic condition has between 30 and 70% ground cover density.

[5] Poor hydrologic condition has less than 30% ground cover density.

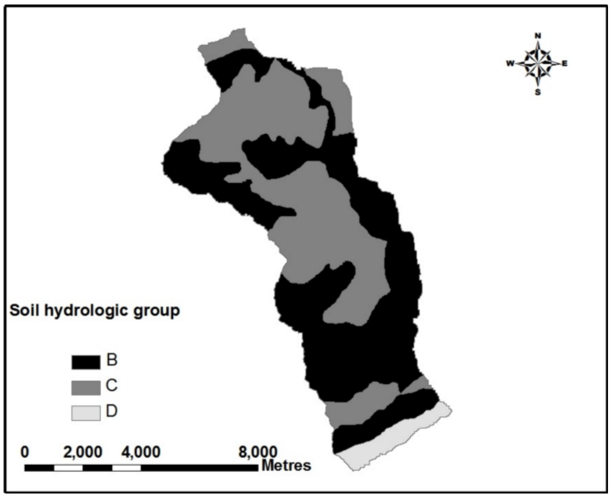

Figure 4. Soil groups in Casilian Catchment: B = low runoff potential; C and D = high runoff potential (Table 2). Source: Geological Survey of Iran.

Table 3. Classification of soil hydrologic groups, defined by hydrological characteristics of at least the upper 0.5 m of soil above an impermeable layer or 0.6 m above the water table (USDA 1986, 1989, 2009).

Soil hydrologic group	Runoff potential	Soil texture	Saturated hydraulic conductivity of the upper soil (m s^{-1})	Rate of water transmission within the soil (mm h^{-1})
B	low	50-90% sand, 10-20% clay	1×10^{-5} to 4×10^{-5}	3.8 – 7.6
C	high	<50% sand, 20-40% clay	1×10^{-6} to 1×10^{-5}	1.2 – 3.8
D	high	<50% sand, >40% clay	$\leq1\times10^{-6}$ if there is an impermeable layer 0.5–1.0 m deep	0 – 1.2

A Log Pearson type III distribution was found to most closely match the data from each station, so this was used to estimate 24-hour rainfall totals for the different return periods (Mandal et al. 2015). These are shown in Table 4. Secondly, these rainfall depths at each station were interpolated throughout the catchment to produce isohyetal rainfall maps for the different return periods (Hajian 2013).

Land use change scenarios

Table 5 and Figures 5 to 10 define the land use change scenarios. Although commercial (and sometimes illegal) forestry operations in northern Iran often involve clear-felling, the logging company that operates in Casilian Catchment selects and cuts the trees individually (Farim Wood Company, Sangdeh, pers. comm.). Therefore, investigations of the impacts on runoff of different deforestation scenarios are very important, particularly for this region. Much of the upstream (southern) half of the catchment, except on the upper mountain slopes, is covered with high quality forest (Fig. 2C; shown as ‘fair’ (J2) and ‘good’ (J and J1) in Fig. 3). As such, significant deforestation in the future is a plausible possibility. The coarse resolution of the available data makes it impossible to reliably represent low-impact change representative of selective logging, so we examined ‘worst case’ conditions of complete forest removal and replacement. Scenarios 1 to 5 represent various spatial patterns and extents of such deforestation. Further downstream there are some

Table 4. 24-hour rainfall value (mm) for each return period at each Casilian Catchment rainfall station.

Return period (years)	Sangdeh	Darzikola	Kale
2	38	33	36
3	42	37	39
5	48	42	43
10	55	47	48
25	64	54	54
50	72	59	59
100	79	64	63
200	88	68	67

Table 5. Land use change scenarios examined in this study.

Scenario	Reference land use	Changed land use	Proportion of catchment undergoing change (%)	The descriptions for this scenario
1	fair forest	poor pasture	17	Deforestation
2	fair forest	poor pasture	19	Deforestation
2 + rf	fair forest	poor pasture	19	Scenario 2 + 20% increase in magnitude of rainfall
2 + sm	fair forest	poor pasture	19	Scenario 2 + high antecedent soil moisture content throughout the catchment[1]
3	fair forest	poor pasture	36	Deforestation
4	fair, good and poor forest	poor pasture	49	Deforestation
5	fair, good and poor forest	poor pasture	70	Deforestation
6	fallow land	fair pasture	15.3	Investigating the effects on runoff of agricultural areas or regions with no farming

Notes:

[1] ‘High’ antecedent soil moisture is assumed to represent saturated or near-saturated soils.

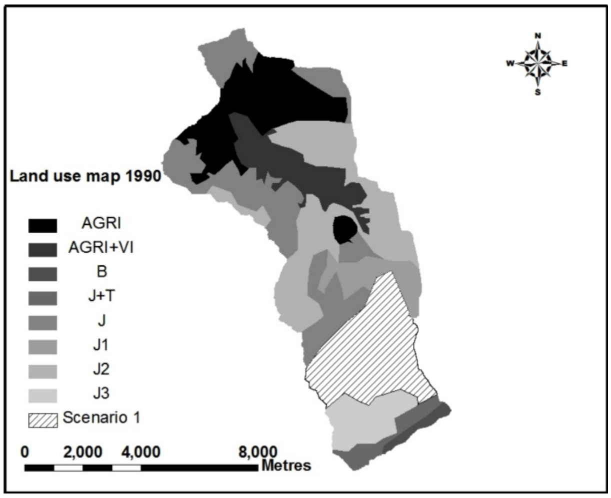

Figure 5. Scenario 1 land use: 17% of the catchment (on the main mountain slopes) changed from fair forest to poor pasture.

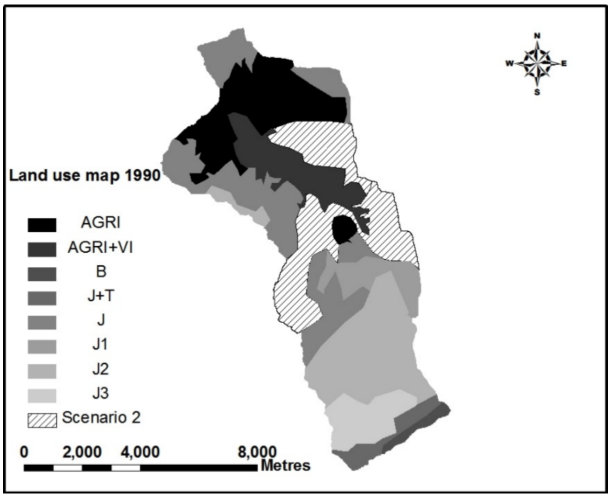

Figure 6. Scenario 2 land use: 19% of the catchment (downstream of the main mountain slopes) changed from fair forest to poor pasture.

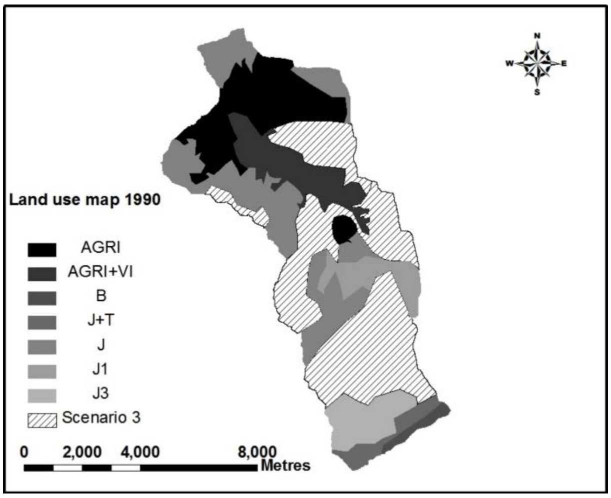

Figure 7. Scenario 3 land use: 36% of the catchment (scenarios 1 and 2 combined) changed from fair forest to poor pasture.

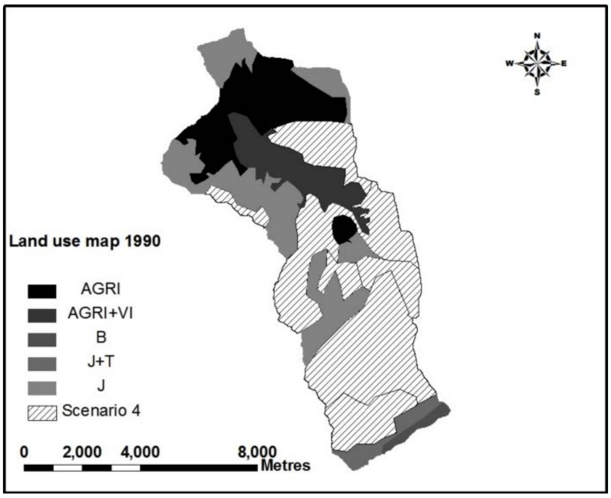

Figure 8. Scenario 4 land use: 49% of the catchment changed from varying quality of forest to poor pasture.

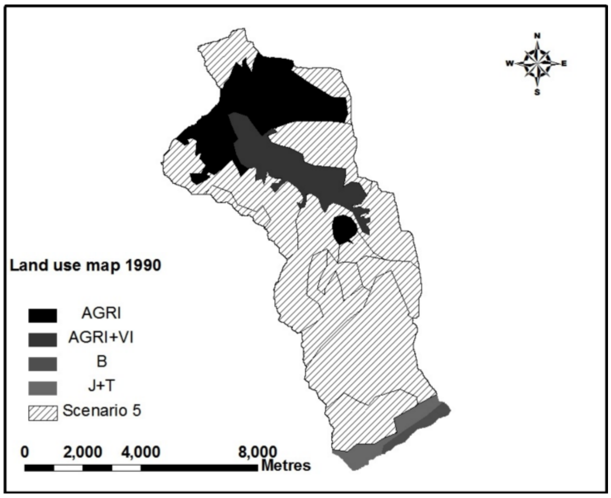

Figure 9. Scenario 5 land use: 70% of the catchment changed from varying quality of forest to poor pasture.

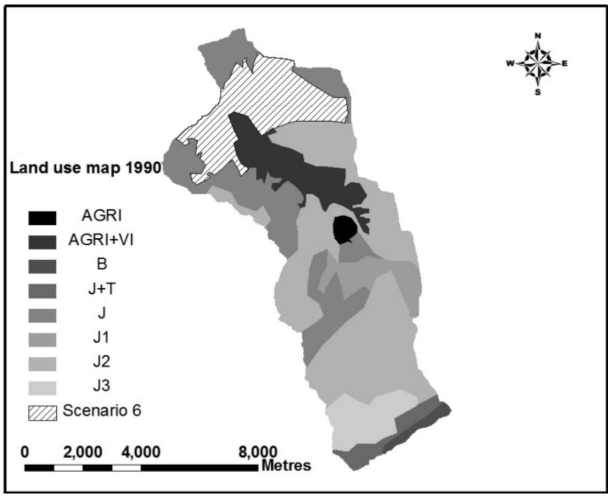

Figure 10. Scenario 6 land use: 15% of the catchment changed from fallow land to fair pasture.

agricultural areas but most of these have been left uncultivated and colonised by wild plants (Fig. 2A). Therefore, scenario 6 was added to represent possible conversion of fallow land to pasture.

The effect of scenario 2 land use change on runoff was investigated in three ways: (a) Deforestation as specified; (b) Deforestation as specified with 20% more rainfall in each storm event (scenario '2 + rf'), for which new isohyetal rainfall maps were prepared; (c) Deforestation as specified but with a 'high' antecedent soil moisture content throughout the catchment (scenario '2 + sm'), for which a CN map was prepared using curve numbers for wet conditions (McCuen 1998). The original specification of high antecedent conditions was based on 'above average 5-day antecedent rainfall' (Woodward et al. 2002), but we take it to mean a 'worst case' condition in which the (mostly thin) catchment soils are mostly saturated.

Derivation of runoff hydrographs

Firstly, a CN map of the catchment for the initial land use conditions and scenarios 1 to 6 (Table 5) was prepared by overlaying each land use map (Figs. 3 and 5–10) on the soil hydrologic group map (Fig. 4) in

ARC-GIS. The combinations of CN relevant to this study are summarised in Table 6. Secondly, runoff maps for different 24-hour rainfall return periods and for all scenarios of Table 5 were prepared from the CN map and isohyetal rainfall maps using the SCS-CN method (USDA 1986; 2004). Next, the time to peak and the peak discharge of the SCS dimensionless unit hydrograph were calculated and the coordinates of this unit hydrograph were obtained using those values following McCuen (1998, p. 534-540). The corresponding hydrographs providing runoff volumes and peak discharges for each return period were derived by multiplying: (i) the mean depth of direct runoff calculated from the runoff maps for each return period, by (ii) the coordinates of the unit hydrograph for the initial land use condition and all scenarios of Table 5. Table 7 presents a summary of these rainfall and runoff characteristics for the initial condition. A change of land use therefore required changes to the CN map, runoff maps, unit hydrograph and the time of concentration of the catchment.

The 'Introduction' section of this paper highlighted the cautious acceptance of the general (global) applicability of the SCS-CN method despite its origins in agricultural states of the USA. Some researchers determined the initial abstraction ratio, $\lambda = I_a / S$, and lag time, which are both related to CN and LULC and thus required for simulations using HEC-HMS, through calibration (Saghafian et al. 2008). The initial abstraction, I_a , is the amount of rainfall needed to initiate runoff (Hawkins et al. 2003) or 'the rainfall that occurs prior to the start of direct runoff' (McCuen 1998, p.479). If event precipitation $P \leq I_a$ then the direct runoff depth $Q = 0$. S is the potential maximum retention or storage within the catchment after runoff starts (USDA 1986), i.e. 'the maximum possible difference between P and Q' as P becomes very high (Hawkins et al. 2003, p.1). In the original CN method, $I_a = 0.2S$ (i.e. $\lambda = 0.2$) but many studies have shown this to be too high, leading to runoff from large events being underestimated (Shi et al. 2009). Ajmal et al. (2015) redefined this critical parameter as $I_a = 0.02P$ for several catchments across South Korea, but many studies have found that using $\lambda = 0.05$ produces satisfactory runoff estimates (Woodward et al. 2003; Shi et al. 2009; Papathanasiou et al. 2015). On the other hand, McColl and Aggett (2007) found through calibration that they needed $\lambda = 0.30$-0.45 to account for additional abstractions such as interception and surface detention from forest-dominated subcatchments.

Using a different value of λ requires a different set of CNs to be developed from a sufficiently large and appropriate set of catchment rainfall-runoff data. Given the difficulties of addressing the potential inaccuracy of $\lambda = 0.2$ for this study, particularly inadequate data to support calibration of a bespoke value for λ and no feasible means of determining a suitable CN conversion, we proceeded (a) on the understanding that runoff depths arising from LULC change in the study catchment may be higher than the values we obtained using $\lambda = 0.2$ based on results obtained by Shi et al. (2009) though perhaps offset by the overestimation of runoff found by McColl and Aggett (2007), and (b) in the knowledge that the standard method would be replicable as a management tool as long as the critical assumption of (a) and its implications are fully understood.

Table 6. Curve numbers (columns 4–6) relevant to this study for the various combinations of LULC and soil types assuming average antecedent moisture conditions (condition II) as presented by the US Soil Conservation Service (McCuen1998).

Land use description	Treatment or practice	Hydrological condition	Soil hydrologic group		
			B	C	D
Fallow (agricultural land)	Straight row or bare soil		86	91	94
Evergreen deciduous forest		Poor	73	82	86
Evergreen deciduous forest		Fair	65	76	82
Evergreen deciduous forest		Good	58	72	79
Pasture or range	No mechanical treatment	Poor	79	86	89
Pasture or range	No mechanical treatment	Fair	69	79	84
Pasture or range	No mechanical treatment	Good	61	74	80

Table 7. Mean catchment rainfall, runoff and peak discharge (estimated from the unit hydrograph) for each return period, showing results for the initial condition (land use in 1990).

Return period (years)	Mean rainfall (mm)	Mean runoff (mm)	Peak discharge ($m^3\ s^{-1}$)
2	35.8	9.5	7.0
3	39.7	11.3	8.3
5	45.1	13.9	10.2
10	51.1	16.9	12.4
25	59.0	21.5	15.8
50	65.6	25.4	18.7
100	71.5	29.2	21.5
200	78.0	33.5	24.7

Results

Table 8 shows the effects of the selected LULCC scenarios on the hydrological characteristics of the catchment. Tables 9 and 10 show the changes in the mean runoff and peak discharges from the catchment for the LULCC scenarios resulting from different 24-hour rainfall return periods, with peak discharge values shown in Fig. 11. For 'deforestation' (Scenarios 1-5), Figure 12 shows how the catchment responses vary with the proportion of catchment affected by this type of change. Rainfall and runoff maps for the various return periods, and CN maps, for the initial land use condition and all scenarios are presented in Hajian (2013).

Conversion of forest to pasture (scenarios 1 to 5) reduces infiltration and, as a result, increases the CN. Reduced infiltration for deforested areas causes the runoff to begin sooner than for the pre-deforestation condition. Conversion of forest to pasture also reduces the surface roughness and litter on the ground and increases the velocity of runoff (Ifabiyi 2012). These changes result in a decrease in the time of concentration (T_c) and the time to peak (T_p) depending on the area of deforestation (Table 8). Consequently, an increase/decrease in the time of concentration results in a decrease/increase in peak discharge of the unit hydrograph (McCuen 1998) (Table 8). Following deforestation, the volume of direct runoff and the peak discharge of the outflow from the catchment are predicted to increase due to higher surface runoff generated from pasture compared with forest (Tables 9 and 10).

Table 8. The effects of the scenarios on catchment hydrological characteristics.

Land use change scenario	Average curve number for the catchment	Time of concentration (h)	Time to peak (unit hydrograph) (h)	Peak discharge (unit hydrograph)[1] ($m^3 s^{-1}$)
Reference condition	74.0	27.9	18.6	7.3
1	77.0	25.7	17.1	7.9
2	77.0	25.7	17.1	7.9
2 + rf	77.0	25.7	17.1	7.9
2 + sm	90.5	16.1	10.7	12.7
3	79.0	24.2	16.1	8.5
4	80.3	23.2	15.4	8.8
5	84.0	20.6	13.7	9.9
6	72.0	29.6	19.7	6.9

Notes:
[1] The peak discharge here depends on rainfall depth (e.g. 24-hour rainfall totals for different return periods) and spatial pattern of land use represented by the CN, adjusted to correspond with 10 mm of rainfall excess (i.e. direct runoff) represented by the SCS dimensionless unit hydrograph.

Table 9. Change in mean volume of runoff (%) for each scenario and 24-hour rainfall return period.

Scenario:	1	2	3	4	5	6	2 + rf	2 + sm
Return period (y)								
2	18	20	38	47	71	-38	58	95
3	17	19	37	47	69	-35	59	91
5	17	18	36	46	68	-30	56	87
10	17	18	36	45	66	-26	57	82
25	15	16	33	41	61	-22	54	74
50	15	16	32	40	58	-20	51	70
100	14	15	30	38	55	-18	51	66
200	14	14	29	36	53	-16	49	62

Table 10. Change in peak discharge (%) for each scenario and 24-hour rainfall return period. Corresponding discharge magnitudes are shown in Fig. 11.

Scenario: Return period (y)	1	2	3	4	5	6	2 + rf	2 + sm
2	27	30	59	76	126	-41	71	239
3	27	29	54	81	127	-39	74	231
5	27	28	59	73	124	-34	73	226
10	27	29	58	77	123	-30	73	217
25	25	27	56	67	120	-27	67	203
50	25	26	50	65	112	-25	62	195
100	24	24	50	64	107	-23	63	187
200	24	24	48	64	105	-21	61	180

Conversion of fallow land to pasture (scenario 6) increases infiltration and organic content and, as a result, decreases the CN. The higher infiltration of pasture land causes the runoff to begin later than it would have done previously and the greater surface roughness of pasture reduces the velocity of runoff (Ifabiyi 2012). This LULC therefore increases both the T_c and T_p (Table 8). Consequently, the volume of direct runoff and the peak discharge are predicted to decrease due to less surface runoff being generated on pasture compared with fallow land (Tables 9 and 10).

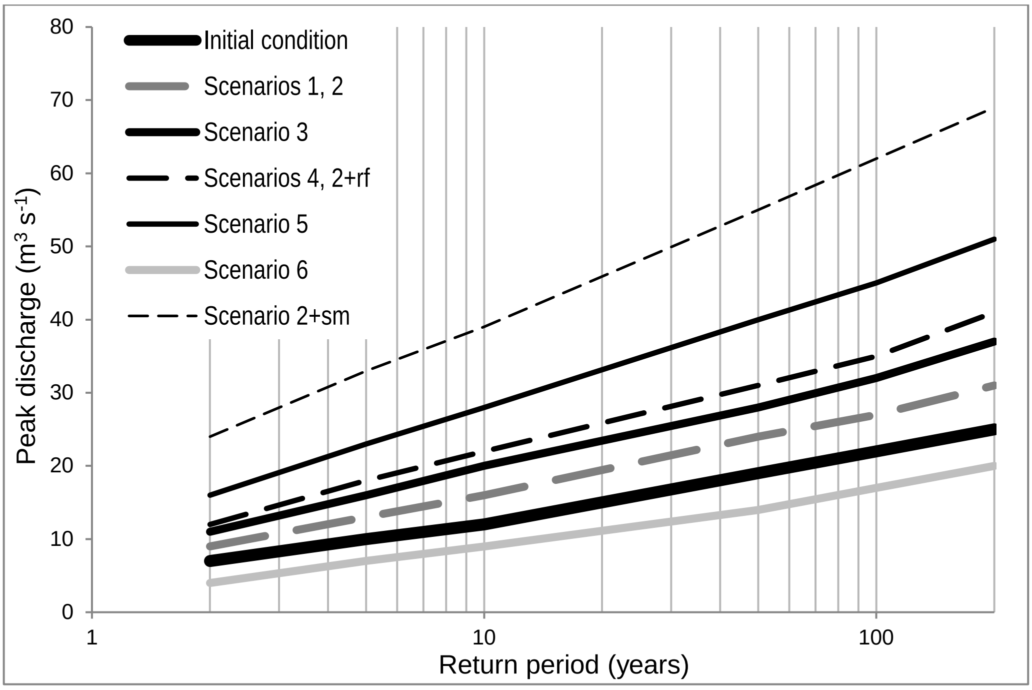

Figure 11. Peak discharges (m^3 s^{-1}) for all scenarios and return periods considered in this study.

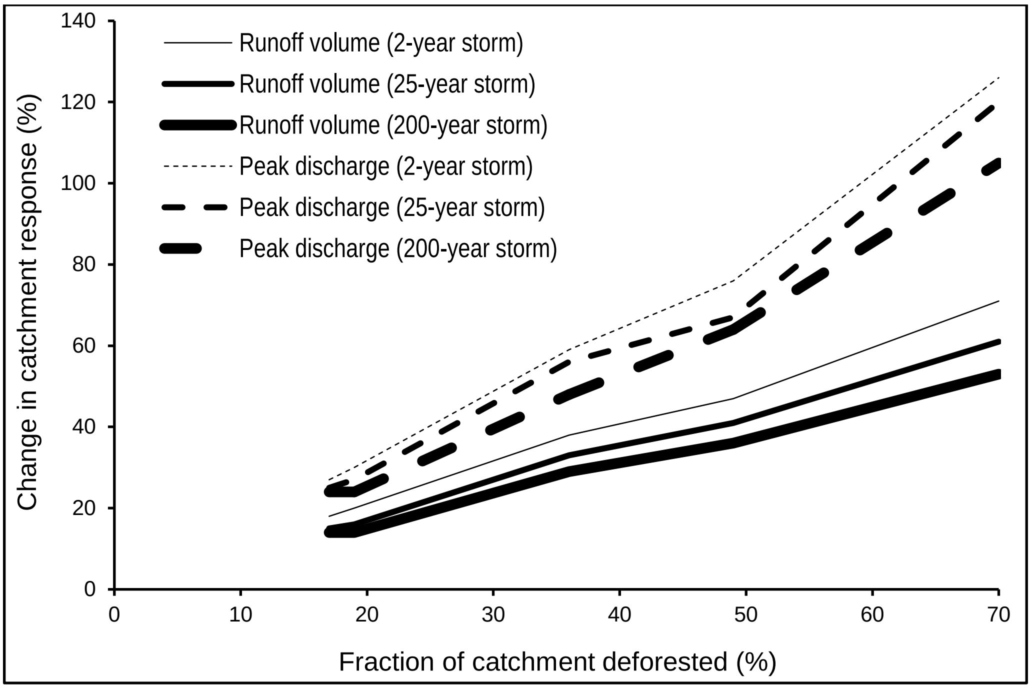

Figure 12. Catchment runoff responses to rainfall of varying return periods when different proportions of the catchment area have been deforested.

In addition to any land use change in the catchment, other factors may affect the magnitude and patterns of runoff: (i) In scenario '2 + rf', 20% more rainfall in each event resulted in noticeable increases in both the volume of direct runoff and the peak discharge from the catchment (Tables 9 and 10); (ii) If the antecedent soil moisture content is high (scenario ‘2 + sm’), i.e. assumed to be saturated for this study, the ground acts like a somewhat impervious surface with a very low infiltration rate. Frozen ground has a similar effect (de Roo et al. 2003). The runoff begins sooner than for unsaturated (and unfrozen) soil and the surface runoff moves faster towards the streams and rivers. Both T_c and T_p were calculated to be much lower when the antecedent soil moisture content is high (Table 8), which results in a significant increase in the runoff volume and peak discharge (Tables 9 and 10).

Selective logging vs. clear-felling

Our results suggest significantly higher storm runoff in response to clear-felling of varying proportions of Casilian Catchment as a worst-case scenario. In reality, selective logging is undertaken in this catchment and clear-felling is not expected to be considered. Hydrological impacts of selective logging can be severe but are usually highly localised along forestry access roads and skid trails. Compaction of surface soils may reduce the saturated hydraulic conductivity and, thus, infiltration (Ziegler et al. 2006; Suryatmojo et al. 2014), although increased surface runoff generated on these areas may infiltrate into undisturbed soils before reaching a stream channel and/or contribute to the rising limb of the hydrograph and not affect the peak discharge (Chappell et al. 2006). Consequently, any increased runoff due to selective logging may be effectively negligible (Chappell et al. 2006) and recovery to pre-disturbance conditions (skid trails in particular) may be expected within perhaps two (Suryatmojo 2014; Suryatmojo et al. 2014) to four decades (Ziegler et al. 2006). Abari et al. (2017) also found, from preliminary plot studies from Hyrcanian forest in western Mazandaran Province in Iran, that selective logging as undertaken in Casilian Catchment had little effect on runoff compared with skid trails or canopy reduction due to other more damaging logging methods.

Discussion

The potential for significantly higher peak discharges during the flash floods that climate change predictions suggest will become more common in Casilian Catchment if deforestation occurs (Hajian et al. 2016). However, deforestation is a diminishing threat overall due to implementation of more sustainable timber extraction methods, particularly minimum disturbance selective logging (i.e. without creating even local skid trails), and a forthcoming ban on all logging activities. In any case, the relationships between peak discharges and LULC patterns and/or changes within a catchment are not simple and may not be easily assessed. Notwithstanding the limitations of this study and corresponding uncertainty in the results, discussed below, there appears to be a sound basis for the development of strategies to minimise, or at least mitigate, the possible effects of future flooding within the study catchment and, thus, the many similar forested catchments across northern Iran.

Flood risk from land use/land cover change

Deforestation in Casilian Catchment would cause increased peak discharges from high magnitude rainfall events (Fig. 11) roughly proportional to the area of catchment affected by this change (Fig. 12). In fact, Casilian Catchment is not likely to experience these effects because of selective logging rather than clear-felling but across northern Iran, where the total forest cover reduced from 18 million ha in 1950 to 12 million ha by 2011 (Majidi et al., 2011), the most likely type of LULCC is deforestation. Adverse hydrological effects of deforestation have been observed in many other parts of the world (Bradshaw et al. 2007). Our results suggest that the area of land and soil types affected may have at least as much influence as topographic controls (an effect observed on cultivated plots by Vaezi et al. 2017; Cheng et al. 2008). More generally, our finding is similar to that of Solín et al. (2011) who found that the type of land use change may be less important than the area of the change, although others (e.g. Warburton et al. 2012) have found that contributions of different LULC to streamflow do not vary with proportions of catchment area. Other catchments in northern Iran may not display similar patterns of response because of the inherent spatial and temporal complexity of catchment hydrological processes and pathways (Blöschl et al. 2007; Pattison and Lane 2011; Fox et al. 2012; Sanyal et al. 2014; Lacombe et al. 2016) and will need their own specific assessments of flood risk. Notwithstanding the above, Figure 12 also shows that the relative increase in peak discharge for a given area of deforestation decreases for larger storms, which is consistent with many previous studies (e.g. Chen et al. 2009; Komatsu et al. 2011; Olang and Fürst 2011; Sriwongsitanon and Taesombat 2011; Wang and Kalin 2011; Chen and Yu 2015) and can reasonably be expected to apply across the region.

Although there appears to be little actual risk of increased flood discharges in Casilian Catchment because of the negligible impact of selective logging on runoff, Fig. 11 shows that moderate return period rainfall events (e.g. 10-100 years) can produce significant flood events with peak discharges of perhaps up to 40 m^3/s if the rain falls on saturated soils (using the results for scenario 2 and scenario 2+sm as a guide), particularly during periods of spring snowmelt (Bernsteinová et al. 2015). The flash flood hazard is predicted to increase even without LULCC due to climate change, most likely as intense (probably convective) rainfall of relatively limited spatial extent (Hajian et al. 2016) although the effects may be offset somewhat by higher evapotranspiration arising from higher temperatures (e.g. Schüler et al. 2017). These general findings are probably applicable to most of northern Iran. Consequently, some form of flood reduction management seems essential even in the absence of significant deforestation, urbanisation or other adverse LULCC.

Forest protection measures alone should limit the increase in flood hazard from climate change, with higher evapotranspiration due to higher temperatures increasing soil moisture storage capacities to offset the more frequent high intensity rainfall events. Furthermore, Scenario 6 of our study (re-use of fallow land for pasture across 15% of Casilian Catchment) revealed small but potentially useful reductions in peak discharge. These results show that strategic planning and management of LULCC, i.e. a combination of elements of NWRM/NBS, could be effective in reducing the flood hazard further, at least for smaller floods (Andréassian 2004; Saghafian et al. 2008; Zope et al. 2016). The characteristics of this catchment are such that land use change has a larger effect on the peak discharge than on the volume of direct runoff (Tables 8 and 9). Consequently floods with any return period may be reduced by means of careful land use management, and it is likely that a similar approach could be effective throughout much of northern Iran.

Utility and limitations of methodology

One of the major difficulties for authorities and managers responsible for land and water resources, infrastructure development and maintenance, civil protection and other economic activities such as tourism promotion, is the lack of relevant data. Casilian Catchment has a greater availability of hydro-meteorological data than many other similar catchments in this region of northern Iran, but even here there are data limitations – such as rainfall only being measured on a daily basis – that prevent many common types of analyses and modelling investigations from being even attempted. Likewise there are no records of snowfall for the catchment, although discharge data from Valikbon station show variations that can only be the result of snowmelt on the mountains at the southern end of the catchment (Hajian et al. 2016).

We used the SCS-CN method because it only requires rainfall and an index value to represent the runoff-generating capability of each LULC. In fact we were able to obtain spatial LULC and soil class data, although of very coarse resolution, that facilitated a semi-distributed analysis of catchment storm runoff. There are undoubtedly uncertainties regarding the values of runoff changes that we have obtained, given our use of using standardised empirically-based methodologies originally developed for the USA although subsequently shown to be more generally applicable (Soulis and Valiantzas 2012). However, we are confident that the patterns of results are broadly realistic (c.f. Table 1 in Andréassian 2004). As such, despite the very limited data, we have generated indicative findings that appear sufficiently consistent with other published studies to be considered reasonably valid and, therefore, operationally useful.

Future assessments of flood risks from the study catchment could be greatly enhanced by three simple (but potentially expensive) improvements to the hydrographic network. Firstly, replacement of the Sangdeh raingauge with an automatic recording tipping bucket raingauge would allow intensity and accurate timing of rainfall events to be recorded, which would facilitate more detailed runoff modelling – including continuous simulations – that could also represent LULCC effects. Secondly, a recording rain+snowgauge with remote telemetric data transfer capability would ideally be installed on the upper mountain slope near the head of the catchment to provide the first estimates of snowfall and snowmelt contributions to runoff as well as allowing improved calibration and validation of catchment runoff simulations. The latter would provide a greater operational simplicity than attempting to incorporate rainfall radar (Caseri et al. 2016) and/or other satellite rainfall estimates (e.g. Bajracharya et al. 2017) into modelling algorithms and in any case these latter approaches would require adequate raingauge data for calibration. Thirdly, automatic continuous recording of the streamflow at Valikbon, for example using a submersible pressure transducer with regular recalibration of the stage-discharge relationship, would allow almost any type of rainfall-runoff model to be utilised for future runoff change research and operational flood prediction studies.

Ecological context

One further climate change consideration is the possibility of ecological responses to warmer climates with different rainfall distribution, resulting in tree species assemblages in the forests that have different direct (water uptake and transpiration) and indirect (e.g. leaf characteristics affecting interception or litter and root characteristics affecting infiltration) effects on catchment hydrology and runoff responses. However, the Caspian Hyrcanian forest dates back to the early Cenozoic Era and its biodiversity is thought to have been largely unaffected by past climatic changes such as the Pleistocene glaciations (UNESCO 2018). Therefore it is assumed that as long as proposed forest protection measures are implemented and enforced, then significant ecological changes with hydrological impacts are unlikely.

Conclusions

In the forested catchments of northern Iran along the northern flanks of the Alborz Mountains, there appears to be a significant hazard from flash floods in the forested catchments. Deforestation increases the hazard due to higher peak discharges, although it is likely that selective logging has little impact on runoff. Forest disturbance is expected to reduce to insignificant after 2020 due to new protective legislation, but the flood hazard is expected to increase in any case due to climate change effects. Protection of the forests for ecological reasons will effectively serve as a ‘nature-based’ method for flood reduction, and there may be other specific land use changes that could reduce the peak flows, and thus the flood risk, such as introducing grazing livestock to existing fallow land. These findings are consistent with studies in other parts of the world and are considered sufficiently robust to inform flood reduction strategies. Use of the SCS-CN method facilitates routine analyses using the limited available data, notwithstanding uncertainties in the results arising from the simplicity and assumptions of the method. However, small enhancements to the hydrometric network could allow more sophisticated and, thus, reliable analyses of flood hazards to be undertaken.

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