Hydro-geomorphic assessment of erosion intensity and sediment yield initiated debris-flow hazards at Wadi Dahab Watershed, Egypt

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Abstract- This study is an attempt to assess slope and channel erosion for modeling their implications on debris-flow occurrences in Wadi Dahab watershed (WDW). Remote sensing and Geographic Information System (GIS) were integrated to appraise erosion rates from a hillslope and channel storage throughout WDW. A mass-wasting database was built initially for modeling hazard zones and validating the final map using a bivariate statistical analysis. An Erosion Hazard Model (EHM) was developed to evaluate the erosion intensity and sediment yield throughout WDW and to prognosis the hazard zones due to debris-flows. The EHM was developed based on hydrological and geomorphic controls which are responsible of disintegrating bedrocks, delivering detritus downslopes, and accelerating debris through channels. Multi-source datasets including topographic and geologic maps, climatic, satellite images, aerial photographs, and field-based datasets, were used to derive factors associated with the hydro-geomorphic processes. A spatial prediction of erosion intensity was obtained by the integration of both static and dynamic factors generated hazards in GIS platform. The erosion intensity map classifies WDW relatively to five intensity zones in which the most hazardous zones are distributed in steep-sloping terrains and structurally controlled channels covered by metamorphic and clastic rocks. The erosion intensity map was correlated and tested against the debris-flows dataset which was not used during the spatial modeling process. The statistical correlation analysis has confirmed that the debris-flow locations increase exponentially in the highly erosion intensity zones. The holistic integration approach provides the promising model for forecasting critical zones prone erosion intensity and their associated hazards in WDW.

Keywords: Erosion intensity; Sediment yield; Debris-flow hazards; Remote sensing; Geographic Information System (GIS); Wadi Dahab watershed (WDW).

1. Introduction

Soil represents the vital natural resource that supports crucial ecosystem functions (Kouli et al. 2009), and provides several crucial environmental resources (Alexakis et al. 2013). Soil erosion represents the critical environmental hazard causing land degradation and threatening infrastructure, possessions, and lives of local inhabitants; especially in the mountainous regions. Impacts of soil erosion on ecosystem attract concern for researchers from all over the world (Bouaziz et al. 2011; Pradhan et al. 2012; Pal and Chakrabortty 2019a; Saha et al. 2020). A large amount of quantitative data at global scales are required to evaluate the socio-economic implications of soil erosion (Devatha et al. 2015). The spatial prognosis of erosion potential is a necessary task in mountainous areas to avoid the catastrophic impacts (Abuzied et al. 2016c). A worldwide study considered the assessment of sediment yield and slope erosion potential to expand management policy (Pradhan et al. 2012; Alexakis et al. 2013; Devatha et al. 2015; Pal and Shit 2017; Pal and Chakrabortty 2019b). Since the last decades, the policy-makers focus on Sinai Peninsula, Egypt (Fig. 1) to support its economic development (Abuzied 2016; Abuzied et al. 2016 a, b, and d; Abuzied and Alrefaee 2017). WDW exemplifies one of the risky areas in the Sinai Peninsula due to slope and channel erosion, mass-wasting, and flash floods (Abuzied and Mansour 2019). Wadi Dahab was investigated as a strategic location for management and development plans in many studies (Selmi and Abdel-Raouf 2013; Abuzied and Mansour 2019). WDW is mainly steep topography, with hilly areas, and lowland areas which are already developed (Abuzied and Mansour 2019). Dahab represents attractive tourist Egyptian city holding a relatively large population. Recently, the development efforts of economic sectors have been increased, causing greater urbanization. Hence, the evaluation of erosion intensity and its related hazards in WDW is particularly significant due to the socio-economic impacts and population growth.

Generally, the natural factors; especially the weather factor, are extremely erosive in semi-arid and arid provinces. The geomorphological processes such as erosion by rain splash and surface runoff are widely distributed in mountainous environments (Lim and Lee 1992; Pradhan 2010; Abuzied et al. 2016c). Rainfall is believed one of the most serious factors initiating soil erosion in WDW (Abuzied and Mansour 2019). The high intensity of rainfall within short durations is the main cause for soil loss leading to shallow landslides/debris-flows (Abuzied et al. 2016a). Therefore, the erosivity of rain and runoff are responsible for failing slopes and eventually inducing mass-movements such as debris-flows, rock-slides, and rock-falls (Brunsde and Prior 1984; Lim and Lee 1992; Straub and Schubert 2008; Abuzied and Alrefaee 2018). The slope erosion and sediment yield in Wadi Dahab basin increase the disastrous impacts of debris-flows. In addition to the weather factor, unpaved roads built by the Bedouin community to improve accessibility, contribute as another factor in exposing steep slopes to erosion resulting several environmental hazards such as flash floods and shallow landslides/debris-flows (Abuzied and Mansour 2019). All these activities have contributed mainly to the destruction of exposed steep slopes leading to erosion. Hence, erosion intensity is considered as the fundamental reason initiating shallow slope failure in Wadi Dahab; and its control becomes crucial to avoid catastrophic impacts of debris-flows. The debris-flow hazards can be reduced by controlling the responsible factors which are triggered by fluvial erosion such as rainfall intensity and surface runoff. Therefore, the geospatial mapping of erosion intensity zones is required to predict the sensitivity of hazard occurrences due to debris-flows.

GIS is a powerful technique to incorporate multi-datasets and evaluate any active environment exposing to soil erosion (Pradhan et al. 2012). Several studies have been achieved by different methods to assess soil erosion and sediment yield using GIS (Adinarayana et al. 1999; Millward and Mersey 1999, 2001; Mati et al. 2000; Renschler and Harbor 2002; Bissonnais et al. 2002; Beatriz et al. 2002). These studies vary from rule-based systems to empirical process-based systems (Huffman et al. 2000; Martínez-Casasnovas et al. 2002; Lee 2004). Universal Soil Loss Equation (USLE) model was used in hilly watersheds due to its ease of estimating parameters (Pandey et al. 2007; Pradhan et al. 2012; Devatha et al. 2015). However, The USLE model was applied in several studies to evaluate erosion from sheet and rill throughout watersheds (Jain and Das 2010; Pal and Shit 2017; Saha et al. 2020). Therefore, several modifications were recommended to improve the compatibility of USLE in different circumstances (Safamanesh et al. 2016). These modifications were suggested new approaches including Revised Universal Soil Loss Equation (RUSLE), Modified Universal Soil Loss Equation (MUSLE), Food and Agriculture Organization (FAO). Pacific Southwest Inter Agency Committee (PSIAC), Modified PSIAC (MPSIAC), and Erosion Potential Method (EPM) (Alijani et al. 2016).

The assessment of sediment yield in ungauged Wadi Dahab basin is challenging work but it is necessary to reduce the impacts of flash flooding and debris flowing. The Pacific Southwest Inter Agency Committee (PSIAC) model is the semi-quantitative model which considers the effect of many sediment sources and sinks (Johnson and Gebhardt 1982; Verstraeten et al. 2003; de Vente et al. 2005). The PSIAC was modified to MPSIAC and applied effectively in several studies to analyze erosion rates in arid and semi-arid regions (Ownegh and Nohtani 2004; Bagherzadeh and Daneshvar 2011). The PSIAC and MPSIAC models can evaluate successfully erosion hazards in the case of the systems complication and process interaction with limited data (Tangestani 2006; Garg and Jothiprakash 2012; Ndomba 2013). The models were built based on nine factors including rainfall, runoff, topography, geology, soil types, land use, vegetation cover, upland erosion, and channel erosion (Abdullah et al. 2017).The MPSIAC model considers and integrates several drainage basin characteristics to assess erosion sensitivity and sediment transport (Safamanesh et al 2006; Najm et al. 2013; Noori et al 2016; Noori et al. 2018). Therefore, the rating scheme of MPSIAC factors has been selected in the current study using GIS environment to evaluate the erosion intensity and its associated hazards due to debris-flows in WDW.

The integration of remote sensing (RS) and GIS approach facilitate the prediction of erosion potential and related hazards with better accuracy and reasonable costs (Tangestani 2006; Rahman et al. 2009; Saha et al. 2020). Several GIS models have been applied for evaluating erosion hazards in different areas around the world (Saha et al. 2005; Dahal et al. 2008; Kanungo et al. 2009; Gemitzi et al. 2011; Bayraktarli et al. 2011; Abuzied and Mansour 2019). The bivariate statistical analysis is the simplest GIS statistical model where the distribution analysis defines hazard locations from different data sources, and hence suggests information on the relation between hazards and their causative factors (Abuzied and Alrefaee 2018). The bivariate statistical analysis includes several methods such as frequency ratio (FR) method, Information value (IV) method (Westen 1997), nominal risk factor (NRF) method (Gupta and Joshi 1990), weights-of-evidence (WoE), and logistic regression (Yin and Yan 1988; Bughi et al. 1996; Saha et al. 2005). The bivariate statistical analysis is the logical analytical model where the defined hazard locations contribute to adopt the numerical weights and ranks (Abuzied and Alrefaee 2018). Therefore, the NRF method was used in this study to assign representative weights for the classes of contributing factors which were selected as essential causes for upland and channel erosion. Furthermore, the FR method was applied to evaluate the competence of EHM by determining statistical relationships between hazard zones in the erosion intensity map and the spatial distribution of hazard locations in the mass-wasting inventory map.

It is clear that no consistent or economically feasible efforts have been paid for measuring erosion intensity or delineate its related hazards in WDW. There is a rising locally demand for expecting erosion potential and delineating the geographical distribution of its associated hazards to prepare suitable technical plans for the management. Both hillslopes and channels represent different sources producing large amount of sediments which can hypothetically be transported into streams network producing debris-flows. Hence, this study adds the promising model to evaluate the erosion intensity rate from the hillslope and channel system, and estimate the sediment yield caused debris-flow hazards in WDW.

2. Study area

WDW lies between the southeastern corner of Sinai Peninsula and the southwestern coast of Gulf of Aqaba (Fig. 1). Dahab city is situated on an alluvial fan comprising of deposited alluvium and debris flow deposits which accumulated due to a sudden change in Wadi Dahab gradient when it exists from a mountain range. WDW covers 2080 km^2 and occupies the area between latitude 28^{O} $22^{\backslash}$ $43.4^{\backslash\backslash}$ and 28^{O} $52^{\backslash}$ $18.5^{\backslash\backslash}$ N and longitude 33^{O} $55^{\backslash}$ $46.9^{\backslash\backslash}$ and 34^{O} $31^{\backslash}$ $28.8^{\backslash\backslash}$ E (Fig. 1). The topography in the study area varies from steep to gentle terrains, sloping towards the Gulf of Aqaba. The relief of WDW differs from low terrains to high impassable mountains ranging from 100 to 2527 m respectively (Fig. 1). Different cycles of alluviation shaped the existing streams during rainy periods and Quaternary times (Gilboa 1980). There are numerous active wadis appear as detached drainage networks flowing through the study area such as Wadi Saal, Wadi Nasb, Wadi Abu khasheib, and Wadi Zaghraa. These active wadis are responsible mainly about a formidable quantities of flash floods in Wadi Dahab (Abuzied and Mansour 2019). Their main tributaries contribute essentially in the erosional processes occurred in the southwestern coast of Gulf of Aqaba due to the seasonal floods fed regularly the existing wadis (Abuzied and Mansour 2019).

WDW is characterized by an arid climate in which high rainfall intensity during winters, high temperature and high evaporation rate during summers. The highest temperature in the study area may reach 37°C, while the lowest temperature is recorded at −3°C in the high regions such as Saint Catherine (Abuzied and Mansour 2019). The rainfall rises in the western side of WDW where the average yearly rainfall is recorded about 64 mm and reach up to 76 mm/day during storm events (Fig. 2). Infrequently, the rainfall may exist as snow on the peaks of existing mountains. The runoff hazards take occur seasonally in Wadi Dahab because of convective rains (Dayan and Abramski 1983). The western hydrographical watersheds represent the main source of catastrophic flash floods and debris flows in Wadi Dahab because their steep sloping streams flow from the high terrains where the highest amounts of precipitation exist to eastern lowlands (Figs. 1 & 2). Numerous flash flood hazards happened in Wadi Dahab basin in the past years but the most vicious one happened in 1994 (Abuzied and Mansour 2019). During this event, the water level at the channel outlet elevated to more than 2.5 m causing great destruction in infrastructure and property (WRRI 2006).

The geological characteristics of Wadi Dahab was considered as a part of the Precambrian Arabian-Nubian shield distributed from southern side of Sinai Peninsula to western side of Saudi Arabia. Several lithological units subsist in the study area with different weathering rates (Fig. 3). The lithological units could be classified chronologically to recent and quaternary deposits, sedimentary succession, and Precambrian basement rocks (Said 1962; Abuzied and Mansour 2019). The recent and quaternary deposits occupy the main wadis of the study area. These wadis play chief role for creating alluvial fans when the stream suddenly decreases its velocity (Fig. 3). The recent and quaternary deposits cover approximately 17% of the total area of WDW shaping wadis deposits, terraces, and alluvial fans. The sedimentary succession occupies approximately 13% of the total area of WDW representing the age from upper Cretaceous to Cambrian. The Precambrian basement units of Sinai Peninsula include primarily metamorphic and igneous rocks. The metamorphic rock exist in 7% of WDW while, the igneous rocks exist in 63% of Wadi Dahab watershed (Fig. 3). Precambrian basement units represent mainly deeply weathered rocks covering the steep hills as fragmented blocks vulnerable to transport. The steep sloping lands accelerate these weathering fragments into the main wadis when the shear strength lessens. Structurally, WDW is essentially affected by red Sea rifting which takes NW-SE and NE-SW trends (Fig. 3). The NW-SE faults follow the direction of Gulf of Suez fault, which controls mainly the faults at Wadi Ghaieb and Wadi Nasb. The NE-SW trending faults represent the major existence which follows the direction of Gulf of Aqaba fault (Said 1962).

3. Data and Methods

WDW is particularly susceptible to several hazards due to the accumulative impacts of its natural environment aspects. Hence, the integrated technique was achieved to evaluate the impacts of hillslope and channel erosion on debris-flows initiation considering hydrological, geomorphological, geological and topographical characteristics. The evaluation workflow was summarized in figure (4) which displays the datasets identified from the following multi-source:

1. Climate data including precipitation and temperature, were collected from eight Egyptian stations according to General Meteorological Authority (GMA) from 1990 to 2016 to derive hydrological factors such as a rainfall isoheyt map (Fig. 2) and to evaluate climate effects on runoff and erosion intensity in WDW. The GMA stations include El-Tur, Nuweiba, Dahab, Sharm El-Sheikh, Saint Catherine, Nekhel, Abu Rudeis, and Ras Sudr stations (Fig. 1).
2. Topographic map (scale of 1:100,000) was used to draw the major stream network. The designed network was performed to attain the extraction of hydrological features using terrain processing analysis. The stream networks was used to prepare some hydrological factors such as distance to drainage and drainage density.
3. Shuttle Radar Topography Mission (SRTM) data with 30 m spatial resolution, contributed to delineate Wadi Dahab watershed and its drainage network. The SRTM was also used to obtain some geomorphological factors such as elevation, slope, aspect, curvature, compound topographic index (CTI), stream power index (SPI), and sediment transport index (STI), through spatial analysis in ArcMap 10.5 (Esri, Redlands, California, United States).
4. Geological map (scale of 1:250,000) was chosen to define the different lithological units and to guide the supervised image classification.
5. Operational Land Imager (OLI) Landsat 8 satellite images (picked up in June 2017) used to determine the different lithological units (Fig. 3) using distinct processing techniques in ENVI 5.4. (Exelis, Boulder, Colorado, United States). The OLI satellite images were also adopted to classify different land uses and soils (Figs. 5 and 6) using Isocluster and maximum likelihood classification methods. Aerial photographs were used to detect the spatial distribution of debris-flows.
6. Field observations using Global Positioning System (GPS) apparatus to detect the multiple erosion zones and debris-flow hazards to validate the erosion intensity map.

3.1 Spatial datasets of EHM

The Erosion Hazard Model (EHM) was developed according to the numerical assessment in which the contributing factors were existed mathematically based on geo-environmental characteristics of WDW. The EHM was established to exhibit an interaction between different geo-environmental conditions including hydrological, geomorphological, geological and environmental characteristics. The model was achieved to evaluate slope and channel erosion by estimating the sediment yield throughout the watershed and predict the hazard zones due to debris-flow. The EHM was created based on nine factors representing the different geo-environmental conditions such as rainfall, runoff, topography, geology, soil types, land use, vegetation cover, upland erosion, and channel erosion. Different weights were assigned to the different classes of each factor using MPSIAC rating process (Johnson and Gebhardt 1982). The upland and channel erosion could be acquired in MPSIAC model based on Bureau of Land Management (BLM) method (Johnson and Gebhardt 1982). However, the upland and channel erosion were achieved for the EHM using different parameters; especially affected in WDW such as aspect, curvature, compound topographic index (CTI), stream power index (SPI), sediment transport index (STI), lineament intensity, drainage density, proximity to faults, and proximity to erosive streams.

The EHM factors could be attained from topographic and geologic maps, meteorological, remote sensed, and field-based datasets (Fig. 4). The EHM factors have different erosion sensitivities, and different possibilities of sediment delivery. Consequently, the highest score has been set to the highest drainage characteristic susceptible to erosion while the lowest score has been set to the lowest drainage characteristic susceptible to erosion. Each factor could be classified into different classes representing different susceptibility impacts. In order to calculate erosion intensity rate, the scores of all factors (S_n) have been summed spatially and expressed by R. The EHM predicts erosion intensity zones as a function of integrating all the nine factors whose ranks could be expressed numerically at a specific location (EQ. 1).

$$R = \sum_{n=1}^{9} S_n \qquad (1)$$

Where R is the total scoring value (m^3/ (km^2Y)) and S_n is the score of each factor n. The scoring value in the EHM has been given from 0 to 150 and classified into five relative categories of erosion intensity. The rate of the sediment yield (Q_s) has been estimated in WDW using equation (2) (Johnson and Gembhart 1982).

$$Q_s = 18.06\, e^{0:0360R} \qquad (2)$$

Where Q_s represents the rate of the sediment yield (m^3/ (km^2Y^{-1})), and R is the estimated erosion rate (m^3/ (km^2Y)). The total sediment amount of the surface area (T_s in m^3/Y) could be estimated as a function of multiplying the rate of sediment yield at each catchment (Q_S in m^3/ (km^2Y) with surface area (A in Km^2) (EQ. 3).

$$T_s = Q_s \times A \qquad (3)$$

3.1.1 Surface Geology factor (S_1)

The surface geology was defined in WDW using several datasets including geological map (scale of 1:250,000), aerial photographs, satellite images and field studies (Abuzied and Mansour 2019). Different methods of digital image processing were applied for that purpose using ENVI 5.4 (Exelis, Boulder, Colorado, United States). Two scenes of OLI Landsat-8 satellite images were pre-processed for lessening the fog influences before applying mosaic and clip tasks. Several techniques of image enhancement were achieved to categorize different lithologies of WDW (Fig. 3). A mixture of enhancement methods was applied in each spectral band to attain the best contrast on lithologies. Visible (VIS), near-infrared (NIR) and infrared (IR) bands were spatially enhanced using image fusion with a panchromatic band (15m). A Hue, Saturation, and Value (HSV) method was selected as a spectral sharping transform to change RGB to HSV coordinates. Furthermore, bands 6, 7, and 4 were enhanced by decorrelation stretch and IHS transformation (Abuzied and Mansour 2019). Principle component analysis

(PCA) and band ratioing (BR) were performed for all bands to select the PC with the most information. A combination of PC3, PC4, and PC5 was formed to evaluate different lithologies. A combination of BR4/3, BR7/3 and BR6/2 was also created and compared with the PCs combination (3, 4, and 5). The BRs combination was selected as the good input to classify WDW lithologies (Abuzied and Mansour 2019). Seventeen classes were produced using maximum likelihood classification (Fig. 3). The geological map was tested and verified using a geological map of EGSMA (Egyptian Geological Survey and Mining Authority 1993). The enhancement processing methods classify the different lithologies in WDW to three main groups including Precambrian igneous rocks, Precambrian metamorphic rocks and Phanerozoic rocks (Abuzied and Mansour 2019).

The surface geology factor was reclassified to different categories with different weights ranged from 0 to 10 based on range of erosion sensitivity (Johnson and Gembhar 1982). The weight values represent the rock resistance to erosion and could be assigned based on different rock characteristics (Table1). These rock characteristics were estimated from several sources such as aerial photographs, satellite images, field studies, and literature review (Said, 1962 Conoco 1982; EGSMA 1993). These characteristics vary from rock to other according to its type, hardness, weathering rate, and lineament intensity (fractures and joints).

3.1.2 Soil factor (S_2)

The soil factor (S_2) could be attained using a soil erodibility factor (K) in RUSLE method (EQ. 4). The erodibility factor is the inherent vulnerability of surface materials to disinterest and transport under specific circumstances. The K-factor could be expressed quantitatively by soil susceptibility to erosion according to the runoff rate for an exact rainfall, estimated under standard theoretical plot (Wischmeier et al. 1971). Therefore, the K-factor represents the reflection of the effect of rainfall erosivity leading to soil loss. The detailed study of soil attributes including the distribution of particle size, the density of eroded soil and the content of organic matter, was achieved to determine reasonable soil erodibility factor (K). The K-factor could be estimated (Table 1) as a function of the percentage of soil structure, soil permeability, and soil texture (Johnson and Gebhardt 1982). The soil types in WDW were classified to five classes varying in their soil characteristics (Table 1) using the OLI8 satellite images based on a mixture of unsupervised and supervised classifications (Fig. 5). A physiographic soil map represents a primary layer to create the K-factor map (Fig. 7).

$$\mathbf{S_2 = 16.67 \times K} \qquad \mathbf{(4)}$$

3.1.3 Rainfall factor (S_3)

The rainfall factor (S_3) could be estimated using the rainfall intensity in long-term, thus 26 years of rainfall record (1990 to 2016) from eight stations, was considered according to Water Resources Research Institute (WRRI) and General Meteorological Authority (GMA) records (Figs. 1, 2 & 8). The rainfall data include average and total annual, annual maximum, monthly maximum, and average monthly rainfall. The maximum rainfall and the storm duration depend on the type and nature of rainy storms which cause catastrophic flash floods at any location in south Sinai (Abuzied and Mansour 2019). The 6-hours of maximum rainfall amount with 2-year return period was used (Johnson and Gembhart 1982) to determine rainfall intensity (P in mm) using IDF curve (Fig. 8). The rainfall factor was assigned rank based on MPSIAC rating model (Table 1), and hence the rainfall factor (S_3) was calculated using equation (5).

$$S_3 = 0.2 \times P \qquad (5)$$

3.1.4 Runoff factor (S_4)

The runoff factor (S_4) could be appraised based on annual runoff depth (Q in mm) and peak discharge (Q_p in m^3/ S) at WDW using equation (6). The runoff potential in WDW (Fig. 9) was evaluated based on several controlling parameters such as flow time (hr), runoff velocity (m/sec), runoff depth (mm), and morphometric index (Abuzied and Mansour 2019). The annual runoff depth was estimated using the NRCS method and the peak discharge at each Wadi Dahab catchment was calculated by dividing the flood peak discharge by its area. The flood peak discharge at WDW was estimated using a Spatially Distributed Unit Hydrograph (SDUH) method (Abuzied and Mansour 2019).

$$S_4 = 0.006Q + 10Q_p \tag{6}$$

3.1.5 Topography factor (S_5)

The topographic factor (S_5) was achieved as a function of average slope (H in %) using equation (7). The slope map could be created using SRTM DEM at 30 m spatial resolution (Fig. 10).

$$S_5 = 0.33 \times H \tag{7}$$

3.1.6 Land cover factor (S_6)

The land cover factor (S_6) acts as a decisive factor leading to severe erosion intensity. However, it represents a readily managed factor to avoid the impacts of slope and channel erosion. Commonly, erosion intensity increases exponentially with scarce vegetation because the vegetation cover intercepts raindrops supporting infiltration rates and avoiding the runoff impacts (Wang et al. 2007; Jiang et al. 2015). WDW is a mountainous region with a rare vegetation cover and a high bare terrain (Table 1). The land use/land cover (LULC) map was prepared in the current study from the classification of land cover using OLI8 satellite images (Fig. 6). The LULC map was derived using Isocluster and maximum likelihood classification methods. The ground control points (GCPs) was defined in the field to guide the supervised classification. The boundaries of the different land cover classes were tested and verified during the field work. The bare terrain could be expressed by (P_b in %) and the land cover factor (S_6) could be calculated based on the percentage ratio of bare terrain at each class of LULC map (EQ.8).

$$S_5 = 0.2 \times P_b \tag{8}$$

3.1.7 Land use factor (S_7)

The land use factor (S7) was used to estimate the effect of vegetation cover on erosion intensity. The land use factor was created based on the percentage of plant canopy at each land use class (P_c) using equations (9, 10 & 11). The percentage of plant canopy (P_c) could be obtained (EQ.10) from the relation with Normalized Difference Vegetation Index (NDVI). The NDVI could be created using remotely sensed data such as LANDSAT satellites. The NDVI is essentially reliant on the area of vegetation which was generated based on near-infrared band (NIR) and red band showing maximum and minimum reflection of electromagnetic energy (EQ.11). Generally, the NDVI varies theoretically between - 1 and 1 which the highest estimate is allocated to cultivated lands (Fig. 11).

$$S_7 = 20 - (0.2 \times P_c) \tag{9}$$

$$P_c = (46.1 \times \mathrm{NDVI}) + 15.9 \tag{10}$$

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{VIS}}{\mathrm{NIR} + \mathrm{VIS}} \tag{11}$$

3.1.8 Upland erosion factor (S_8)

The upland erosion (S_8) could be determined using the MPSIAC equation (EQ. 12) where G represent the score summation of seven factors contributed on the upland erosion. The upland erosion could be delineated in MPSIAC model using the BLM method in which the seven effective parameters include surface leaf crops, rock fragments, surface stoniness, surface streams, soil mass movement, and rill and gully erosion (Daneshvar and Bagherzadeh 2012). However, the upland erosion could be delineated in our model (EHM) using different seven effective parameters including slope aspect (Fig. 12), plane curvature (Fig. 13), stream transport index (STI) (Fig. 14), compound topographic index (CTI) (Fig. 15), drainage density (Fig. 16), lineament intensity (Fig. 17), and proximity to faults (Fig. 18). These factors represent numerically equivalents for rill and gully erosion, soil mass movement, surface streams, surface stoniness, and rock fragments.

$$S_8 = 0.25 \times G \tag{12}$$

SRTM DEM was used essentially to prepare the different effective parameters including slope aspect, plane curvature, compound topography index (CTI), stream transport index (STI) and drainage density. The slope aspect map was extracted automatically in ArcGIS 10.5 (Fig. 12). The plan curvature is also an important parameter describing geomorphological variation and terrain morphology (Chaplot 2013). Commonly, the plan curvature effects on the rate of upland erosion according to water divergence or water convergence during downslope flow (Conforti et al. 2011) The plan curvature map was derived also automatically in ArcGIS 10.5 using SRTM DEM (Fig. 13). The sediment transport index (STI) is another critical parameter describing the process of erosion and deposition (Fig. 14). The STI can be achieved from the relation between the specific catchment area (A) and the local slope gradient in degrees (β) using equation (14). The CTI can be adopted to estimate topographic control on hydrological processes. Commonly, gullies occur as the flow velocity overruns the soil shear stress, which is a function of slope and its related energy to surface runoff (Fig. 15). Therefore, the CTI reflect the impacts of flow velocity, potential discharge, and transport capacity which represent runoff erosive power. The CTI can be achieved from the relation between the specific catchment area (A) and the local slope gradient in degrees (β) using equation (15).

$$\mathrm{STI} = (A/22.13)^{0.6} \times (\sin\beta/0.0896)^{1.3} \tag{14}$$

$$\mathrm{CTI} = \ln(A/\tan\beta) \tag{15}$$

Numerous environmental characteristics of WDW affect the drainage pattern such as the geological units, soil types, infiltration rate, and slope degree. The drainage density map was prepared using Line Density tool in ArcMap10.5 (Fig. 16). The lineament intensity is essential parameter indicating the upland erosion. The lineament intensity represents the degree of rock fracturing which increases the susceptibility of chemical and physical weathering. Lablacian and sobel convolution filters are two linear detection enhancement algorithms which have been applied to extract lineaments using OLI8 satellite images. The lineament features could be manually delineated from the convoluted filtered image. The lineament intensity was attained for each catchment by dividing the total lineament length by catchment area (Fig. 17). In most cases, upland erosion is linked to the faults, disintegrating the surface lithology and facilitating the evacuation of rock fragments from upland. The distance from faults was considered to explore the influence of structural setting on upland erosion. Hence, the distance calculation was created to derive the proximity to faults using Multi-buffer tool in ArcMap10.5 (Fig. 18).

The bivariate statistical methods were selected to evaluate the actual contribution of parameters causing upland and channel erosion and then occurring shallow mass-wasting especially; debris-flows. These methods include the frequency ratio (FR) and nominal risk factor (NRF). The FR analysis is the simplest bivariate statistical method to define the actual contribution of each parameter class on erosion intensity. The analysis gives information based on the relation between the spatial distribution of parameter pixels and the mass-movement pixels (due to erosion intensity). The index analysis could be easily obtained by dividing the mass-wasting intensity for each class by the mass-wasting intensity for the entire map (EQ. 16). The NRF was used to assign representative weights for effective parameters (EQ. 17). The weights could be computed only for the classes having mass-wasting because the analysis depends on the statistical correlation between the mass-wasting inventory map and the effective parameters. The FR and NRF analyses were completely achieved in the attribute tables of the effective parameters using ArcMap 10.5 (Table 2).

$$IV = \ln\left[\frac{\mathrm{Npix}(\mathrm{S_{CG}})/\mathrm{Npix}(\mathrm{N_{CG}})}{\sum_{\mathrm{C}=1}^{\mathrm{n_G}}\mathrm{Npix}(\mathrm{S_{CG}})/\sum_{\mathrm{C}=1}^{\mathrm{n_G}}\mathrm{Npix}(\mathrm{N_{CG}})}\right] \qquad (16)$$

$$\mathrm{W_{CG}} = \ln\left[\frac{\mathrm{Npix}(\mathrm{S_{CG}})}{\sum_{\mathrm{C}=1}^{\mathrm{n_G}}\mathrm{Npix}(\mathrm{S_{CG}})/\mathrm{n_G}}\right] \qquad (17)$$

Where IV and W_{CG} are the information value and weight assigned to the C^{th} class of a specific parameter (G), Npix (S_{CG}) is number of class pixels containing mass-wasting, Npix (N_{CG}) is the total number of pixels in a specific parameter class, and n_G is the number of classes in a parameter (G). The upland erosion (S_8) factor was generated from the total summation of different weights (W_{CG}) assigned for the different classes of effective parameters (EQ. 13 & 16).

3.1.9 Channel erosion factor (S_9)

The channel erosion could be determined using the MPSIAC equation (EQ.18). The channel erosion could be delineated in MPSIAC using the relationship between annual rainfall and gully erosion based on BLM method. However, the channel erosion could be delineated in the EHM using an effective relation between sediment power index (SPI), and proximity to erosive streams. The SPI represents the stream erosion power and is considered as a parameter affecting the slope stability within WDW (Fig. 19). The SPI is an essential parameter monitoring slope erosion, since erosive power of runoff straightly affects river incision and slope toe erosion. The SPI can be attained from the relation between the specific catchment area (A) and the local slope gradient in degrees (β) using equations (19).

$$\mathrm{S_9} = 1.67 \times \mathrm{G} \qquad (18)$$

$$\mathrm{SPI} = \mathrm{A} \quad \mathrm{x} \tan \beta \qquad (19)$$

Usually, gullies are associated to the stream network, accelerating the removal of the eroded sediments from upland areas to channel system (Clark and Hartwich 2001; Martinez-Casasnovas 2003). The factor of distance from streams was considered to reveal the role of drainage network on erosion process. Hence, the distance calculation was attained to derive the proximity to streams using Multi-buffer tool in ArcMap10.5 (Fig. 20).

3.2 Mass wasting inventory map

Mass wasting represents a rapid form of erosion in which detritus, regolith, and rock fragments move downslope as continuous or discontinuous mass. The mass wasting is the hydro-geomorphic process in which the mass movement occurs under the influence of gravity and other erosional agents. There are different types of mass wasting exist in WDW include slides, flows, topples, and falls. These types have different characteristic features and different timescales varying from seconds to hundreds of years. Commonly, the mass wasting may cause catastrophic impacts when the area exposes to earthquakes (Kaneda et al. 2008; Owen et al 2008; Parsons et al. 2008; Gorum et al. 2011; Wasowski 2011). Although, the mass-wasting events occur at very slow rate at WDW, the events may cause catastrophic impacts when the area receives sufficient rainfall during rainy storms or the area exposes to earthquakes. In this case, the mass wasting occur at very high speed, such as in rock-slides, landslides, or debris-flows with devastating impacts. Commonly, the devastating impacts take place in various zones in WDW due to debris-flows associated with erosion intensity. Several factors vary the mass wasting potential in WDW such as slope angle, weakening of rocks by weathering, water content, and land use/land cover (Dahal et al. 2008; Kanungo et al. 2009). Rainfall and runoff play important role in the erosion intensity and hence, in mass-wasting occurrences because the water rise or reduce the slope stability. The heavy rainfall create large amounts of runoff that transport sediments and rock fragments down slope. Therefore, water increases the erosion intensity and triggers the process of mass-wasting in which the rock and debris are certainly washed down slope. Debris-flows are geological process in which runoff inducing masses of fragmented rock rush down mountainsides and then into stream channels. The debris-flows mostly have bulk densities comparable to other types of mass-wasting. In most cases, the main conditions required for initiation of debris-flows, are slopes steeper than 25^{o}, the abundant of loose sediment or weathered rock, and intense rainfall to carry the loose masses to stable terrain. Debris-flows are easily recognizable in the field which generate most of debris cones along steep mountain fronts. The debris-flow deposits could be distinguished by poor sorting of sediment grains.

As it is so challenging to reach all erosion zones in the mountainous area for validating their intensity, the locations of mass-wasting could be used to test the erosion intensity map and to derive the relation between erosion zones and debris-flow occurrences. Different data sources including remote sensing images, aerial photographs, and field survey, were used in this study to delineate the distribution of mass-wasting and to build the mass-wasting database. The mass-wasting database was considered the most important task for modeling hazard zones and validating the erosion intensity map based on a bivariate statistical analysis. WDW was divided in grids to distinguish homogenously all locations of mass movements. A total number of 1500 mass-wasting locations were detected from Google Earth images and field observations (Fig. 21). These locations represent upland erosion, channel erosion/debris-flows, shallow landslides and rock-falls. The channel erosion and debris-flows represent 1050 locations of the total number. The mass-wasting inventory map represents the backbone of this study to get acquaintance linkage between the mass-wasting locations and the erosion intensity zones (Fig. 21). We selected 1000 locations from mass-wasting dataset to use their distributions in the spatial modeling process. The mass-wasting locations were contributed in the NRF analysis to derive weights for the different classes of parameters produced channel and upland erosion. Furthermore, the remaining 500 locations of mass-wasting (mainly are debris-flows) which were not used in the model, were overlaid with the erosion intensity zones for correlation purpose. The frequency ratio-based statistical approach was used to perform the correlation analysis and to define the linkage between debris-flow locations and erosion intensity (Pradhan and Lee 2010). The frequency ratio of each erosion intensity zone were computed from their relation with debris-flow occurrences (Table 3). The frequency ratio could be calculated by dividing the area where debris-flows existed in a specific area of erosion intensity zone. One was adopted as an average value for the frequency ratio in the relationship analysis. Therefore, the higher correlation could be expressed when the value of the frequency ratio is greater than 1. While, the lower correlation could be expressed when the value of the frequency ratio is lower than 1(Fig. 23).

Table 3: The frequency ratio-based statistical approach displays the correlation analysis to define the linkage between debris-flow locations and erosion intensity

Class level	Soil erosion zones	Class pixels	Area of risk zones % (a)	Debris-flow pixels	Area of debris flow % (b)	Ratio b/a
1	Very low	978609	43.40	3473	1.19	0.027
2	Low	411863	18.26	5864	2.32	0.127
3	Moderate	186847	8.29	11973	8.07	0.974
4	High	512090	22.71	40732	32.96	1.451
5	Very high	165646	7.35	61537	55.46	7.550

4. Results

The erosion Intensity and debris-flows inventory maps were created and compared in this study to reveal the hazard zones and avoid their catastrophic impacts (Figs. 21 and 22). The erosion intensity map classifies the study area relatively to five hazard zones including very high (>90 $m^3/(km^2Y)$), high (70-90 $m^3/(km^2Y)$), moderate (50-70 $m^3/(km^2Y)$), low (50 - 30 $m^3/(km^2Y)$), and very low (< 30 $m^3/(km^2Y)$). The very high and high hazard zones in the erosion intensity map cover respectively 7% and 23% of the total area of WDW (Fig. 22). The rates of sediment yield in the five intensity zones differ from 21.1 to more than 500 $m^3/(km^2Y^{-1})$ for very high intensity zone (Table 1). Furthermore, the total sediment amounts of surface area vary from 5494 to 87831 m^3/Y for very high intensity zone. This outcome will assist the decision makers to predict the maximum area that is susceptible to erosion and associated hazards; especially debris-flows. Consequently, different scenarios will be estimated for LULC changes to apply better protection and management plans.

The erosion intensity map suggests the furthermost risky zones which are the most sensitive to soil loss. Most of these risky zones mainly exist in the western and southern sides of the mapped watershed. The most risky zones are located on steep sloping channels which consist of Quaternary terraces, Precambrian and clastic rocks Therefore, the high sediment classes correspond well to metavolcanics, serpentinite group, metagabbro and older granitoids, and clastic rocks covering Arab, Nubia and Naqus formations. The very high and high intensity zones exist in numerous wadis including Wadi Rimthy, Wadi Nasb, Wadi Khasheib, and Wadi Zaghraa (Fig. 22). The erosion intensity map indicates that 152.79 km^2 of Wadi Dahab total area (7.4 %) is very high hazard zone while the very low hazard zones occupy an area about 902.6 km^2 (43.4% of the total mapped area). The moderate intensity zones exist in scattered locations of Wadi Dahab representing 8.2% of the mapped area. The high hazard zones cover 472.3 km^2 indicating 22.7% of the study area, while the low hazard zones cover 379.8 km^2 indicating 18.3% of the study area (Fig. 22).

Since it is arduous to access all erosion zones in the mountainous region such as Wadi Dahab watershed, mass-wasting database (Fig. 22) was created to validate and test the erosion intensity map. Based on the field investigations, the debris-flow locations were noticed extensively close to several zones which have abundant ability to erosion. Therefore, the debris-flow locations were correlated with the erosion prone zones using frequency ratio-based statistical analysis (Fig. 23 and Table 3). The frequency ratio analysis discloses the higher correlation between the distributions of debris-flows and high erosion intensity zones. The frequency ratios for very high and high erosion intensity zones, were computed and set to be 7.5 and 1.5 respectively denoting their high probability to trigger the debris-flows (Fig. 23 and Table 3). The frequency ratios for very low and low erosion zones, were computed and set to be 0.03 and 0.12 respectively denoting their low probability to activate debris-flows (Fig. 23 and Table 4). In short, the results of correlation analysis reflect reasonable concurrence between the erosion intensity zones and the debris-flow locations.

5. Discussion

The natural environmental conditions of WDW play an important role in erosion intensity. The spatial distribution of hazard zones was evaluated through a time of several processes to predict carefully the sensitivity of different zones to sediment loss. Different EHM factors (S_1 to S_9) reveal a strong contribution in the occurrences of erosion intensity and in turn on associated debris-flow hazards.

5.1 Surface Geology (S_1)

Surface geology play an essential role to estimate erosion intensity and associated hazard zones. Most of the Precambrian lithological units in WDW exposed to a long period of weathering process resulting very susceptible lithologies for cracking, fracturing and sliding. Furthermore, the structural setting in WDW create different stress degrees causing several weak zones in the weathered rocks. The disintegrated rocks due to weathering and structural lineaments, increase water flow along the steep channels during heavy rains. Henceforth, any runoff travel along structural features stimulates the erosional processes. Mostly, the Precambrian basement rocks, clastic formations, and quaternary terraces are located in steep sloping terrain with high relief prompting the erosional process and associated hazards. Consequently, these lithologies especially; metavolcanics, serpentinite group, metagabbro and older granitoids, and clastic rocks of Arab, Nubia and Naqus formations, have the highest weight in EHM (Table 1). However, the carbonate rocks of cenomanian, turonian, albian, and aptian formations have the lowest weight in the model (Table 1). Consequently, the zones close to Precambrian metamorphic rocks, clastic formations, and quaternary terrace; are the most vulnerable to erosion and debris-flow hazards.

5.2 Soil factor (S_2)

The soil factor (S_2) represents the second important factor indicating the different rates of erosion (Fig. 7). The soil factor (S_2) could be estimated using soil erodibility factor (K) of RUSLE model. The K-factor varies in WDW from 0.059 to 0.449 $t\ ha\ h\ ha^{-1}\ MJ^{-1}\ mm^{-1}$ (Fig. 7). The K-factor depends primarily on several soil characteristics including texture, the content of organic matter, permeability, and structure. For example, soil texture plays a significant role in increasing soil erosion susceptibility. The high silt concentrations in soils increase the erosion susceptibility comparable to high clay concentrations. Correspondingly, the content of organic matters contributes as an essential characteristic in decreasing soil erosion susceptibility. The high content of organic matters in soils decreases the erosion susceptibility comparable to the low content of organic matters. Hence, the soils without organic matters have the highest erosion susceptibility creating sever risk zones (Wu and Tiesson 2002). In addition, the permeability participates as a fundamental characteristic in diminishing soil erosion susceptibility where fast infiltration rate exists in wide preamble zones. However, the slow infiltration rates cause the great erosion susceptibility producing catastrophic impacts. The soil characteristics of WDW are substantially affected by parent materials and geological forces. Therefore, the spatial distribution of K-factor varies with the different LULC types and different lithological units. The parent materials are created from different lithological units (Fig. 3) such as Quaternary deposits, upper Cretaceous formation, lower Cretaceous formations, Cambrian formation, Firani group, phyillite, metasediments, acidic meta-volcanic, basic meta-volcanic, Metagabbro, ring dyke, Catherina volcanics, monzogranite, alkaline granite, diorite, and granodiorite (Abuzied and Mansour 2018). Bulk mineralogical composition of these parent rocks are mica, pyroxene, feldspar, plagioclase, quartz, garnet, and calcite. The values of soil factor (S_2) vary in WDW from 0.83 to 7.5 for the class of mountains with low permeability (Table 1). The low values of soil factor are assigned for fine Wadi deposits and carbonate hills (Table 1). The high values of soil factor distributes mainly in the southwestern and southeastern parts of Wadi Dahab watershed, where the Precambrian rock units are located (Fig. 7). Unlike rainfall and runoff distribution, the high values of K-factor distributes in different zones of Wadi Dahab Watershed. Thus, the management plans for erosion intensity and its associated hazards are very critical in the fragile environments of arid areas to preserve the system sustainability.

5.3 Rainfall factor (S_3)

The rainfall erosivity (S_3) represents one of the critical factor contributing mainly to surface erosion and sediment loss (Fig. 8). The erosion intensity is still more important than rainfall erosivity because it needs a shorter time to reach a stable value of erosivity and reveals the more risky zones. Generally, the topography of an area affects mostly on erosion rate because the topography controls the velocity of surface runoff, which in turn controls the runoff erosivity. Therefore, longer and steeper slopes in WDW are more susceptible to high erosion rates during the heavy rains (Figs 2, 8 and 10). The highest erosion zones are predicted in the areas of low annual mean precipitation because the heavy rains prevailing in the western highlands of Wadi Dahab run rapidly from the western steep sloping channels in high elevation to the eastern channels in low elevation (Figs. 2, 8 and 10). Hence, the hydrographical terrains on the western parts of Wadi Dahab are accountable for highly erosion risk and great damages in different zones of the study area (Abuzied and Mansour 2018). Furthermore, the steeper terrain in the eastern side of Wadi Dahab is also more prone to different forms of gravitational erosion processes such as debris-flows and landslides (Fig. 3). The lowest erosion intensity zones are predicted in those areas of high annual mean precipitation because of homogenously distribution of the precipitation due to local topography (Figs. 2, 8 and 10).

Rainfall factor (S_3) contribute essentially on erosional process and sediment transport. Several studies identify the initiation threshold of debris-flows based on the rainfall, soil moisture, or hydrological conditions needed for inducing debris-flow (Chleborad et al. 2008; Jakob et al. 2012). Rainfall thresholds can be determined based on conceptual or historical approaches (Wieczorek and Glade 2005; Schneuwly-Bollschweiler and Stoffel 2012). The rainfall thresholds for debris-flow initiation is the most common which consider the relationship connecting rainfall duration to rainfall intensity or to event-cumulated rainfall. Generally, the higher rainfall produces higher erosion rates and in turn higher sediment yield. In arid and semi-arid regions, a comparatively small annual rainfall can create a great individual storm erosivity resulting high erosion problems due to bare soil and vegetation absences(Figs. 2 and 8). Rainfall factor was determined varying from 0.66 to 1.02 mm by the conventional empirical equations using 6- hours rainfall with two years return period (Figs. 8 and 10). The rainfall intensity map displays a spatial allocation of the rain erosive energy. According to all the parameters adopted in determining the S_3-factor, the precipitation seasonality, elevation, and slope have the greatest influence.

5.4 Runoff factor (S_4)

Runoff factor (S_4) was achieved based on analysis of runoff depth and specific peak discharge. In WDW, runoff basically is influenced by atmospheric conditions and surface permeability. Therefore, WDW was classified to different hydrological units. The specific discharge of each hydrologic unit was estimated by dividing the flood peak discharge by its area. The investigation of runoff characteristics in stream network of WDW was attained based on SCS empirical equations. The runoff depth was computed in each catchment to assess stream's likelihood for surface runoff. The surface runoff depends mainly on the amount of Precipitation and the rates of infiltration. Usually, a lesser infiltration rates generate a greater runoff behavior and a higher erosional hazard. The Precambrian basement rocks cover the most area of WDW which are characterized with low infiltration degrees (Figs. 3 and 9). In addition, urban area and highway pavement are characterized of smaller infiltration and thus produce greater runoff. The highest rates of runoff depth are distributed at the northwestern and central parts of WDW especially close to Saint Catherin varying from 47.09 to 70.47 mm. Whereas, the low rates of runoff depth are disseminated at the downstream of Wadi Dahab varying from 12.02 to 35.4 mm. Nevertheless, the downstream of Wadi Dahab is the most risky area due it's the physiographic features including topographic elevation, slope and basin geometry. These features assist the transport and accumulation of runoff from Saint Catherin at upstream to Dahab city at downstream (Figs. 2, 8 and 10). The spatial and temporal distributions of runoff support the erosional processes and thus associated hazards especially debris-flows. Hence, the classes of runoff factor were assigned weights varying from 2.12 to 8.4 in EHM which correspond to their actual influences in arising erosional hazards (Table 1).

5.5 Topography factor (S_5)

The elevation of WDW varies from 0 to 2527 m (Fig. 1) while the slope percentage differs from 0 to 95.5 (Fig. 10). The slope analysis indicated that nearly 30% of WDW is having slope more than 40^o (Abuzied and Mansour 2018). These steep sloping lands trigger surface erosion increasing the rates of sediment loss, even with slight rainfall amount and soil characteristics. Moreover, the steep sloping terrains have very shallow soil depth. Commonly, the slope length and slope steepness increase the surface susceptibility to erosion. The longer slope length increases the volume, velocity, and depth of runoff leading to greater total soil loss. The steeper terrains create faster runoff, greater splash downhill, and higher flow velocity. The topography factor (S_5) varies from 3.3 to 19.8 in Wadi Dahab area while the highest values exist mainly in the Precambrian basement rocks (Table 1). Majority of Wadi Dahab area have values less than 9.9 and individually a few zones near streams have values higher than 19 (Table 1). The slope changes abruptly near the drainage channels which in turn produces high values of S_5-factor. The high values of S_5-factor also distribute in the highly dissected terrain, and very steep topography in the hilly, gully, or mountainous areas. These areas have the highest susceptibility to severe erosion and debris-flow hazards due to their rugged topography (Prasannakumar et al. 2012; Ashiagbor et al. 2013; Sun et al. 2014). The eastern and southern sides of Wadi Dahab are exposed to higher weathering because of the existence of Precambrian basement rocks (Abuzied and Mansour 2018), solar radiation, and temperature amplitudes producing drastic erosion and associated debris-flows (Fig. 12).

5.6 Land cover factor (S_6)

The land cover factor (S_6) is the other key factor indicating risk due to the rate of sediment loss (Fig. 11). The S_6-factor varies in WDW from 0.12 to 3.2 based on the different ratios of barren land (Fig. 6 and Table. 1). WDW consists of different land covers including paved and unpaved roads, agriculture lands, urban zone, Wadi deposits, and sedimentary and basement rocks surfaces (Fig. 6). The land cover factor represents the amount of sediment loss from a region with particular land cover and definitive management actions. The total geographical area of Wadi Dahab basin is 2080 km^2 out of which barren land about 93.5% of total area (Fig. 6 and Table. 1). These lands consist mainly of Phanerozoic sedimentary succession and Precambrian basement rocks which cover steep sloping terrain. Most of these terrains are exposed to progressive weathering processes which raise the amount of erosional processes. WDW is exposed to randomly construction of unpaved roads by the Bedouin community to improve accessibility. The unpaved roads contribute as another crucial reason in triggering steep slopes to erosion due to soil loss (Abuzied and Mansour 2018). All these land cover types assist the damage of exposed steep slopes leading to sever erosion in Wadi Dahab area.

5.7 Land use factor (S_7)

Generally, the vegetation cover protects the soil from severe erosion rate. Unfortunately, WDW is characterized with scarce vegetation cover, thus several zones are exposed to weathering processes and erosion hazards. The land use (S_7) factor was used to evaluate the effect of vegetation cover on weathering rate. It represent the ratio of sediment loss from definitive vegetation zones to the corresponding loss from bare zones. In the current study, the NDVI was assessed to be <-0.17 for barren terrain and 0.85 for strong cover with no erosion susceptibility. The land use (S_7) factor varies based on NDVI from 8.98 (strong cover with no erosion susceptibility) to 18.39 (barren terrain). The highest S_7-factor value, means that most of its area are barren land with rare vegetation cover and directly exposed to weathering effect.

5.8 Upland and channel erosion factors (S_8 & S_9)

The upland and channel erosion (S_8 & S_9) were estimated based on the MPSIAC equations (EQs.12 and 18). However, Different factors were selected in the current study to evaluate the upland and channel erosion, and consecutively related debris-flow hazards. Therefore, we selected carefully the parameters controlling the upland and channel erosion to recognize all hydro-geomorphic processes which contributed in the initiation of debris-flow hazards. Generally, soil depth decreases as a result of erosion intensity. Soil depth affected by overland and the dynamic of intra-soil water which depend on the relief of the study area (Mehnatkesh et al. 2013). Furthermore, soil depth depend on the spatial differentiation of moisture according which controlled by surface morphology (Mehnatkesh et al. 2013). Therefore, soil depth varies spatially as a function of different factors such as slope aspect (Fig. 12), plane curvature (Fig. 13), stream transport index (STI) (Fig. 14), compound topographic index (CTI) (Fig. 15), drainage density (Fig. 16), lineament intensity (Fig. 17), proximity to faults (Fig. 18), and stream power index (SPI) (Fig. 19). For example, the slope aspect (Fig. 12) is usually considered a fundamental factor in geo-environmental hazard assessment and susceptibility mapping (Pourghasemi et al. 2013) due to its indirect influence on erosion processes. It gives good indications about duration of sunlight exposition. In turn, it gives indication about the rate of evaporation, moisture retention, and distribution of vegetation types. Furthermore, it offers indirect indication for the influence of the structural setting. The highest NRF was estimated in NE and SW trend (2.14) which indicate the direction of Gulf of Aqaba and the main fault trend in the study area. The NW and SE trend was assigned the following high NRF (1.59) which indicate the direction of Gulf of Suez and the other main trend in WDW (Table 2). Furthermore, the highest value of IV were evaluated in the E, NE-SW, and NW-SE (0.83, 0.44, and 0.225 respectively). Thus, it was important task to apply bivariate statistical analyses to evaluate carefully the relation between parameters controlling upland erosion and debris-flow occurrences.

For the plane curvature (Fig. 13), the highest NRF was estimated in convex terrain (1.94) followed by concave terrain (1.02) (Table 2). In addition, the highest value of IV were evaluated in the same terrain morphology (0.29 for concave and -0.24 for convex). The plane curvature provides great geomorphological information about the terrain morphology which affects the rates of erosion. Most of erosion occurs in WDW when the rainfall flows convergent or divergent down slopes. Hence, plan curvature was adopted with respect to its effect on triggering erosion and corresponding debris-flows.

Commonly, topography represents one of the major soil forming factors (Moore et al. 1991). Slope, CTI, SPI, and STI are topographic attributes describing the variability in soil depth (Mehnatkesh et al. 2013). Overall, such topographic attributes directly affected by erosional processes controlling the soil depth in the mountainous regions (Mehnatkesh et al. 2013). As slope gradient increases, and erosion intensity tends to increase and hence, and soil depth tends to decrease (Moore et al. 1991). Therefore, CTI, STI, and SPI can be considered as the indices indicating soil erosional processes across the mountainous areas such as WDW. The STI and SPI have negative correlation with soil depth and positive correlation with erosion intensity (Mehnatkesh et al. 2013). The sediment transport index (STI) and stream power index (SPI) represent hydrological based terrain parameters. The STI is a great hydrological index which reflects the erosive power of overland flow (Fig. 14). It can be used to indicate potential zones of erosion risk (Moore and Burch 1986). The highest NRF was estimated to very high STI (2.8) followed by high STI (1.5) (Table 2). In addition, the highest value of IV were evaluated in the same STI classes (2.88 and 1.09 respectively). The SPI is another index which provides great indication about the erosive power of rainfall according to the hypothesis of discharge is directly proportional to catchment area. The SPI measure assumes that flow accelerates in convergence zones and hence predicts net erosion in profile and tangential convexity zones. It also assumes that flow velocity decrease in the concave zones and hence, predicts net deposition in profile concavity zones (Fig. 19). Therefore, the SPI was considered to predict the channel erosion. The highest NRF was estimated to very high SPI (3.58) followed by high SPI (1.16) (Table 2). Furthermore, the highest value of IV were evaluated in the same SPI classes (3.68 and 0.355 respectively).

The CTI and catchment area are recognized to water accumulation and soil genesis processes within the hillslope. The CTI reflects the spatial distribution of water flow, and hence the accumulation processes in a closed catchment. Therefore, the highest soil depth is located in the downslope zones where high values of CTI are represented. While, the lowest soil depth is located in the hillslope reflecting the lowest values of CTI and the highest rate of erosion (Mehnatkesh et al. 2013). The highest NRF was assigned to very high CTI (3.2) followed by high CTI (1.5) (Table 2). Moreover, the highest value of IV were evaluated in the same CTI classes (1.97 and 0.13 respectively). The CTI represents a water related topographic parameter which reflects topographic control in hydrological processes and sequentially in erosional processes. The CTI reflects also the gravity role to transport water downslope and the water behavior to accumulate at any point in the watershed based on the slope. Generally, the flow velocity increases the shear stress, which is considered a function of slope and is associated to power rate of runoff. Therefore, the CTI reflects erosive power of surface runoff and can be used to indicate flow velocity, potential discharge, and transport capacity.

For drainage density (Fig. 16), the highest NRF was assigned to high density (2.01) followed by moderate density (1.56), (Table 2). Additionally, the highest value of IV were estimated in the very high and high density classes (1.7 and 0.588 respectively). Commonly, a high drainage density create greater runoff and in turn greater erosional processes. Different characteristics control the drainage pattern of WDW such as slope, lithologic units, soil types, structural features, and infiltration rate. Mostly, gullies are associated to the stream network to evacuate eroded sediments from upland zones (Conoscenti et al. 2014). Therefore, distance to main streams was considered to reveal the influence of stream network on channel erosion and hence the initiation of debris-flow hazards (Fig. 20). The highest NRF was assigned to distances close to main streams (3.137 and 0.994) (Table 2). In addition, the highest value of IV were adopted to the same distances which close to main streams (1.6 and 0.077 respectively).

For lineament intensity (Fig. 17), the highest NRF was assigned to high and very high lineament intensity (2.083 and 1.568 respectively) and the highest value of IV were estimated in the very high and high intensity classes (1.84 and 0.775 respectively), (Table 2). Usually, the highly fractured and jointed lithologies indicated more potential to erosion and hence, debris-flow hazards. Frequently, the debris-flows occurrence rises with proximity to tectonic structures. The WDW is structurally quite complex because numerous faults and shear zones are identified to traverse the study area. The Red Sea rifting effects on common structures in WDW. Therefore, NW-SE and NE-SW fault trends represent the major faults which are controlled most of hazard occurrences in WDW. The highest NRF in our model was recognized at close and very close distance to faults (2.48 and 2.004 respectively) and the highest value of IV were estimated in the same classes (1.632 and 1.853 respectively), (Table 2). Thus, Proximity to faults (Fig. 18) was considered to reveal the structural influence on upland erosion and the debris-flow hazards.

5.9 Erosion intensity and its implications on debris-flows hazards

All the EHM factors were overlaid in GIS domain to achieve erosion rate in Wadi Dahab watershed. The rates of sediment yield in the entire basin was obtained to be 1114.69 m^3/ ($km^2 Y^{-1}$) and the total sediment amounts of surface area 308490.06 m^3/Y. The higher values of erosion are essentially related to higher rate of sediment yield which are detected on abrupt slopes neighboring the main streams due to their higher length and steepness. In these zones, runoff can carry a higher availability of weathered materials. The steeper sloping terrains are also characterized by rills, and gullies which in turn induce the sediment movement. This phenomenon is common in WDW and was observed clearly during field studies as consequence of its fragile geomorphology. The high erosion intensity was predicted with Precambrian metaphoric rocks, the high rainfall intensity, scarce vegetative cover, and fragile slopes which represent the foremost reasons for the great rates of erosion.

The erosional processes represent one of the critical geologic processes occurred naturally in all lands with different sever rates. The erosion process is mainly associated with the hydrologic cycle because the rainfall and wind are the primary agents to trigger soil loss. In arid regions, like Wadi Dahab, the parent rocks are fragile and greatly impermeable nature, thus soil erosion is rapid and provides huge sediments quantities to steams creating catastrophic debris-flow hazards (Abuzied and Mansour 2018). Therefore, the erosion assessment is a crucial task to avoid its serious environmental impacts. The soil erosion in Wadi Dahab is relatively a slow process that remains unobserved, but it sometimes occurs at a disquieting rate due to heavy rains producing serious risks such as flash floods and debris-flows (Abuzied and Mansour 2018).

The erosion intensity usually arisen in Wadi Dahab area as consequence of rainfall and overland flow (Figs. 8, and 9). The rainfall and overland flow are responsible of sediments loss from different landforms in Wadi Dahab area including sheet, rill, gully, channel and bank. The surface gravity and wind may cause also sediment loss from hillslopes producing drastic erosion risk. The sheet erosion is a surficial process that is occurred when the sediments are exposed to the raindrops. Raindrops carry the sediment particles and splash them into shallow overland flows. The overland flows transport larger amount of the removed deposits to a close rill. Therefore, surface runoff is originated from sheet landform causing gradually devastating flash-floods in Wadi Dahab (Abuzied and Mansour 2018). The sheet erosion is a very active erosive process covering large zones of sloping terrains. Gully erosion is also occurred in the study area in different steep-sides leading to ephemeral flash-floods and landslides (Abuzied and Mansour 2018). The gully erosion occurs frequently after the stage of rill erosion, which occurs after the stage of inter-rill erosion. Several factors control mainly the rate of gully erosion including the runoff characteristics, structural setting, topography, the channel slope, the drainage area, soil characteristics, gully size, and gully shape. The soil loss from the gullies is the most occurred process which causes several critical problems in Wadi Dahab including the gully head erosion by runoff, channel erosion, and hence, debris-flows. The gully erosion is distributed in large zones in the study area due to hillslope failures, landsliding, and debris-flows.

In short, surface erosion is the transportation of soil particles and disintegrated rocks by fluvial and wind processes from sheet, rill, and gully, and in turn, producing mass-wasting such as debris-flows and shallow landslides (Fig. 21). Both fluvial and Aeolian processes occur extremely in arid regions such as Wadi Dahab, where the soil is poorly protected by vegetation (Abuzied and Mansour 2018). Therefore, land use may increase surface erosion greatly above natural rates (Fig. 6). The erosion intensity also depends on the nature of the rock type and mechanical weathering (Fig. 3). Few Phanerozoic sedimentary rocks which are associated with the dynamic tectonic process facilitate the erosion process at the northwestern part of Wadi Dahab (Fig. 3). However, the erosion intensity has a considerable impact in the Precambrian metamorphic rocks because the steep sloping and tectonized nature of these lithologies and the lack vegetative cover aggravates the high surface runoff creating severe flash floods and debris-flows. Hence, the geologic setting of WDW facilitate rock-fall and debris-flows which is observed in the field investigations, resulting active mass wasting in many zones (Fig. 3). Although, the occurrence mechanism of rock-falls differ than debris-flows (Straub and Schubert 2008), the two types exist in WDW. The rock-falls occur firstly at steep slopes due to earthquakes and then the debris-flows frequently take place with catastrophic impacts due to runoff. Climate, land cover, geomorphology, and geology play the connecting role in occurring erosional processes and in turn activate rock-fall and debris-flows (Figs. 2, 3, and 6).

Briefly, debris-flows are commonly known as rapid flowing sediments which transport by gravity and trigger by runoff. In WDW, water floods surge the debris-flows in which sediment is caught in suspension until decreasing fluid mechanical forces. Heavy interactions of the sediment and rainfall are an essential control of the mechanics of debris flows in the study area. In addition, several local conditions initiating debris-flows in WDW such as steep slopes of upland and channels, copious non-cohesive streams and bank sediments, and sufficient runoff which keep the sediment/water ratio induced debris-flow transport (Costa 1984). The initiation mechanisms are broadly summarized into flows creating from landslide initiation, or from sediment entrainment by runoff in a channel (Iverson et al. 1997). Regionally, these initiation mechanisms differs based on surficial geology, basin morphology, and local climate. The debris-flows initiate typically in WDW based on rainstorm characteristics, basin morphometric, and antecedent moisture conditions. Once started, the debris-flows develop speedily carrying disintegrated rocks and sediments along transport zone with high flow velocities which create dangerous debris-flows (Fig. 21). As intense rainfalls can distinguish flash floods in WDW are also usual triggers debris-flows (Fig. 21). The nature of sediment transport type is an essential step to classify Wadi Dahab catchments into those being prone to flash flood or prone to debris-flows. The EHM is a well-established approach to solve this problem based on the analysis of the relationships erosion intensity zones and debris-flows occurrences (Table 1 and 2). The EHM provides the developed approach combined hydro-geomorphic characteristics of drainage basins with structural features to predict all hazard zones due to erosion intensity and debris-flows. The correlation analysis adds confident and reliable results to validate the erosion intensity map (Table3) and to confirm the actual relation between erosion zones and debris-flows in WDW (Figs. 22 and 23).

6. Conclusion

This study estimates erosion intensity and its implications on the triggering debris-flow hazards in Wadi Dahab watershed. The erosion intensity extremely depends on the hydro-geomorphic processes which are affected by the nature of parent rocks, soils characteristics, structural setting, topography (slope), climate (rainfall), and types of land use. The EHM was developed in this study based on from MPSIAC model which considers nine factors including rainfall, runoff, topography, geology, soil types, land use, vegetation cover, upland erosion, and channel erosion. The different classes of these factor were assigned weights using MPSIAC rating equations (Johnson and Gebhardt 1982). We introduce new approach differing than MPSIAC to evaluate the upland and channel erosion and to predict hazards associated erosion such as debris-flows. The new approach estimates the upland and channel erosion based on aspect, curvature, compound topographic index (CTI), stream power index (SPI), sediment transport index (STI), lineament intensity, drainage density, proximity to faults, and proximity to erosive streams. These parameters contribute mainly in increasing erosion intensity and hence triggering debris-flows. The information value (IV) and the nominal risk factor (NRF) methods were adopted in this study to evaluate the actual relationships linking these parameter with mass-wasting locations. The scores calculated from NRF method, were considered as the class weights in EHM.

The erosion intensity map was formed in this study by integrating all the hazards contributing factors in GIS environment. The rates of sediment yield in the entire basin was attained to be 1114.69 m^3/ (km^2Y^{-1}) depending on EHM. Additionally, the total sediment amounts of surface area was achieved to be 308490.06 m^3/Y. The erosion intensity map classifies Wadi Dahab area into five relatively hazardous zones changing from very low to very high. The very high and high hazard zones cover respectively 7% and 23% of the total area of Wadi Dahab watershed. The hazardous zones mostly exist in the southwestern and southern sides of the mapped area distributed along several wadis such as Wadi Rimthy, Wadi Nasb, Wadi Khasheib, and Wadi Zaghraa. Most of hazardous zones occur in steep sloping channels in which the Precambrian basement rocks represent the dominant parent materials.

The erosion intensity map was validated using several sources including field studies, high spatial resolution satellite images, and digital databases of mass-wasting. The mass-wasting inventory map was created to test the accuracy of the erosion intensity map. Most of mass-wasting locations which was recorded, are channel erosion and debris-flows (1050). The debris-flow locations were observed in the field close to several zones which have very high ability to erosion. Hence, the debris-flow locations were correlated with the erosion intensity zones by frequency ratio analysis. The frequency ratio analysis reveals the higher correlation between the distributions of debris-flows and high erosion intensity zones.

This study also suggests that irregular and heavy rainfalls in this arid region can cause slow sheet erosion on low slopes and rapid gully erosion on steep slopes, which have Precambrian basement rocks. The rate of soil erosion in Wadi Dahab is serious because of scarce vegetation, structural setting, randomly unpaved roads, rugged topography, thin soil horizon, and landslides occurrences. The results define the priority zones where different soil conservation actions should be applied by decision makers. Our study recommends some important actions to reduce the sensitivity of erosion such as; (1) Design and adoption some strategies for land use planning and slope management to control surface erosion and runoff velocity; (2) decreasing the slope length and slope steepness by building of contour walls, bench terraces, check dams in gullies to break the slope; (3) maintaining roads, highways and other infrastructure in hilly lands to avoid soil erosion; (4) constructing retentive walls after cutting hillslopes for any infrastructure building.

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Table 1: The weight scores of EHM factor classes display the priority impact of each factor contributing hazards in WDW.

Classes	Attributions	Required parameters	Scores
1	Quaternary and Wadi deposits	Exist in steep slopes	8.00
2	Clastics of Arab, Nubia, and Naqus formations	Highly fragile rocks	6.00
3	Carbonates of cenomanian, turonian, albian, and aptian formations	Massive rocks	2.00
4	Metavolcanics, serpentinite group, metagabbro, and older granitoids	Highly fractured rocks in steep slopes	10.00
5	Younger granites, Dokhan volcanics, Ring dyke, Hammamat group	Massive boulders	0.00
1	Fine Wadi Deposits	$K = 0.05$	0.83
2	Hills of carbonate rocks with thin soil depth	$K = 0.1137$	1.89
3	Hills of clastic rocks with thin soil depth	$K = 0.26$	4.30
4	Alluvial and colluvium association	$K = 0.38$	6.33
5	Mountains with thin soil depth and low permeability	$K = 0.45$	7.50
1	Low rainfall intensity	3.1 mm	0.66
2	Moderate rainfall intensity	4.2 mm	0.84
3	Heavy rainfall intensity	5.1 mm	1.02
1	Low annual runoff, yield of specific flood peak is 0.2	$Q = 20$, $Q_p = 0.2$	2.12
2	Moderate annual runoff, yield of specific flood peak is 0.5	$Q = 47$, $Q_p = 0.5$	5.27
3	High annual runoff, yield of specific flood peak is 0.8	$Q = 70$, $Q_p = 0.8$	8.42
1	Low slope terrain	Average of Slope 10%	3.30
2	Moderate Slope terrain	Average of Slope 30%	9.90
3	High slope terrain	Average of Slope 60%	19.80
1	Paved roads	$P_b\% = 0.59$	0.12
2	Unpaved roads	$P_b\% = 1.42$	0.28
3	Urban zones	$P_b\% = 0.44$	0.09
4	Agriculture lands	$P_b\% = 0.08$	0.02
5	Precambrian basement surface cover	$P_b\% = 81.58$	16.32
6	Sedimentary surface cover	$P_b\% = 18.42$	3.68
7	Wadi deposits	$P_b\% = 16$	3.20
1	NDVI (< -0.17)	$P_c\% = 8.063$	18.39
2	NDVI (-0.16 - 0.34)	$P_c\% = 31.57$	13.68
3	NDVI (0.35 - 0.85)	$P_c\% = 55.085$	8.98
1	Very low erodible surface	0.20	0.05
2	Low erodible surface	0.54	0.14
3	Moderate erodible surface	6.92	1.73
4	High erodible surface	12.44	3.11
5	Very high erodible surface	19.15	4.79
1	Low erodible channel	0.11	0.18
2	Moderate erodible channel	2.30	3.84
3	High erodible channel	5.98	9.99
1	Very low intensity	$R= 19.226$	$Q_s= 36.08$
2	Low intensity	$R= 38.452$	$Q_s= 72.08$
3	Moderate Intensity	$R= 57.678$	$Q_s= 144.01$
4	High intensity	$R= 76.904$	$Q_s= 287.71$
5	Very high intensity	$R= 96.13$	$Q_s= 574.80$

Table 2: the bivariate statistical analysis display the weights of different parameters contributing upland and channel erosion in WDW.

Classes	Factors	Attributions	$N_{pix}(N_{CG})$	$N_{pix}(S_{CG})$	Densclas	Densmap	Densclas/ Densmap	NRF (W_{CG})	IV	Class area%	DF area%
1	**Slope aspect**	N (0-22.5, 337.5 - 360)	378472	863	0.002	0.05	0.046	0.035	-3.084	15.252	0.698
2		S (157.5-202.5), W (247.5 292.5)	549442	2963	0.005	0.05	0.108	0.120	-2.223	22.142	2.398
3		E (67.5-112.5)	238330	27378	0.115	0.05	2.307	1.108	0.836	9.604	22.154
4		NW (292.5-337.5), SE (112.5-157.5)	633988	39523	0.062	0.05	1.252	1.599	0.225	25.549	31.982
5		NE (22.5-67.5), SW (202.5-247.5)	681255	52852	0.078	0.05	1.558	2.138	0.443	27.453	42.768
1	**Curvature**	Flat (0.001-0.05)	216544	2034	0.009	0.05	0.189	0.049	-1.668	8.726	1.646
2		Concave (< -0.001)	1075082	41856	0.039	0.05	0.782	1.016	-0.246	43.324	33.870
3		Convex (> 0.05)	1189861	79689	0.067	0.05	1.345	1.935	0.296	47.950	64.484
1	**Sediment Transport Index (STI)**	Very low	749590	847	0.001	0.05	0.023	0.034	-3.790	30.328	0.685
2		Low	842593	1398	0.002	0.05	0.033	0.057	-3.406	34.091	1.131
3		Moderate	372172	13163	0.035	0.05	0.707	0.533	-0.346	15.058	10.651
4		High	463722	69270	0.149	0.05	2.988	2.803	1.094	18.762	56.053
5		Very high	43495	38901	0.894	0.05	17.888	1.574	2.884	1.760	31.479
1	**Compound Transport Index (CTI)**	Very low (8.5 - 25.47)	375146	196	0.001	0.05	0.010	0.008	-4.561	15.178	0.159
2		Low (6.5 - 8.5)	849025	1112	0.001	0.05	0.026	0.045	-3.642	34.352	0.900
3		Moderate (5.5 - 6.5)	379763	5946	0.016	0.05	0.313	0.241	-1.161	15.365	4.811
4		High(4.5 - 5.5)	646185	36856	0.057	0.05	1.141	1.491	0.132	26.145	29.824
5		Very high (2.8 -4.5)	221452	79469	0.359	0.05	7.177	3.215	1.971	8.960	64.306
1	**Drainage density**	Very low	182982	1197	0.007	0.05	0.131	0.048	-2.034	7.403	0.969
2		Low	721401	6217	0.009	0.05	0.172	0.252	-1.758	29.188	5.031
3		Moderate	869816	38571	0.044	0.05	0.887	1.561	-0.120	35.193	31.212
4		High	598968	49759	0.083	0.05	1.661	2.013	0.508	24.234	40.265
5		Very high	98405	27835	0.283	0.05	5.657	1.126	1.733	3.981	22.524
1	**Lineament intensity**	Very low	553047	243	0.000	0.05	0.009	0.010	-4.728	22.223	0.197
2		Low	600062	594	0.001	0.05	0.020	0.024	-3.915	24.112	0.481
3		Moderate	594055	32511	0.055	0.05	1.102	1.315	0.097	23.871	26.308
4		High	477600	51478	0.108	0.05	2.171	2.083	0.775	19.191	41.656
5		Very high	263876	38753	0.147	0.05	2.957	1.568	1.084	10.603	31.359
5	**Proximity to major faults**	Very close	340381	49527	0.146	0.03	5.112	2.004	1.632	7.839	40.077
4		Close	337645	61290	0.182	0.03	6.378	2.480	1.853	7.776	49.596
3		Intermediate	325146	11871	0.037	0.03	1.283	0.480	0.249	7.489	9.606
2		Distant	297837	654	0.002	0.03	0.077	0.026	-2.562	6.860	0.529
1		Very distant	3040869	237	0.000	0.03	0.003	0.010	-5.900	70.036	0.192
5	**Proximity to erosive streams**	Very close	545263	77531	0.142	0.03	4.996	3.137	1.609	12.558	62.738
4		Close	799197	24559	0.031	0.03	1.080	0.994	0.077	18.407	19.873
3		Intermediate	890593	12945	0.015	0.03	0.511	0.524	-0.672	20.512	10.475
2		Distant	1100985	6573	0.006	0.03	0.210	0.266	-1.562	25.357	5.319
1		Very distant	1005840	1971	0.002	0.03	0.069	0.080	-2.676	23.166	1.595
1	**Stream Power Index (SPI)**	Very low	149590	542	0.004	0.05	0.072	0.022	-2.625	6.052	0.439
2		Low	942593	763	0.001	0.05	0.016	0.031	-4.123	38.137	0.617
3		Moderate	931172	4954	0.005	0.05	0.106	0.200	-2.241	37.675	4.009
4		High	403722	28778	0.071	0.05	1.426	1.164	0.355	16.335	23.287

5		Very high	44495	88542	1.990	0.05	39.799	3.582	3.684	1.800	71.648