Land Use and Land Cover Impact on Probable Maximum Flood and Sedimentation for Artificial Reservoirs: Case Study in the Western United States

Wondmagegn Yigzaw[1] and Faisal Hossain[2]

Abstract: Unanticipated peak inflows that can exceed the inflow design flood (IDF) for spillways and result in possible storage loss in reservoirs from increased sedimentation rates lead to a greater risk for downstream floods. Probable maximum precipitation (PMP) and probable maximum flood (PMF) are mostly used to determine IDF. Any possible change of PMP and PMF resulting from future land use and land cover (LULC) change therefore requires a methodical investigation. However, the consequential sediment yield resulting from altered precipitation and flow patterns into the reservoir has not been addressed in literature. Thus, this study aims to determine the combined impact of a modified PMP on PMF and sediment yield for an artificial reservoir. The Owyhee Dam of the Owyhee River watershed (ORW) in Oregon is selected as a case study area for understanding the impact of LULC change on PMF and sedimentation rates. Variable infiltration capacity (VIC) is used for simulating streamflow (PMF) and the revised universal soil loss equation (RUSLE) to estimate sediment yield over ORW as a result of change in precipitation intensity and LULC. Scenarios that represent pre-Owyhee Dam (pre-dam) and post-Owyhee Dam (post-dam; nonirrigation, control) are used to simulate PMF's and consequential sediment yield. Peak PMF result for pre-dam scenarios increased by 26 (1%) and 81 $m^3\ s^{-1}$ (3%) from the nonirrigation and control scenario, respectively. Considering only LULC change, sediment yield decreased over ORW owing to the transformation of LULC from grassland to shrubland (from the pre-dam period to the post-dam years). However, increase in precipitation intensity caused a significant (0.1% storage loss over a 21-day storm period) increase in sediment yield primarily resulting from reservoir sedimentation. This study underscores the need to consider the future impact of LULC change on IDF calculation and sedimentation rates for more robust reservoir operations and planning. **DOI: 10.1061/(ASCE)HE.1943-5584.0001287.** *© 2015 American Society of Civil Engineers.*

Author keywords: Artificial reservoirs; Dams; Probable maximum precipitation; Probable maximum flood; Land use and land cover; Revised universal soil loss equation (RUSLE); Soil loss; Sediment.

Introduction

Changes in land use and land cover (LULC) around the globe are primarily associated with artificial activities such as urbanization, deforestation, irrigation, and construction of dams. Constructions of dams (artificial reservoirs) have contributed and continue to do so in development of a region (e.g., Biswas 2004; Graf 2003; Petersson and Manfred 2003; Altinbilek 2002; Schultz 2002). Because construction of new dams extends from few to none in developed countries, developing countries are planning and constructing megadams for their emerging economies (Biswas and Tortajada 2001). The majority of dams today were constructed since 1950, with large dams accounting for more than 50% of the global surface water storage (Lemperiere 2006). A staggering statistic shows close to a million dams in the world (Lehner and Döll 2004; ICOLD 1998).

There is a continuing effort to study modification of extreme precipitation and flood behavior as a result of a LULC change. The apparent change in extreme precipitation is further associated with change in streamflow (extreme flood) and soil loss/sediment yield over a given watershed. Previous studies have shown the change in extreme precipitation patterns using land-atmosphere models. Different studies (e.g., Woldemichael et al. 2012, 2013; Nie et al. 2011; Schilling et al. 2010; Cotton and Pielke 2007; Barnston and Schickedanz 1984) have demonstrated the impact artificial reservoirs and/or the surrounding LULC change have on local and regional precipitation and flood pattern. Studies by Moore and Rojstaczer (2001) and DeAngelis et al. (2010) have also shown that there is an increase in precipitation over the Great Plains of the United States as a result of increase in irrigation practice. This change in precipitation is attributed to the extra moisture and increase in evapotranspiration as a result of irrigation water. The linked changes between LULC and precipitation (flood) have significant impact on the operation and future design of artificial reservoirs (Yigzaw et al. 2013a, b). Ultimately, this change is translated to safety and sustainability for future reservoir operation and design in a dynamic world, where spatial and temporal climate variations have become frequent phenomena.

In today's dam design practice, inflow design flood (IDF) for storage and spillway capacity are determined based on historical data analysis that assumes stationarity of the statistical properties of hydrometeorological events. However, change in sedimentation and inflow as a result of change in precipitation (affected by LULC change) also affects the quantity and quality of inflow into a reservoir. Most inflow design floods range from flood with a return period of 100 years to probable maximum flood (PMF), depending

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on the risk and hazard on downstream area should the dam fail (FEMA 2004). This PMF is a result of probable maximum precipitation (PMP), which is defined by the World Meteorological Organization (WMO) as the largest precipitation (of a given duration) expected over a specific area. Attributed to nonstationarity, IDF values are exceeded with higher probability than primarily expected (e.g., Rogers 2010; NRC 1999). According to recent studies, stationarity can no longer be the assumption in frequency analysis for future designs (Salas and Obeysekera 2014; Douglas and Fairbank 2011; Milly et al. 2008; Stedinger and Griffis 2008; Khaliq et al. 2006). Sustainability of a reservoir depends on its life expectancy up to the stage when its storage cannot serve the design purpose. The study of Graf et al. (2010) used the Reservoir Sedimentation Survey Information System (RESIS II) from USGS (Ackerman et al. 2009) to quantify the life expectancy of western American reservoirs. The study argued that most large dams in the interior western United States have a life expectancy ranging between 200 and 1,000 years. This means the issue of sustainability from the perspective of reservoir sedimentation is not a significant problem. The same study stated that small reservoirs are more prone to storage loss attributable to sedimentation. However, there are additional dimensions that need to be looked into by building on the Graf et al. (2010) study of the RESIS II data. These dimensions are river flow and sediment yield variation as a result of today's LULC and climate factors. At the same time, because most of the RESIS II data precedes 1980, there is a high uncertainty in translating the trends into current reservoir sedimentation pattern.

LULC contributes to change in precipitation directly through change in the land-atmosphere interaction consisting of water and energy balance (Seneviratne and Stöckli 2008; Seneviratne et al. 2006; Entekhabi et al. 1992). The indirect impact can be related through change in soil moisture (Delworth and Manabe 1989) and aerosol concentration or size (Junkermann et al. 2009; Charlson et al. 1992). Aerosols from urban areas have been found to suppress or increase rainfall depending on topography and type of cloud (Shepherd 2005). Hydrologically, surface and subsurface flows vary owing to the nonlinear relationship of rainfall-runoff transformation. A study by Yigzaw et al. (2013a, b) on the American River showed significant impact of LULC change and artificial reservoir on extreme flood events with insignificant change for different sizes of artificial reservoirs. The conventional reservoir sedimentation estimation methods that consider historical precipitation pattern and LULC will also change, leading to loss of reservoir storage and consequently, less reservoir life expectancy, because of the change in sediment yield. The impact of LULC change on sediment yield is a phenomenon that in the past has not received as much attention as modified precipitation patterns for artificial reservoirs' design and operation. Sediment yield is highly affected by two factors: the ability of rainfall to erode soil and the potential of the soil to be eroded (Wischmeier and Smith 1958). As precipitation intensity and LULC change, there is a direct change in reservoir sedimentation. Reservoir sedimentation is a problem from the perspective of economics and safety. Storage loss in downstream reservoirs is also a significant problem for flooding and operation (e.g., Verbist et al. 2010; Nelson and Booth 2002). The reserved storage for an assumed sediment deposit, dead storage, may not always serve its purpose because in some reservoirs, this storage is filled before the functional life of the reservoir is over (Palmieri et al. 2001). Because sedimentation poses a significant problem for reservoirs, ICOLD encourages appropriate estimation of reservoir sediment inflow (USBR 2006).

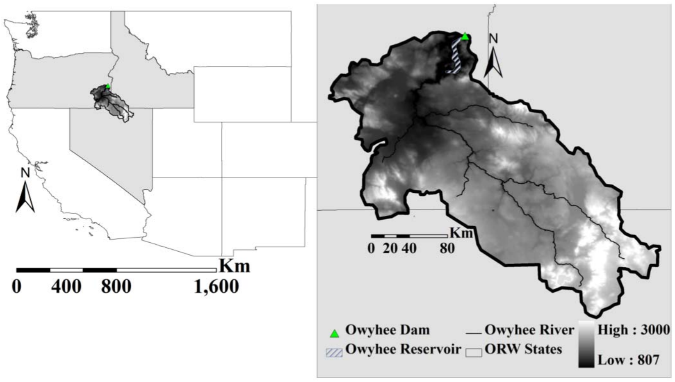
The process of reservoir sedimentation starts from erosion (soil loss). A given percentage of this soil loss becomes a sediment yield, which is dependent on characteristics of the area (topography, LULC, and land management) and the sediment. In most cases, the sediment delivery ratio (SDR) is used to estimate the sediment yield over a given area (Ouyang and Bartholic 1997). Different empirical and direct approaches used in determining the SDR are compiled by Ouyang and Bartholic (1997), which include the ratio between gross soil loss and actual sediment yield, empirical formula as a function of drainage area (Dendy and Bolton 1976; Renfro 1975; Vanoni 1975), topography (Williams 1977; Williams and Berndt 1976), and sediment property (Walling 1983). The soil and water assessment tool (SWAT) factors rainfall and runoff to estimate sediment yield (Neitsch et al. 2011). The first method was implemented in this study. However, the difference was that this study considered only sediment yield as a result of sheet and rill soil erosion. Sediment concentration and the settling pattern, which depends on the reservoir's trap efficiency, determine the final sediment volume stored in a reservoir (Julien 2010; Brune 1953). Every artificial reservoir is designed to lose its storage to sedimentation over a given time, signifying its life of expectancy. The idea of reservoir sedimentation from the outlook of future precipitation intensity and LULC change has not been studied in the past. A connection between reservoir storage and LULC change–driven sedimentation will have an important contribution to understand a subsequent sediment yield and hence change in reservoir storage loss.

By considering the Owyhee Dam on Owyhee River Watershed (ORW), Oregon, this study investigated the impact of LULC change and its nonlinear relationship with change in PMF, total soil loss, and reservoir sedimentation. This study first examined how LULC change and artificial reservoirs modify extreme flood (PMF) inflow into Owyhee Reservoir. The objective of this was to consider the pre-dam and post-dam variables (reservoir and irrigation practice), which affect the hydrometeorological processes, and to find out how probable maximum flood was modified over ORW as a result of PMP change. The second objective was discovering how LULC change and PMP change affect soil loss and sedimentation pattern. Pertaining to changes in precipitation intensity and LULC, this addressed the sensitivity of sediment yield change over ORW. A systematic approach was used implementing the revised universal soil loss equation (RUSLE) and event-based precipitation intensity to quantify change in inflow sediment load to Owyhee Reservoir. The result of this study will be vital in future dam design and current dam operations with safety and sustainability in mind. This paper introduces the study area, data, and methodology; and finally, it presents results, discussions, and conclusion.

Study Area

The selected area for this case study was Owyhee Dam, which forms the Owyhee reservoir located in eastern Oregon near its border with Idaho (Fig. 1). The main inflow into the reservoir comes from upstream Owyhee River Watershed (ORW), which has an area of approximately 28,900 km^2. The elevation of the watershed ranges from 800 m at the dam to 3,000 m above sea level (ASL) at the upstream point. According to the USBR (2009), Owyhee Dam was constructed in the years 1928–1932 as a concrete arch dam with a storage capacity of 1.4 km^3 (out of which 0.82 km^3 is active storage), making it the largest reservoir in Oregon. The dam has a height of 127 m above the riverbed and a crest length of 254 m at an elevation of 815 m ASL. A morning glory type of spillway was provided that can discharge 850 m^3/s at normal water surface elevation (814 m ASL).

The primary purpose of the dam is to provide water for irrigation of more than 425 km^2 in eastern Oregon (72%) and southeastern



[14] **Fig. 1.** Study area: Owyhee River watershed (data from USGS 2014; Gesch et al. 2009)

Idaho (28%). Approximately 20% of the storage is used for flood control in downstream areas of the Owyhee and Snake Rivers. The annual economic value that is obtained from irrigated crops, livestock industry, recreation, and flood prevention reaches up to US $221 million (USBR 2009). Water is delivered to irrigation lands and canals from the reservoir using tunnels. The city of Nyssa, Oregon, with an approximate population of 3,200, is approximately 25 km downstream of Owyhee Dam.

The climate of ORW is highly influenced by moisture from the Pacific Northwest. According to Koeppen-Geiger climate classification (Kottek et al. 2006), ORW falls in the arid (B) category. Heavy precipitation occurs in the winter period, usually between the months of December and March. During this period, the inflow into Owyhee Reservoir reaches its peak. Flood events of February 1986, March 1993, and January 1997 are some examples of large inflows. The argument that this study raises lies on the change in the magnitude and frequency of extreme floods associated with the presence of an artificial reservoir and change in LULC. The flood event of December 1996/January 1997 is considered for this case study. The selected flood event is the third largest flood event that occurred in Owyhee River, which has caused total property damage close to US$90 million in Malheur County only and close to US $1 billion in western Nevada. The same storm event over the western United States triggered the U.S. Army Corps of Engineers (USACE) to reconsider design flood values of the Folsom Dam, which is found southwest of Owyhee. The magnitude of the flood event and the year it occurred makes it an appropriate representative for the study of LULC change and extreme flood modification.

Methodology

Hydrological Modeling

[15] The first approach used in this study was to set up a distributed hydrological model to simulate the daily flow over ORW. A calibrated model was used to simulate different precipitation scenarios [16] that were simulated by Woldemichael et al. (2013) based on various LULC settings. The specific period of flow simulation was December 1996 to January 1997, which corresponds to a flood event of the same period over ORW. Woldemichael et al. (2013) [17] simulated two sets of precipitation values—normal precipitation, representing actual events; and maximized precipitation, representing probable maximum precipitation. The PMP results were achieved by keeping the relative humidity at 100% in the land-atmospheric interaction model, Regional Atmospheric Modeling System (RAMS) (Pielke et al. 1992). That is, the flow simulation also has a normal (i.e., actual) flood event and a PMF event. Although the PMP results were available at ~3 km grid resolution, a spatial aggregation based on mean was applied to get a 0.125-degree (~13 km) grid resolution, which was used in the hydrological model. A detailed setup of RAMS can be found in Woldemichael et al. (2012, 2013). [18]

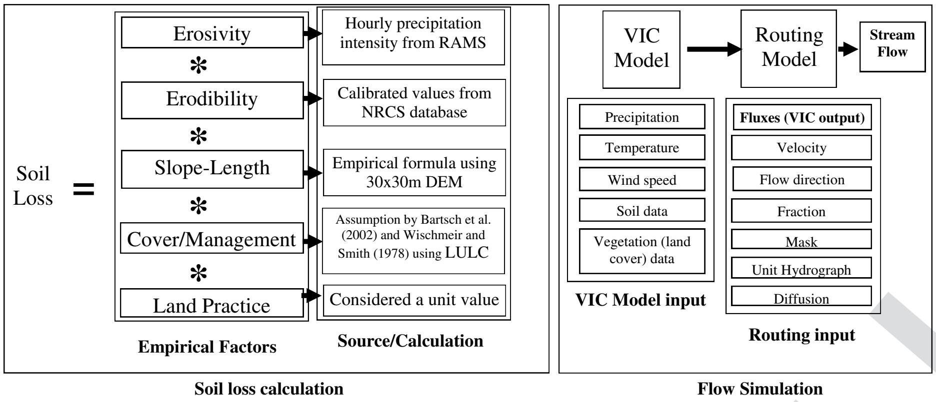
Variable infiltration capacity (VIC) (Liang et al. 1994, 1996) and a coupled routing model (Lohman et al. 1996) were used to simulate runoff fluxes and streamflow. The advantage of VIC was its assumption of a variable soil infiltration from layer to layer over a spatially distributed (grid-based) area. The study of Yigzaw et al. (2013a, b) effectively used VIC to understand the impact of LULC change and artificial reservoirs over the American River. Four important inputs (meteorological forcing) for VIC were precipitation, minimum temperature, maximum temperature, and wind speed. The selection of grid resolution depends on the availability of data and the objective of the study. There was a readily available daily gridded meteorological forcing data for a large part of the United States at a 0.125-degree spatial resolution, which was appropriate for the objective of this study. Moreover, the routing model runs only on a daily time step. The routing model used watershed information like unit hydrograph, flow direction, flow fraction, flow velocity, and diffusion. Because fluxes were available grid by grid, a specific station should be selected that represents an outflow point. The calculation of flow direction (which depends on the quality of elevation data) was very important in representing the actual river network. The flowchart of streamflow simulation is shown in Fig. 2. For ORW, two stations were selected—one representing the USGS station (USGS 13181000) near Rome; and the other representing the inflow into Owyhee Reservoir (USGS 13182000). The station near Rome was used for calibration, whereas the station representing reservoir inflow was used for the analysis of LULC change on PMP. Owyhee River network and selected stations are shown in Fig. 3.

Soil Loss Calculation

The objective of the soil loss model was only to understand the scale (and quantity) at which LULC and precipitation intensity change affects a possible sediment yield from an area upstream of an artificial reservoir. This part of the study was the implementation of a one-dimensional soil loss/sediment yield over the area that is upstream of Owyhee Dam. The revised universal soil loss (RUSLE) model (Renard et al. 1997) was used for this objective. An argument may be made that instead of using two separate models (hydrological and soil loss), a single model with water quality simulation capacity (for example SWAT) could be used. However, such models were not quite efficient in representing the LULC and precipitation change on a spatially distributed manner (instead, subbasins and subwatersheds are used), which is one of the primary objectives of this study (Neitsch et al. 2011). The RUSLE model is an empirical model that uses LULC, soil, and precipitation characteristics to calculate the soil loss from a given area. The modified formula is given in Eq. (1) (Renard et al. 1997)

$$a = r \times k \times ls \times c \times p \tag{1}$$

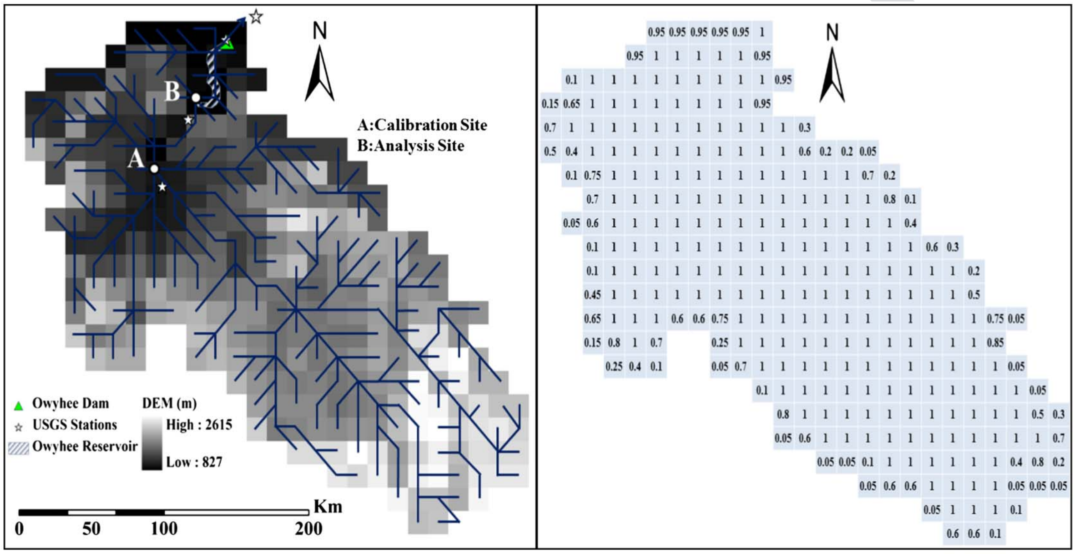
where a = soil loss from sheet and rill erosion $(\mathrm{t(ha \cdot year)^{-1}})$; r = rainfall erosivity factor $(\mathrm{MJ \cdot mm \cdot (ha \cdot year)^{-1}})$; k = soil erodibility factor $(\mathrm{t(MJ \cdot mm)^{-1}})$; ls = slope length and steepness factor(-); c = cover and management factor (-); and p = support practice factor (-). The erosivity factor (r) is calculated using the 30-min maximum rainfall intensity and the intensity of the selected duration (usually 30 min) with the expression of Eq. (2) (Wischmeier and Smith 1978)



(a) (b)

F2:1

Fig. 2. (a) Flowchart for soil loss calculation; (b) steam flow simulation



					0.95	0.95	0.95	0.95	0.95	1														
				0.95	1	1	1	1	1	0.95														
	0.1	1	1	1	1	1	1	1	1	1	0.95													
0.15	0.65	1	1	1	1	1	1	1	1	0.95														
0.7	1	1	1	1	1	1	1	1	1	1	1	0.3												
0.5	0.4	1	1	1	1	1	1	1	1	1	1	0.6	0.2	0.2	0.05									
	0.1	0.75	1	1	1	1	1	1	1	1	1	1	1	1	0.7	0.2								
		0.7	1	1	1	1	1	1	1	1	1	1	1	1	1	0.8	0.1							
	0.05	0.6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.4							
		0.1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.6	0.3					
		0.1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.2				
		0.45	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.5				
		0.65	1	1	1	0.6	0.6	0.75	1	1	1	1	1	1	1	1	1	1	1	1	0.75	0.05		
		0.15	0.8	1	0.7			0.25	1	1	1	1	1	1	1	1	1	1	1	1	0.85			
			0.25	0.4	0.1			0.05	0.7	1	1	1	1	1	1	1	1	1	1	1	1	0.05		
										0.1	1	1	1	1	1	1	1	1	1	1	1	1	0.05	
											0.8	1	1	1	1	1	1	1	1	1	1	1	0.5	0.3
											0.05	0.6	1	1	1	1	1	1	1	1	1	1	1	0.7
													0.05	0.05	0.1	1	1	1	1	1	1	0.4	0.8	0.2
															0.05	0.6	0.6	1	1	1	1	0.05	0.05	0.05
																		0.05	1	1	1	0.1		
																			0.6	0.6	0.1			

(a) (b)

F3:1

Fig. 3. (a) River network used in VIC with selected stations; (b) flow fraction used to adjust for grid representation

$$r_s = EI_{30} \tag{2}$$

where r_s = storm erosivity; E = storm energy; and I_{30} = maximum 30-min intensity. Eq. (3) provides the calculation of E (Wischmeier and Smith 1978)

$$E = \sum_{k=1}^{m} e_k \Delta V_k \tag{3}$$

where e = unit energy (energy content per unit area per unit rainfall depth) in the kth period, and ΔV = amount (depth) of rainfall in the kth period; k = index for periods during the rainstorm, where rainfall intensity is considered uniform; and m = number of periods in the rainstorm. Unit energy is computed using the following formula (Renard et al. 1997):

$$e_k = 0.29[1 - 0.72e^{(-0.082 i_k)}] \tag{4}$$

where e_k = unit energy $(\mathrm{MJ}(\mathrm{mm}\cdot\mathrm{ha})^{-1})$ for the kth period; and i_k = rainfall intensity (mm/h) for the kth period. For the case of ORW, the finest temporal resolution for rainfall is 1 h as shown in Eq. (5)

$$\Delta V_k = i \times \Delta t = I_{1\ h} = \text{hourly rainfall depth} \tag{5}$$

Therefore for this study

$$r = \left[\sum_{k=1}^{24*21} e_k I_{1\ h}\right] \times I_{1\ h\max} \tag{6}$$

where $I_{1\ h\max}$ = maximum hourly rainfall intensity. The maximum rainfall intensity is observed on January 2, 1997, at 00:00 hrs; therefore, this value was considered. Calculation of the ls factor is based on the formula given by Goldman et al. (1986).

The LULC scenario in RAMS simulations were represented in the RUSLE model in the form of precipitation. This was because the LULC changes considered in RAMS were outside (downstream) of ORW, and they did not have direct physical impact on the soil loss calculation. However, the c factors in the RUSLE model were calculated for four LULC scenarios (pre-dam 1992, 2001, and 2006) (Fig. 4). Clearly, soil loss calculation for these scenarios was using the storm event of the December 1996 to January 1997 as simulated in RAMS. Such consideration gave a good result in terms of the soil loss sensitivity to LULC change and different storm intensity (normal and maximized precipitation).

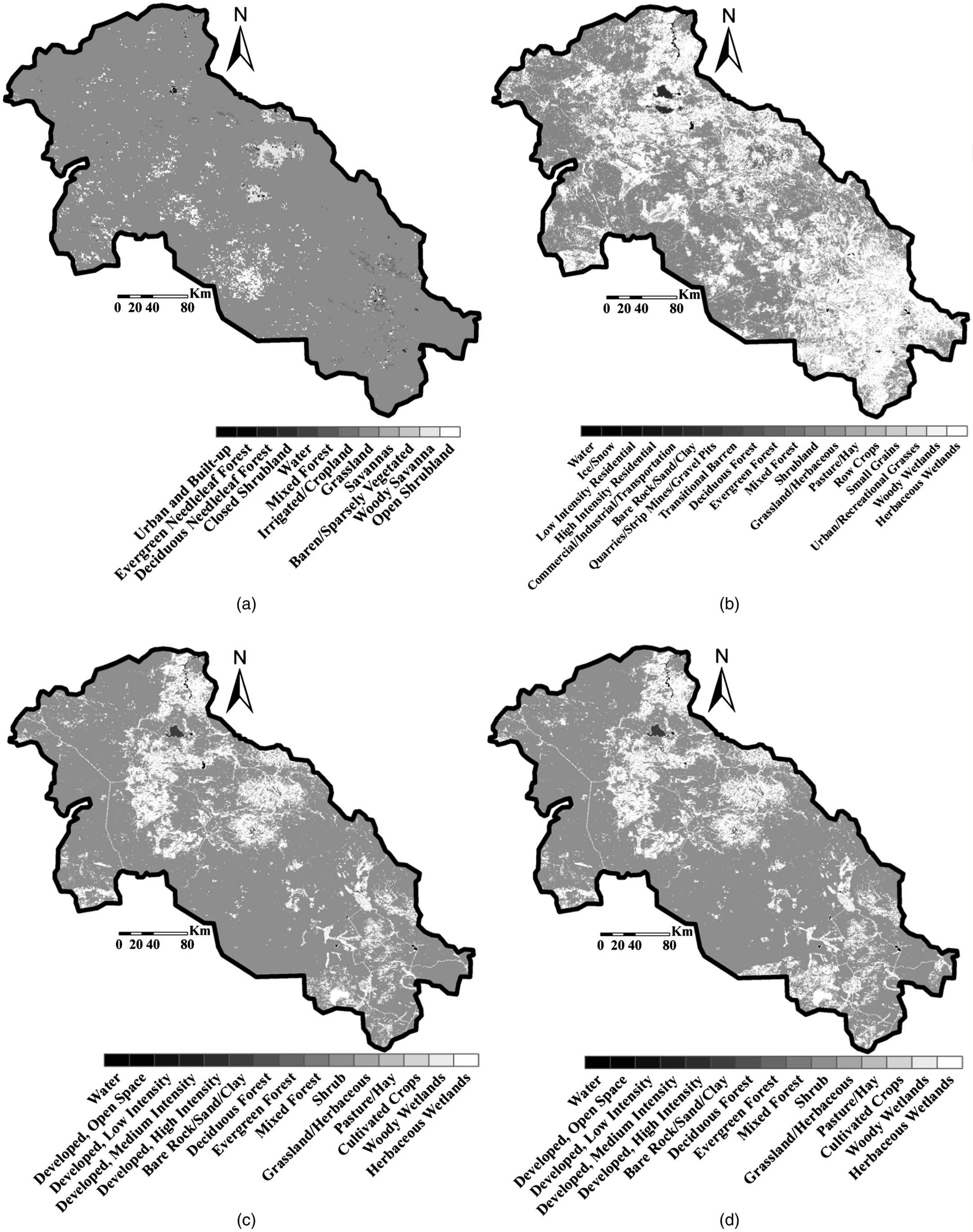


Fig. 4. (a) Land use land cover for the pre-dam (prior to 1932) period classified according to HYDE; (b) according to USGS's NLCD for the year 1992; (c) 2001; (d) 2006

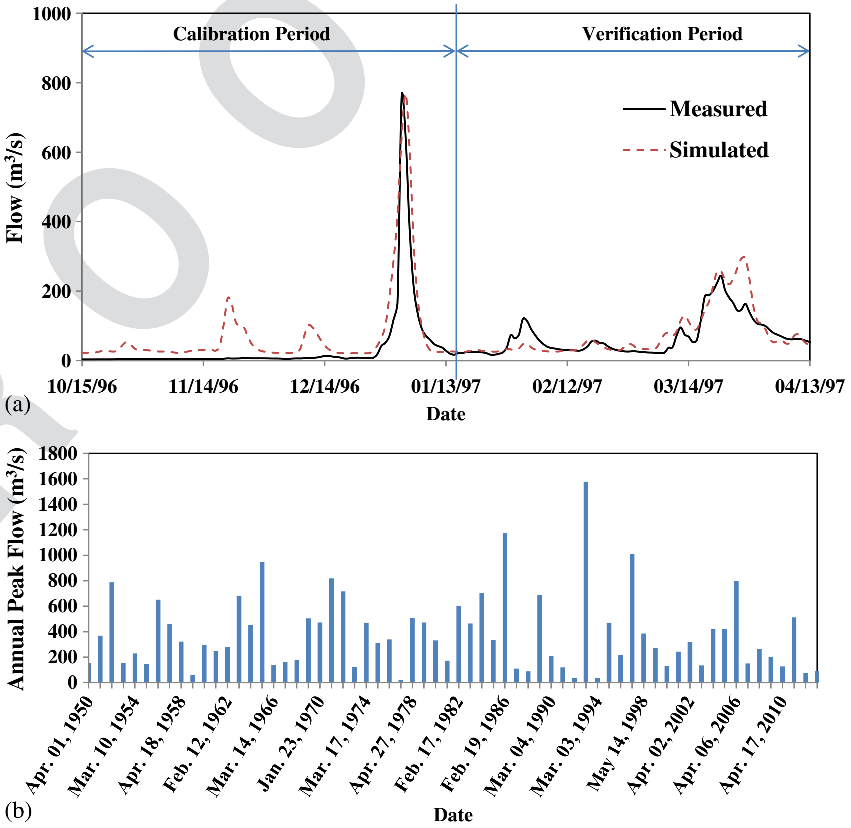
Data

Hamlet and Lettenmaier (2005) developed a daily gridded meteorological data at 0.125-degree resolution for parts of the United States (University of Washington). Elevation data at 30-m resolution, daily flow data (station ID USGS 13181000) for calibration and verification, and suspended sediment data for eastern Oregon were obtained from the USGS. Unfortunately, there is no sedimentation data for Owyhee Reservoir from the Reservoir Sedimentation Database (RESSED or RESIS-II) and USGS. Two sets of LULC were used for soil loss calculation using RUSLE: three (for the years 1992, 2001, and 2006) from the USGS's National Land Cover Database (NLCD), and three (for periods representing predam, control, and nonirrigation) from the History Database of the Global Environment (HYDE) (Klein et al. 2011) available at http://themasites.pbl.nl/en/themasites/hyde/index.html. Soil erodibility (*K* factor) for ORW was extracted from the soil database of the Natural Resources Conservation Service (NRCS). Cover and management factor for corresponding LULC were assigned using the assumptions of Bartsch et al. (2002) and Wischmeier and Smith (1978). Other inputs into the RUSLE model were calculated using empirical expressions shown in "Soil Loss Calculation."

Model Calibration and PMF Simulation

Hydrological models are used to simulate the rainfall-runoff process from a given watershed/basin with the main objective representing observed flows. This objective further extends to the idea of flood forecasting, real-time operation, and historical data analysis (Plate 2009; Maneta et al. 2007). Calibration and the verification step are generic to all models. That is, the performance of a specific model is determined by its ability to represent the observed data using different performance metrics. This calibration involves both temporal and spatial data. Based on the objective of the model setup, the temporal calibration data can be selected. For a model that is used to simulate a specific flood event, the use of a long period for calibration/verification may lead to underestimation or overestimation of the specific flood event values that are intended to be simulated. The fact that most hydrological models do not simulate extreme events (peak floods and low flows) with exact representation, a calibration and verification procedure considering a short period, when the flood event of interest are inclusive, can be used in such instances.

With the preceding premise, VIC was set up over ORW, and the December 1996 to January 1997 flood event was simulated. The location of ORW, which is on the leeward side of the Cascade Range in the western United States, experiences most of the extreme floods in the months from January through April (Fig. 5). As the objective of this study was to simulate the 1996/1997 flood event, the calibration could be done for this period only. The model was calibrated and verified using 6 months of flow data. The model was calibrated and validated for the periods of October 15, 1996 to January 15, 1997 and January 16, 1997 to April 15, 1997, respectively. The rainfall data used for calibration is from RAMS. The reason for this was to avoid any uncertainty incurred by the RAMS model while comparing scenario-simulated flow results. That is, because the hydrological model is calibrated using RAMS, all flow comparisons will be relative, and the difference between actual rainfall and simulated rainfall will not be carried. Woldemichael et al. (2014) gives a detailed result and discussion of the RAMS simulated rainfalls that are used in this study. A Nash-Sutcliffe efficiency of 0.71 and 0.55, correlation coefficient of 0.92 and 0.87, and volume ration of 0.5 and 0.9 were obtained for calibration and verification, respectively. The model performance was evaluated



F5:1 **Fig. 5.** (a) Calibration and verification using the USGS station near Rome (USGS #13181000); (b) annual peak flow at the same USGS station

Table 1. Model Performance Metrics Values for Calibration and Verification

Metric	Calibration	Verification
Correlation coefficient	0.92	0.87
Nash-Sutcliffe efficiency	0.71	0.55
E_{RMS}	63	36
RSR	0.56	0.67
Residual mean	−37	−8
R^2	0.85	0.76
Volume ratio	0.50	0.90

Table 2. Maximum Daily Precipitation (mm) over Owyhee River Watershed between December 21, 1996, and January 10, 1997

LULC scenario	Normal case	Moisture maximized/PMP case
Pre-dam	23.86	38.38
Nonirrigation	24.76	39.97
Control	28.18	41.10

using the metrics Nash-Sutcliffe efficiency, coefficient of determination (R^2), correlation coefficient and root-mean squared error (E_{RMS})-observation standard deviation ratio (RSR) (Moriasi et al. 2007; Krause et al. 2005; Benaman et al. 2005). Table 1 summarizes results of other metrics used, and Fig. 5 shows the plot between simulated and measured flows.

Based on the calibrated setup, six flow scenarios were simulated using three normal and three extreme precipitation events (considered probable maximum precipitation) that correspond to different LULC-atmosphere interactions used in Woldemichael et al. (2013). [24] PMP results from Woldemichael et al. (2013) were for the period from December 21, 1996, to January 10, 1997. The LULC scenarios [25] were divided into three: pre-dam (LULC corresponding to the period before Owyhee Dam was built); control (post-dam LULC, which also represents the current condition); and nonirrigation (a control LULC scenario in which no irrigation is practiced). The comparison of results was done at a location upstream of Owyhee Reservoir, which represents the reservoir inflow.

Because there is no measured sediment data, which was a challenge in calibrating soil loss and hence sediment loss, an attempt was made to transfer the sediment-discharge relationship of neighboring and downstream USGS stations to Owyhee River Watershed (ORW) that are found in Oregon. The basis for the transfer was discharge correlation between stations. Data from ten USGS suspended sediment stations (http://co.water.usgs.gov/sediment/bias [26] .frame.html) were used to formulate a power sediment-discharge relationship. Parameters (coefficient and power) were estimated for the selected stations together with a discharge correlation against the calibrating station in ORW (Rome, Oregon). The problem with this process was that the sediment data are for a short period and are very old. The record year extends from 1958 to 1980 with the longest data available being for 9 years (1962–1970), and the shortest available data was for 2 years. With the assumption of a similar land practice in these stations, sediment volume at the inflow location to Owyhee Reservoir were calculated for the specific study period. The estimation from this power relationship showed highly overestimated values. Arguably, this overestimation is a result of complex process (e.g., topography, hydrology, and LULC) that varies from watershed to watershed and an unrepresentative data set (short and old). Hence, this paper bases its sediment loss result accuracy on that the soil erodibility and erosivity factors of the RUSLE model are calibrated values supported by a distributed crop management factor.

Result Discussion

LULC Change and Reservoir Inflow

Using the calibrated model, streamflow was simulated at a station (Fig. 3) that represented inflow into Owyhee Reservoir. There were a total of six flow simulation scenarios using six precipitation values (three using normal precipitation and three more using PMP) [27] from Woldemichael et al. (2013). The 24-h maximum of PMP values used in the simulation are shown in Table 2. Fig. 6 shows the hydrograph of all six scenarios. The immediate observation for both normal and PMF was that there was an increase in flow from the pre-dam period. The peak flow increases for January 3, 1997, are shown in Table 3. For normal flood, the increase in peak flow from the pre-dam scenario to nonirrigation and control were [28] 8 m m^3 s^{-1} and 17 m m^3 s^{-1}, respectively. These increases in terms of flow rate look insignificant compared with the absolute pick discharge of approximately 800 m^3 s^{-1}. However, from the perspective of Owyhee Reservoir, it is not only the peak inflow but also inflow volume over a specific flood event that affects its operation. Table 4 shows the average inflow volume for the different scenarios. For the 21-day flood event, there was an additional 3×10^6 m^3 of water that flows to Owyhee Reservoir between the pre-dam and nonirrigation scenarios. Between the pre-dam and control scenarios, there was an increase of 7×10^6 m^3 inflow volume. The volume increase for the two cases represent 0.4 and 0.9% of the reservoir's active storage, respectively.

When PMP was used, the increase in peak PMF values from pre-dam to nonirrigation and control scenarios were 26 m^3 s^{-1} (1%) and 81 m^3 s^{-1} (3%), respectively. The corresponding increase in the reservoir inflow volume was 12×10^6 m^3 (1%) and 34×10^6 m^3 (3%), respectively. This accounts to 1.46 and 4.15% of the reservoir's active storage, respectively. Comparing the post Owyhee Dam scenarios shows that irrigation practice has increased the normal flood by 9 m^3 s^{-1} and the PMF by 55 m^3 s^{-1}. In terms of inflow volume, the increase translates to 4×10^6 m^3 (0.49% of active reservoir volume) and 22×10^6 m^3 (2.68% of active reservoir volume), respectively.

Two physical reasons were attributed to the flow changes between the scenarios considered. The first reason was the presence of an artificial reservoir after the year 1932 (control scenario). During the pre-dam scenario, there was no large open water surface that could be a source of extra moisture and evaporation. As the artificial reservoir becomes part of the land-atmosphere interaction, the local precipitation pattern definitely changes. The change brings an increase in precipitation amount and its spatial distribution [30] as demonstrated in Woldemichael et al. (2012, 2013). The second reason was the impact LULC change (e.g., irrigation practice, urbanization) has on streamflow. This impact can be direct or indirect. Directly, LULC change affects infiltration and evaporation pertaining to water balance of the watershed (Schilling et al. 2008). When the LULC change occurs outside of a watershed, similar to the case of a downstream irrigation practice that has no direct physical impact on upstream areas, the impact on streamflow will be indirect. Meteorological variables affected by the irrigation practice extend spatially beyond its boundary (Yigzaw et al. 2013a). That means change to precipitation patter due to evaporation and energy balance alteration as a result of crop lands will affect the flow pattern in adjacent areas (upstream watersheds for impounded areas).

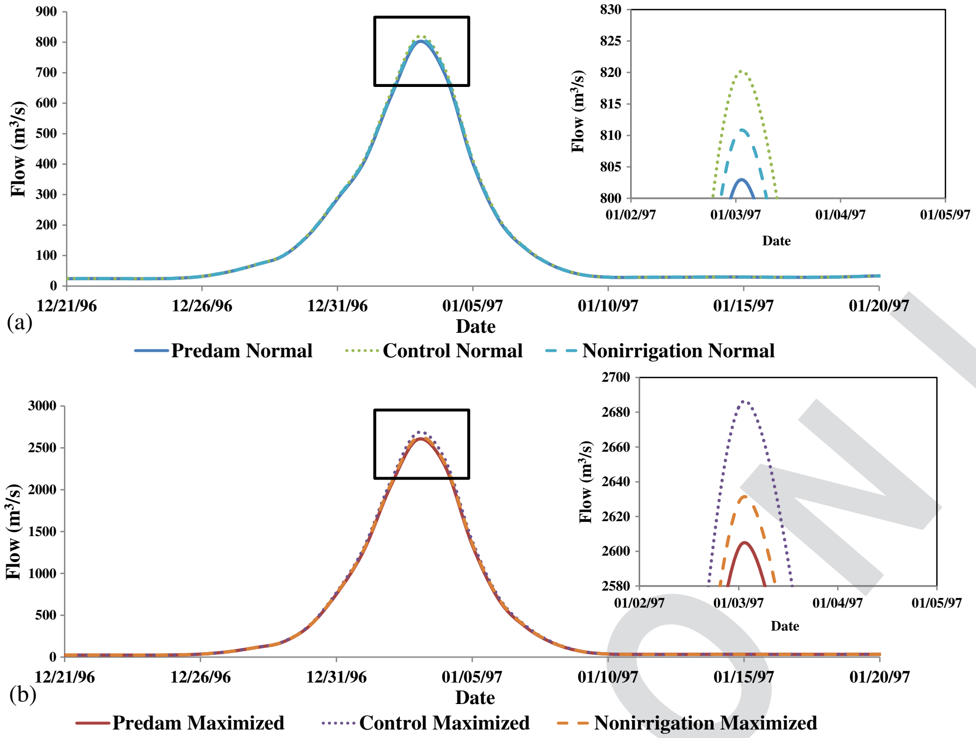


Fig. 6. Simulated inflow into the Owyhee Reservoir for the period from December 21, 1996 to January 10, 1997: (a) normal; (b) PMP

[29] **Table 3.** Simulated Peak Flood Using Normal Precipitation and PMP over Owyhee River Watershed during the Flood Event between December 21, 1996, and January 10, 1997

Flood type	Pre-dam	Nonirrigation	Control
Normal flood ($m^3\,s^{-1}$)	802	810	819
PMF ($m^3\,s^{-1}$)	2,602	2,628	2,683

Table 4. Simulated Volume Inflow into Owyhee Reservoir for the Period between December 21, 1996, and January 10, 1997

Flood type	Pre-dam	Nonirrigation	Control
Normal volume (mm^3)	365	368	372
PMF volume (mm^3)	1,076	1,088	1,110

LULC Change and Sediment Yield

The soil erodibility (k) extracted from the NRCS database and the calculated slope-length (ls) factors for ORW are shown in Fig. 7. Constant values of k and ls factor were used for the selected LULC scenarios. However, the cover management factor (c), which represented the LULC change, was assigned to four of the scenarios [31] selected (pre-dam, USGS's NLCD-1992, 2001, and 2006). The pre-dam scenario c factor (Fig. 8) was dominated by the grassland coverage, which accounted for 96% of the watershed. As the LULC evolved to the year 1992 and beyond, the dominant LULC became shrub land. Table 5 shows the compiled LULC area percentage for the four scenarios. Because grassland has a higher c value than shrub land, the dominant value over ORW decreases from pre- [32] dam to NLCD 2006 as shown in Fig. 8. Results of precipitation erosivity calculated using hourly precipitation are shown in Fig. 9. Eq. (6) shows higher precipitation intensity will give higher erosivity. PMP-based precipitation intensity gives a high erosivity factor compared with normal precipitation intensity. Erosivity also has a dependency on seasonality (wet or dry) (Millward and Mersey 1999).

After individual factors have been obtained, soil loss was calculated over ORW grid by grid with a spatial resolution of approximately 3×3 km. The total duration of the storm was 21 days, meaning that the soil loss shown in the table is only for 21 days. The spatial mean soil loss is shown in Table 6. Mean soil loss decreased from pre-dam to control scenarios for both normal precipitation and PMP. The total soil loss over ORW is more informative than the mean values. Qualitative results from Figs. 10 and 11 show soil loss results for actual precipitation and PMP, respectively. The soil loss results from PMP were intended to represent a possible increase in sediment yield from extreme storm events. For actual precipitation, soil loss in the pre-dam scenario mostly ranged between 0 and 34 ($t \cdot ha^{-1}$). Most soil loss after the construction period of Owyhee Dam (specifically 1992, 2001, and 2006) dramatically decreased to a value of 0–3($t \cdot ha^{-1}$). As illustrated in Table 5, the reason for such temporal discrepancy in soil loss was due to LULC changing greatly from grassland to shrub land. Although the decreasing trend remains the same, soil loss as a result of PMP is much higher. The majority of the area had a soil loss of 0–145($t \cdot ha^{-1}$) for the pre-dam scenario, whereas for the post-dam period scenarios, the range remained the same at 0–3($t \cdot ha^{-1}$).

To understand the significance of LULC change on sediment yield, this study used precipitation simulated from different LULC scenario and calculated the corresponding soil loss. This gave a soil loss result to pre-dam precipitation-LULC (pre-pre-normal and pre-pre-maximized), nonirrigation precipitation-LULC and control precipitation-LULC. Results for nonirrigation and control each had three sets: one for the year 1992 (control-92-normal/maximized, nonirrigation-92-normal/maximized), one for 2001 (control-01-normal/maximized, nonirrigation-01-normal/maximized), and the other for 2006 (control-06- normal/maximized, nonirrigation-06-normal/maximized). This gave the opportunity to see sediment

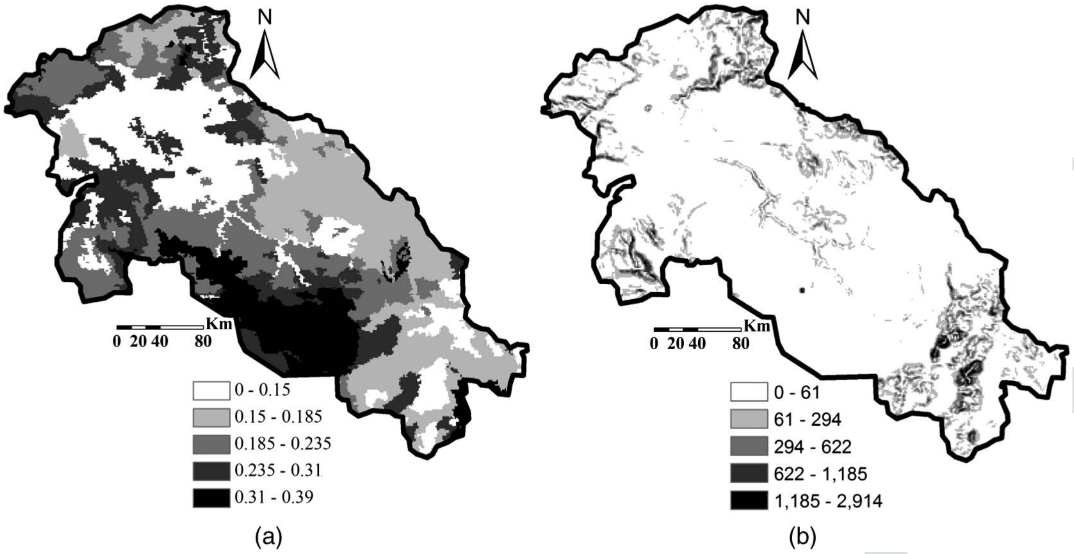


Fig. 7. (a) Erodibility (*k*) factor and (b) calculated ls values using the expression in Goldman et al. (1986) for the Owyhee River watershed

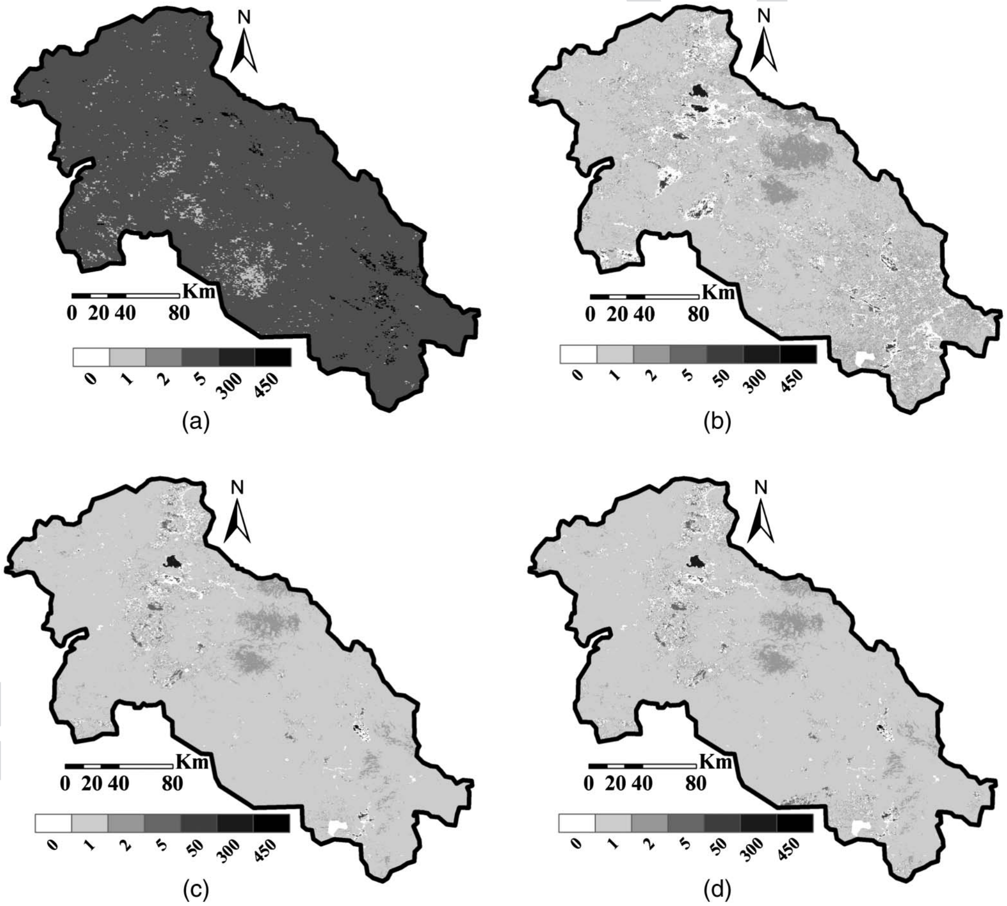


Fig. 8. (a) Cover and management c factor assigned to LULC of the pre-dam period; (b) 1992; (c) 2001; (d) 2006

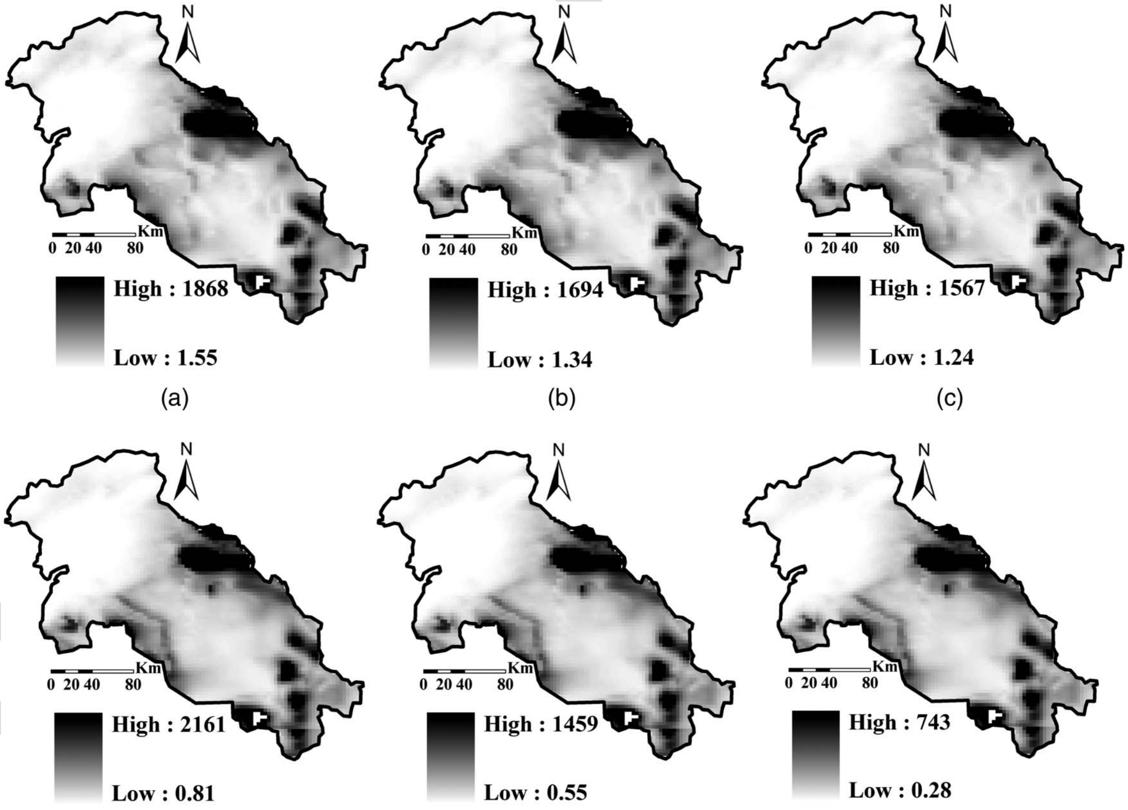
yield from the aspect of precipitation intensity and LULC change independently. Table 7 shows the total soil loss, which is a result of a 21-day storm using such combination. Again, the same storm was used for the different LULC scenarios considered.

Soil loss using pre-dam normal precipitation and pre-dam LULC (pre-pre-normal) had a total of 34.69×10^6 tons. For PMP (pre-pre-maximized), this value increased to 42.79×10^6 tons. The increase, which was approximately 25%, was merely a result of an increase in precipitation intensity. In the post-dam period, the nonirrigation precipitation had higher soil loss than that of the control precipitation. Soil loss (in 10^6 t) from nonirrigation was higher by 1.1 (for the 1992 LULC), 0.76 (for the 2001 LULC), and 0.81 (for

Table 5. Land Cover Class Percentage for Different Scenarios

	HYDE (%)	USGS NLCD (%)		
Description	Pre-Dam	NLCD 1992	NLCD 2001	NLCD 2006
Open water	0.02	0.32	0.27	0.26
Developed, open space	—	—	0.20	0.20
Developed, low intensity	—	0.00	0.05	0.05
Developed, high intensity	—	0.07	0.00	0.00
Urban and built-up	0.01	—	—	—
Barren land (rock/sand/clay)	0.06	0.62	0.39	0.40
Deciduous forest	—	0.27	0.30	0.31
Deciduous needleleaf forest	0.04	—	—	—
Evergreen needleleaf forest	0.05	—	—	—
Evergreen forest	—	2.96	1.90	1.90
Mixed forest	0.01	0.00	0.00	0.00
Shrub/scrub	0.07	83.33	92.24	91.48
Open shrub land	2.73	—	—	—
Grassland/herbaceous	94.60	9.46	3.47	4.16
Pasture/hay	—	2.43	0.40	0.41
Savannas	0.16	—	—	—
Woody savannas	1.33	—	—	—
Cultivated crops	0.91	0.01	0.16	0.16
Small grains	—	0.05	—	—
Woody wetlands	—	0.11	0.43	0.43
Emergent herbaceous wetlands	—	0.34	0.20	0.25
Total	100	100	100	100

the 2003 LULC) for normal precipitation. The higher values were possibly a result of the difference in spatial distribution of nonirrigation and control precipitation. Although control precipitation was higher as shown in Table 2, its spatial distribution did not guarantee a higher erosivity and soil loss because a combination with other spatial factors like LULC can give a different result. When soil loss was calculated using nonirrigation PMP values, there was an increase of approximately 25 (1992), 16 (2001), and 15% (2006)



(a) (b) (c)

(d) (e) (f)

Fig. 9. Erosivity (r) factor calculated over Owyhee River watershed using hourly precipitation intensity from December 21, 1996, to January 10, 1997; normal precipitation: (a) pre-dam period; (b) nonirrigation; (c) control; PMP: (d) pre-dam period; (e) nonirrigation; (f) control

Table 6. Average Soil Loss (t/ha) Summary Calculated for Combination of Different LULC and Precipitation Scenarios Using the Storm for the Period of December 21, 1996, to January 10, 1997

	Precipitation scenario					
	Normal			PMP		
LULC scenario	Pre-dam	Nonirrigation	Control	Pre-dam	Nonirrigation	Control
Pre-Dam	11.99	—	—	14.78	—	—
NLCD_1992	—	0.78	0.40	—	—	—
NLCD_2001	—	0.53	0.27	—	0.62	0.56
NLCD_2006	—	0.57	0.29	—	0.66	0.60

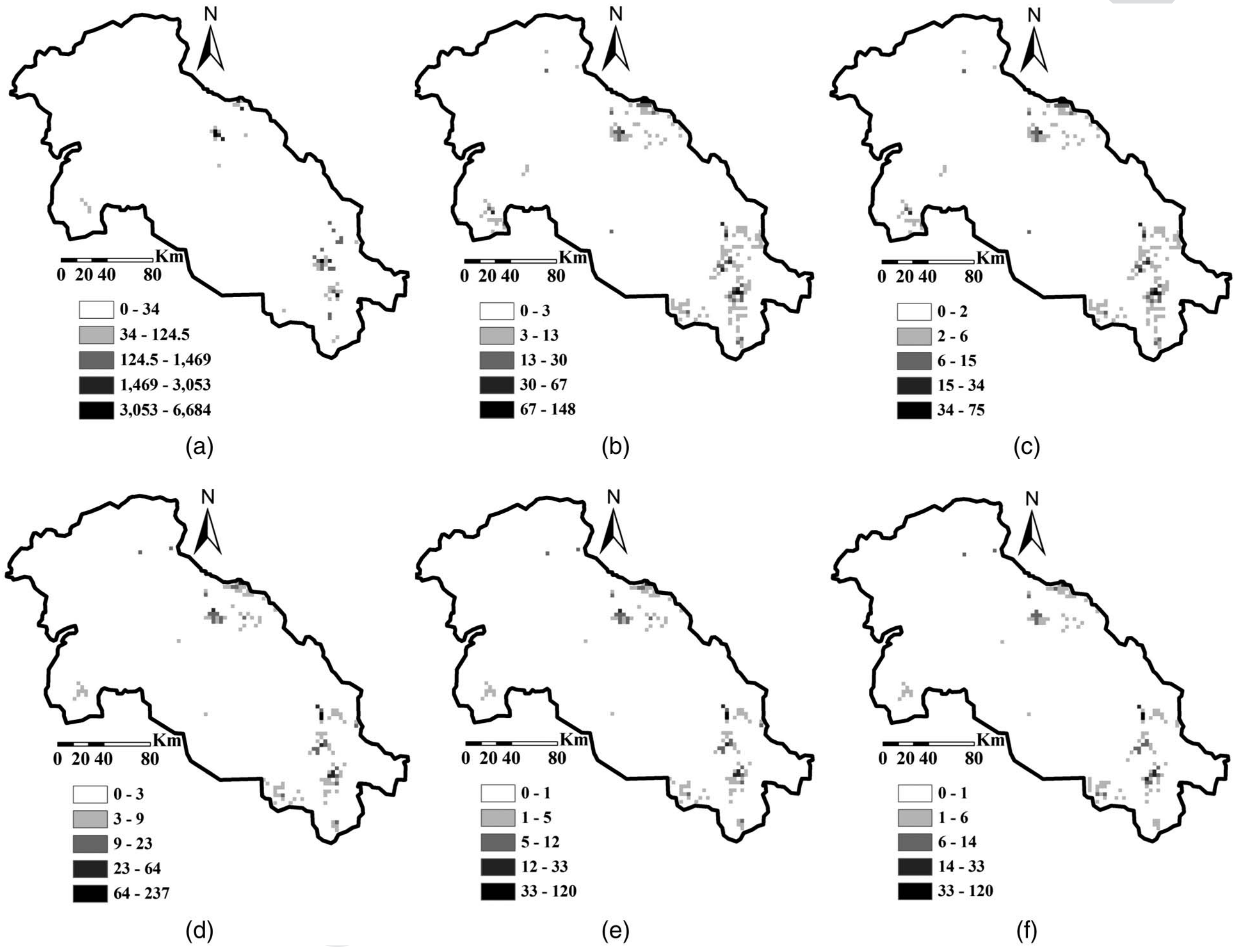
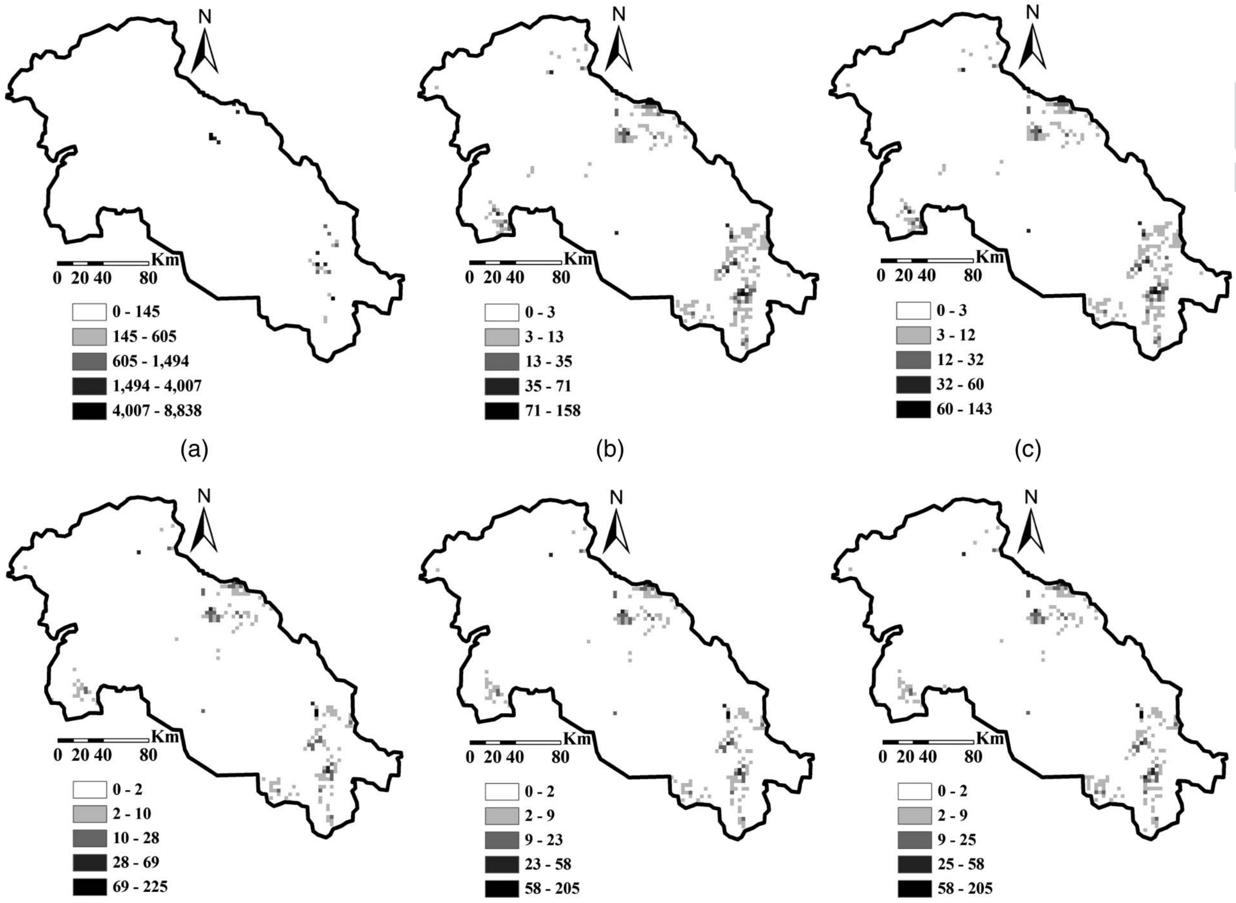


Fig. 10. Soil loss ($t \cdot ha^{-1}$) over Owyhee River watershed for the period from December 21, 1996, to January 10, 1997, using normal precipitation: (a) pre-pre-normal; (b) nonirrigation-92-normal; (c) control-92-normal; (d) nonirrigation-01-normal; (e) control-01-normal; (f) control-06-normal

from normal precipitation condition. However, for control PMP, the increase was significantly higher with values of 120 (1992), 109 (2001), and 107% (2006). The same argument of change in precipitation intensity and LULC from grassland to shrub land, forest, and few urbanized area apply in this case for a decrease in soil loss from year 1992 to 2006.

Because the control scenario represented the LULC between 2001 and 2006, the significant increase in soil loss could represent a potential problem for Owyhee Reservoir. A study by Owyhee Watershed Council (2001) on the upper Owyhee Watershed found that sediment yield from some areas accounts for 25% of the soil loss. A similar trend can be applied, and the total sediment yield calculated for ORW. That is, from Table 7, the control precipitation and 2006 LULC scenario could cause a sediment yield of 0.21×10^6 and 0.43×10^6 t for normal precipitation and PMP, respectively.

The final result of the sediment yield needed to be transported through the channel system (Owyhee River) to the Owyhee Reservoir and then converted into volume to understand the storage significance. Sediment transport was beyond the methodology of this study. No sediment-load measuring station was available inside ORW to establish a discharge-sediment load relationship. The attempts made to quantify the sediment yield from RUSLE were based on basic assumptions using previous studies on ORW. Soil density over ORW ranges from 1,200 to 1,400 kg/m^3 (USBR 1994). It was assumed that the entire sediment yield was transported to Owyhee Reservoir, with a sediment bulk density of 1,600 kg/m^3,



(a) (b) (c)

(d) (e) (f)

Fig. 11. Soil loss (t · ha^{-1}) over Owyhee River watershed for the period from December 21, 1996, to January 10, 1997, using PMP: (a) pre-pre-maximized; (b) nonirrigation-92-maximized; (c) control-92-maximized; (d) nonirrigation-01-maximized; (e) control-01-maximized; (f) control-06-maximized

Table 7. Total Soil Loss (10^6 t) Summary Calculated for Combination of Different LULC and Precipitation Scenarios Using the Storm for the Period of December 21, 1996, to January 10, 1997

	Precipitation scenario					
	Normal			PMP		
LULC scenario	Pre-dam	Nonirrigation	Control	Pre-dam	Nonirrigation	Control
Pre-dam	34.69	—	—	42.79	—	—
NLCD_1992	—	2.24	1.14	—	2.76	2.51
NLCD_2001	—	1.54	0.78	—	1.79	1.63
NLCD_2006	—	1.64	0.83	—	1.89	1.72

Table 8. Total Sediment Volume (10^6 m^3) Calculated for Combination of Different LULC and Precipitation Scenarios Using the Storm for the Period of December 21, 1996, to January 10, 1997

	Precipitation scenario					
	Normal			PMP		
LULC scenario	Pre-dam	Nonirrigation	Control	Pre-dam	Nonirrigation	Control
Pre-dam	21.68	—	—	26.75	—	—
NLCD_1992	—	1.40	0.71	—	1.73	1.57
NLCD_2001	—	0.96	0.49	—	1.12	1.02
NLCD_2006	—	1.03	0.52	—	1.18	1.07

the total sediment volume becomes as shown in Table 8. For example, for the control precipitation and 2006 LULC, the sediment volume increased from 0.52 to 1.07×10^6 m^3 when PMP was considered. This increase accounted for 0.1% of Owyhee Reservoir's dead storage for 100% trap efficiency. The decrease in sediment yield from pre-dam to control scenario was 3.62 and 4.34% of Owyhee Reservoir for normal and maximized precipitation, respectively. If only a 21-day heavy storm event caused such an increase, then over multiple years, a higher storage loss as a result of sedimentation can be expected. The majority of the storms that caused high flood in Owyhee River occurred after the construction of Owyhee Dam. As shown in Fig. 5, there are recurring flood events that are close to the magnitude of the 1996/1997 event. For example, 54 events have occurred since 1950 that have registered the historic river level rise as registered by National Oceanic and Atmospheric Administration (NOAA; http://www.water.weather.gov). This means the sediment yield estimated in this paper can be anticipated to occur with a frequency that can lead to a storage loss faster than previously expected. The life expectancy of Owyhee Reservoir can definitely be affected from such storage loss, which is in the range of 0.1% for only a 21-day storm event.

Conclusion

The objective of this study was to understand the impact of artificial reservoir and LULC change on extreme floods and watershed sediment yield from the aspect of reservoir storage. Construction of a dam leading to creation of an artificial reservoir increases normal and extreme flood events. In addition to peak flow increase, the volume of water flowing into Owyhee Reservoir is also a considerable amount, especially for PMF case. LULC change in the form of irrigation practice has a significant impact on flood and precipitation over ORW. The LULC change impact observed over ORW for the nonirrigation scenario is interesting in that the irrigation practice considered is downstream of Owyhee Reservoir. This asserts the idea that artificial reservoirs and LULC change impact local climate.

Sediment yield change over ORW is also significant as a result of precipitation and LULC change. Because it is already shown that LULC change affects precipitation pattern, ultimately it can be stated that LULC is the governing factor in increasing reservoir inflow, and hence sedimentation (for both upstream and downstream LULC change). However, sedimentation is more affected by the increase in precipitation intensity (owing to the power relationship between sediment yield and discharge) than LULC change because the later evolves steadily in upstream areas. There are some limitations to the results shown in this study. Soil loss calculation, PMP, and PMF will be greatly affected by the grid resolution. As the grid resolution increases, the intensity of the rainfall will be more distributed increasing the soil loss from a given area. The fact that there is a power relationship between intensity and soil loss makes the impact of grid resolution high in terms of the final result. However, the impact of grid resolution on is less as compared to soil loss. One storm event is used in this paper for three different LULC scenarios. However, a specific storm simulated using the corresponding LULC can give a better understanding into the case study considered. The assumptions used in terms of sediment density can be strengthened if there were any sediment analyses and measurements over ORW. The availability of sediment measurement can also help in establishing a sediment-discharge relationship.

Given the constant changes in LULC and precipitation pattern, it is necessary to question and perhaps revise the paradigm used in current dams design and operation. A 3% increase in peak flow and a loss of 0.1% reservoir's dead storage in just 21 days is significant enough to prompt a revision of design and operation procedures. For existing dams, a new inflow and sediment load estimation should be carried out. There is encouraging progress from the engineering community that stresses the need to study future climate changes for infrastructure design (NRC 1999). Artificial reservoirs take a major share in energy and food production, water supply in general, and flood protection. With a large number of dams projected to be constructed in developing and economically emerging countries, revisiting design procedure is of great importance for sustainability. Recent focuses are on change in precipitation and streamflows. However, future study should look beyond the change in extreme flow and incorporate sediment yield change as a result of LULC change.

Dams that are already operational can benefit from apparent flow and sedimentation changes by modifying their spillway capacity and operation procedure. This is especially true for aging dams that account for a large number of the total. The two important parameters, inflow design flood and sediment inflow, that are crucial for dam design are well discussed by considering artificial reservoir and LULC change. The results presented in this study are a very good indication of the significant impact change in precipitation intensity has on sediment yield from the perspective of an impounded watershed. The results also emphasize the need for change in the conventional dam design giving possible layout procedures that can be used in the process.

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