Chapter 20
Soil Erosion Prioritization of Yarmouk River Basin, Jordan Using Multiple Approaches in a GIS Environment

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20.1 Introduction

Soil and water are among the most important renewable natural resources on earth. A primary natural resource, the soil is a key player in natural ecosystems (Singer and Warkentin 1996), and an important habitat for living organisms such as plants, animals, agricultural crops, as well as human beings. However, there are many environmental challenges facing the soil such as erosion. Soil erosion is a natural problem exacerbated by human activities, and if serious sediment management strategies are not put in place, its danger in watersheds may increase. Soil erosion has increased at the global scale and is predicted to increase by an average of 14% across the universe by the end of this century (Yang et al. 2003). Soil erosion is a significant environmental issue and has become a major threat to terrestrial ecosystems, particularly to the sustainable development of agriculture (Sun et al. 2013). If the current rate of soil erosion continues in the future, it will have serious consequences such as (1) the loss of fertile topsoil and hence a decrease in land productivity (Pimentel 2006); (2) decline in environmental quality and biomass productivity (Lal 2004); (3) increase in sedimentation rates of rivers and lakes, leading to more flood-related disasters and water pollution (Rothwell et al. 2005); and (4) change in contents of soil nutrients (e.g., carbon, nitrogen, and phosphorus). Consequently, sustainable management of natural resources is essential to preserve them for the future. Watershed management

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implies the proper use of all land and water resources of a watershed for optimum production with minimum hazard to natural resources (Sebastian et al. 1995).

Recognizing the hazardous effects of soil erosion on water quality and agricultural production, different approaches have been developed for prioritizing watersheds and mapping soil erosion prone areas. Various methods have been applied for soil erosion assessment such as the Universal Soil Loss Equation or morphometric analysis method. Many researchers prioritized the watersheds based on morphometric analysis (Ameri et al. 2018; Farhan and Anaba 2016; Shivhare et al. 2018). Also, Land use/land cover has been used by many researchers (Javed et al. 2009; Shivhare et al. 2018) to prioritize watersheds. Morphometric analysis has been used in several fields such as the assessment of natural resources and environmental hazards, and prioritizing watersheds to protect water and soil resources (e.g., Ameri et al. 2018; Bisht et al. 2020; Singh et al. 2008, 2014). Research findings showed that the morphometric analysis provides basic information about hydrogeology erosion-prone areas and characteristics of watersheds in terms of ground and surface water potential.

Morphometry refers to the measurement and mathematical evaluation of the configuration of the earth's surface, and the shape and dimensions of its landforms (Clark 1966). Morphometric parameters describe the form and structure of drainage basins and their drainage networks (Biswas et al. 1999). The physical characteristics of a watershed's vulnerability to various geohazards, such as soil erosion and floods, are identified and understood using morphometric metrics (Bhatt and Ahmed 2014). Different parameters (e.g., lithology, topography, drainage pattern) are important for watershed management (Pisal et al. 2013). Geology, relief, and climate are the key players in running water ecosystem functioning at the basin scale (Frissell et al. 1986). The quantitative analysis of morphometric parameters is a cornerstone in watershed prioritization for soil and water conservation (Kanth 2012). Morphometric descriptors represent relatively simple approaches to describing basin processes and comparing basin characteristics (Mesa 2006). Thus, prioritizing a watershed based on morphometric characterization is crucial for improved water and soil conservation measures (Aher et al. 2014). According to Biswas et al. (1999), watershed prioritization is the ranking of different sub-watersheds of a watershed according to the order in which they must be taken for treatment and soil conservation measures.

Remote sensing and geographic information systems (GIS) are highly efficient and effective in developing, managing, and prioritizing the sub-watersheds for many geohazards such as soil erosion (Chatterjee et al. 2014; Malik et al. 2011; Okumura and Araujo 2014; Pandey et al. 2009; Rudraiah et al. 2008). The availability of free access to high-quality resolution topographic data (digital elevation models) has equipped researchers with effective GIS tools to study drainage basins and to quantify with high accuracy different parameters (basic, linear, shape, and relief) of drainage basins. Additionally, it assists in the prioritization of sub-watersheds for soil erosion or flood susceptibility (Biswas et al. 1999; Farhan and Anaba 2016; Nooka Ratnam et al. 2005; Patel et al. 2012). Awawdeh and Bani Domi (2007) assessed soil erosion of the Yarmouk River Basin using RUSLE in a GIS environment. The results showed that about 4.5% of the basin suffers erosion rates higher than the soil loss tolerance (10 tons/ha/yr) with 0.5 ton/ha/yr mean value of sediment yield. The overall objective

of this study was to prioritize the Yarmouk River Basin in terms of soil erosion. The area of investigation is undergoing a rapid land use/land cover change induced by rapid development, urbanization, and agricultural expansion. Two approaches will be applied to prioritize the study area, namely morphometric analysis and land use/land cover.

20.2   Study Area

The Yarmouk River forms the present northern boundary between Syria and Jordan for 40 km and then continues to form the border between Jordan and Palestine. About 1393 km^2 of the YRB basin total area (7242 km^2) lies within the borders of Jordan (Fig. 20.1), while the remainder is in Syria.

The altitudes of the basin vary from about 186 m below sea level in the northwest (Jordan Valley) to more than 1214 m in the south (Ras Munif) (Fig. 20.2). The climate is arid to semi arid (Awawdeh and Jaradat 2010), with mean annual rainfall ranging from about 133 mm in the east to about 460 mm in the west.
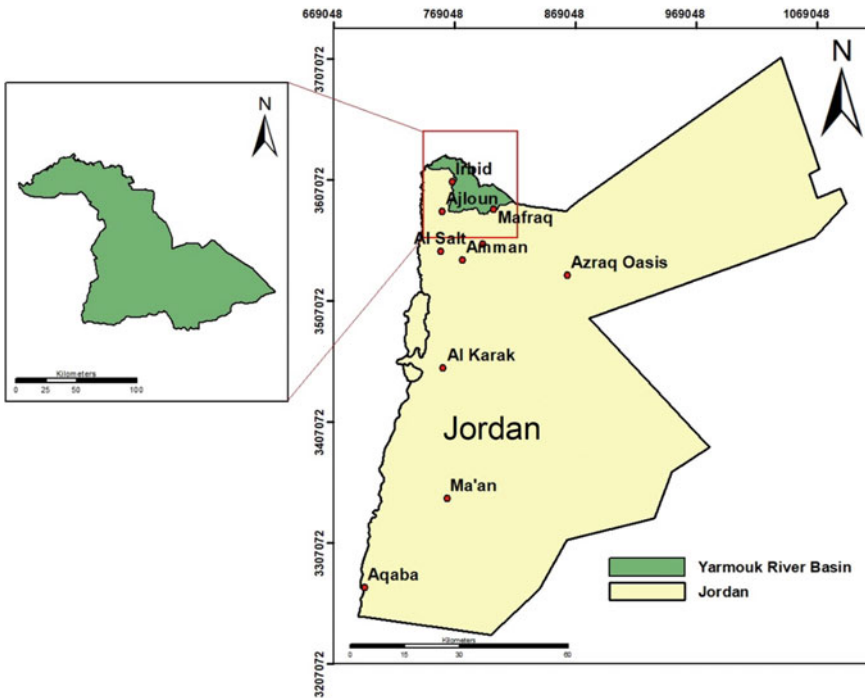

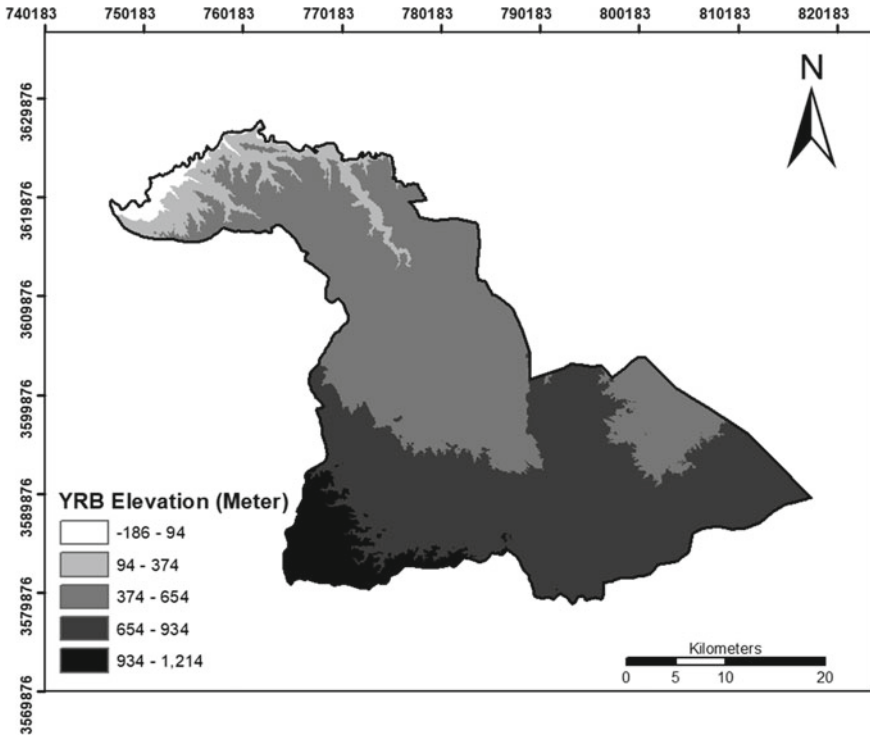**Fig. 20.1** Location map of the study area

Fig. 20.2 Digital elevation model (DEM) of the study area

The exposed rock formations YRB (Fig. 20.3) include the Ajlun Group, Balqa Group, and Jordan Valley Group of Upper Cretaceous to Tertiary age (Strahler 1952; Makhlouf et al. 1996; Moh'd 2000).

The oldest is the Wadi Es-Sir Limestone (WSL) formation belonging to the Ajlun Group. It consists of massive limestone, dolomite, and dolomitic limestone with chert nodules (Obeidat 1993). The WSL formation is overlain by rocks of the Balqa Group which include the formations: Wadi Umm Ghudran (WG), Amman Silicified Limestone (ASL), Muwaqqar Chalk-Marl (MCM), Umm Rijam Chert-Limestone (URC) and Wadi Shalala (WS). WG formation (the base of the Balqa Group) consists of marl, marly limestone, chalk, and chert. The ASL formation overlying WG consists of limestone, chert, chalk, and phosphorite beds that are exposed in the southern part of the basin. Bituminous marl and clayey marl of the MCM formation exposed in the central part of the basin overlies the ASL formation (Parker 1970; Makhlouf et al. 1996; Moh'd 2000). Alternating beds of limestone, chalk, and chert of the URC formation overlies the MCM formation (Awawdeh and Jaradat 2010). Basaltic flows (BS formation) of the Jordan Valley Group (Oligocene age) cover rocks of the Balqa Group in the eastern part of the basin. Additionally, basalts were found as
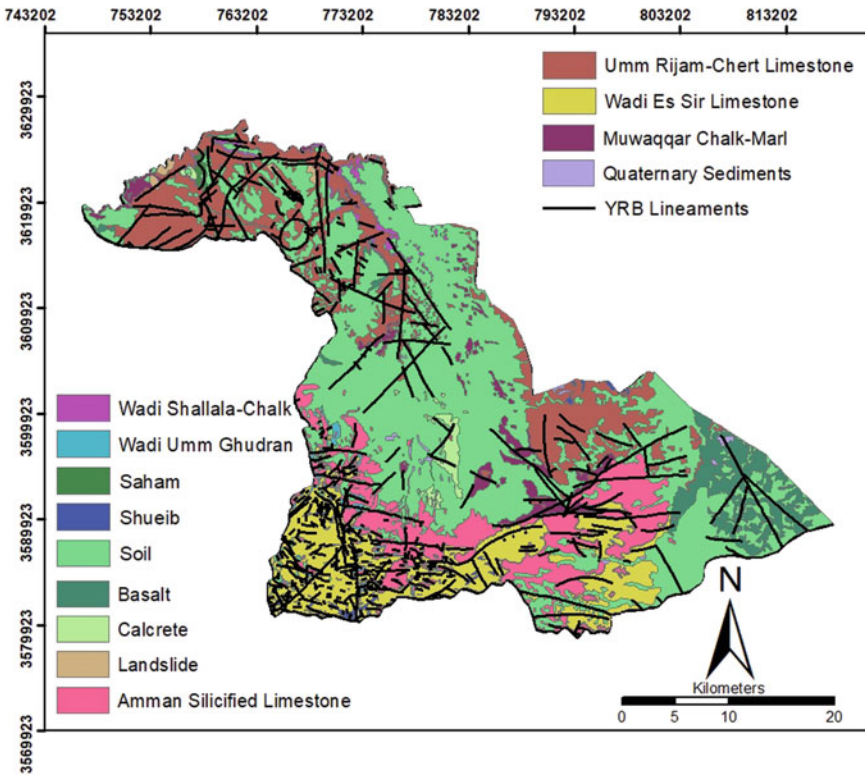
Fig. 20.3 Geological map of YRB

small exposures scattered to the south, north, and northwest of Irbid (Awawdeh and Jaradat 2010).

20.3   Data and Methods

20.3.1   Morphometric Analysis

20.3.1.1   Data Preparation

The following steps were carried out to calculate the morphometric parameters and to prioritize the sub-watersheds:

A digital elevation model from radar imagery (2006–2011), with 12.5 m resolution and UTM coordinate system zone 36 N was downloaded from Alaska Satellite Facility (2017). The DEM was preprocessed to fill in missing data (NoData) by applying the formula:

Filled = arcpy.sa.Con(arcpy.sa.IsNull(in_raster),arcpy.sa.FocalStatistics(in_raster, arcpy.sa.NbrRectangle(5,5),'MEAN'), in_raster).

Based on the stream network and flow direction maps, the watershed was subdivided into sub-watersheds.

The maps of the main sub-watersheds and drainage networks were obtained using a suitable threshold value to evaluate the main and minor streams using the method described by Strahler (1952, 1964). Stream order, number, lengths of streams of each different order, and other basic morphometric parameters were used to classify the watershed into sub-watersheds.

The basic morphometric parameters were calculated using ArcGIS 10.3 software.

Other morphometric parameters were calculated using the standard methods and formulae (Appendix 1).

The Morphometric Ranking Method is based on classifying the morphometric parameters according to their risk potential. The parameters are divided into two groups: group I included morphometric parameters that are considered directly proportional to soil erosion risk, which means that the highest value represents high susceptibility to the risk. By contrast, group II includes morphometric parameters that are considered inversely proportional to soil erosion risk, which means that the highest value represents low susceptibility to the risk. Prioritizing the sub-watersheds by using the morphometric ranking method, based on the compound factor. Preparing the soil erosion susceptibility maps according to the results of the morphometric ranking method.

20.3.1.2 Prioritization by Morphometric Analysis

Morphometric analysis was carried out to assess the susceptibility of YRB to soil erosion with the aid of GIS. The YRB was divided into 44 sub-watersheds based on the digital elevation model using the Hydrology toolbox in ArcGIS 10.3 (Fig. 20.4), and twenty-one morphometric parameters related to the soil erosion were calculated to rank and prioritize the sub-watersheds and evaluate their soil erosion susceptibility (Appendix 1).

The morphometric parameters were classified into four groups: basic, linear, shape, and relief. Basic parameters were derived from the digital elevation model using GIS techniques and included basin area, basin length, basin perimeter, number of streams, lengths of streams for each stream order, and bifurcation ratio. The stream frequency, drainage density, drainage texture, form factor, elongation ratio, and circularity ratio were estimated using mathematical equations (Appendix 1) elaborated by (Strahler 1952). Other important geomorphometric parameters (e.g., relative relief, basin relief, and ruggedness number) were also quantified according to mathematical formulas.

Prioritizing the sub-watersheds for soil erosion can be performed using the Compound Factor (Farhan and Anaba 2016; Shivhare et al. 2018; Ameri et al. 2018). Some of the morphometric parameters are directly related and others are inversely related to soil erosion potentiality (Table 20.1). Linear and relief parameters have
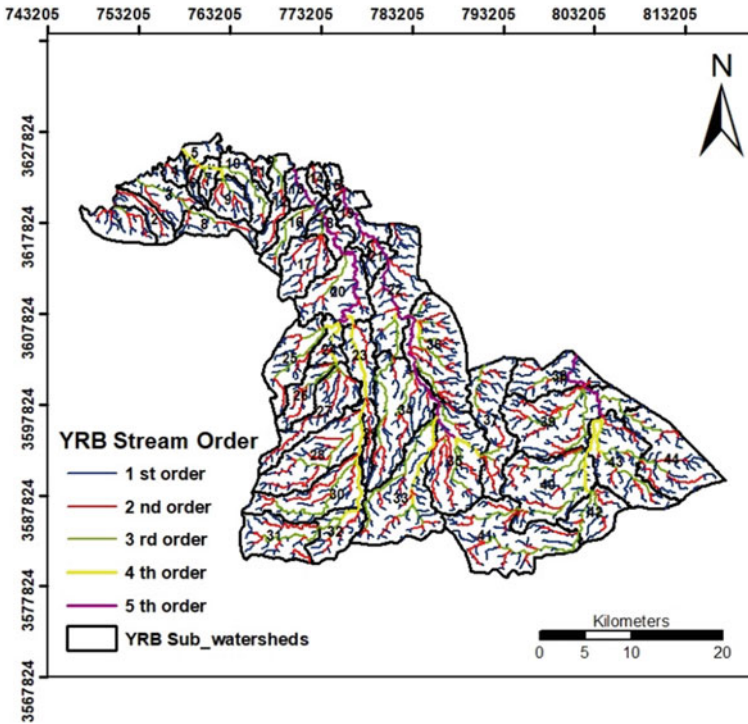
Fig. 20.4 Stream order and drainage pattern of YRB

a direct relationship with erodibility. Thus, the highest value of the linear or relief parameter was rated as rank 1, the second highest value as rank 2, and so on (Farhan and Anaba 2016; Javed et al. 2009). By contrast, the shape parameters have an inverse relation with erodibility (Farhan and Anaba 2016; Javed et al. 2009), which means that the lowest value of the shape parameter was rated as rank 1 and second lowest as rank 2 and so on. Parameters having the same values were assigned similar rankings.

The parameters which have a direct relationship with erodibility are: mean bifurcation ratio (R_{bm}), drainage density (D_d), length of overland flow (L_o), drainage texture (D_t), stream frequency (F_s), relief ratio (R_r), basin slope (S_w), and ruggedness number (R_n) (Farhan and Anaba 2016; Ameri et al. 2018). The parameters which have an inverse relationship with erodibility are: elongation ratio (R_e), circularity ratio (R_c), shape factor (B_s), and compactness coefficient (C_c) (Farhan and Anaba 2016; Ameri et al. 2018). After ranking sub-watersheds, the ranking values for all parameters of each sub-watershed were added up and then divided by the number of all parameters to calculate the compound factor (C_f). From the group of sub-watersheds, the highest prioritized rank was assigned to sub-watersheds which had the lowest compound factor and vice versa (Patel et al. 2012). The values of the compound factor were normalized from 0 for the lowest rank value and 1 for

Table 20.1 Morphometric parameters applied for soil erosion assessment

	Par. No.	Morphometric parameter
Direct relationship	1.	Mean bifurcation ratio (R_{bm})
	2.	Drainage density (D_d)
	3.	Length of overland flow (L_o)
	4.	Drainage texture (D_t)
	5.	Stream frequency (F_s)
	6.	Relief ratio (R_r)
	7.	Basin slope (S_w)
	8.	Ruggedness number (R_n)
Inverse relationship	9.	Elongation ratio (R_e)
	10.	Circularity ratio (R_c)
	11.	Shape factor (B_s)
	12.	Compactness coefficient (C_c)

Table 20.2 Classes of soil erosion prioritization based on C_f normalization

Normalization	Priority
0.0–0.2	Very high priority
0.2–0.4	High priority
0.4–0.6	Moderate priority
0.6–0.8	Low priority
0.8–1.0	Very low priority

the highest rank value to obtain a uniform scale, which was then grouped into five priority categories (very high, high, moderate, low, and very low) (Table 20.2).

20.3.2 Prioritization by Land Use/Land Cover (LULC)

Jawarneh and Biradar (2017) developed a Land Cover Database for Jordan at 30 m resolution. Based on this study, sub-watersheds of YRB were prioritized for soil erosion. Eight classes of LULC were considered for prioritization of the sub-watersheds: barren land, agriculture, rangeland, orchards, forest, rocky outcrops, built-up area and water body. The area and the proportion of each LULC class where calculated in each sub-watershed, and then each class rated for soil erosion priority (from 1 to 8). The highest priority (rate = 1) was assigned to barren land, and lowest priority (rate = 8) was given to water bodies according to local experts and litera-ture. The weight of each class was calculated by multiplying the area by its rating. The weighted values were summed to calculate the compound factor (C_f) value for each sub-watershed. In the final step, all sub-watersheds were then grouped into

five priority categories (very high, high, moderate, low, and very low) based on the compound factor (C_f) values as follows:

$$C_f = \sum_{i=1}^{n} \frac{A}{100} 100\% \times R$$

where: C_f: compound factor, A: LULC type area in each sub-watershed, R: LULC rating value, n: number of sub-watersheds.

20.4 Results and Discussion

20.4.1 Prioritization Based on Morphometric Analysis

The results of the morphometric analysis of the whole basin are presented in Appendix 2, and those for the sub-watersheds are shown in Appendix 3. The dominating drainage pattern is dendritic (Fig. 20.4), which develops on a land surface that is homogeneous, non-porous, steeply sloped, with no structural control, and the underlying rock is of uniform resistance to erosion (Kabite and Gessesse 2018; Soni 2017). YRB is a fifth-order basin with a total area of 1393 km^2, a length of 76.94 km, and a perimeter of 247.70 km. The total number of streams (N_u) is 2109, where first-order streams formed 51.78% of the total streams. The mean bifurcation ratio (R_{bm}) is 2.05 indicating a low disturbed watershed by geologic structures (Strahler 1952).

20.4.1.1 Morphometric Parameters

1. **Basic Parameters**

The drainage area (A) indicates the volume of water that can be generated from precipitation and the number of streams that may increase runoff (Farhan and Anaba 2016). The drainage area of sub-watersheds in YRB ranges from 5.31 km^2 (SW6) to 74.34 km^2 (SW41). The smallest areas were found in sub-watersheds: 6, 14, 4, and 15, respectively. The largest areas were found in sub-watersheds: 41, 39, 33, and 34, respectively. The study showed that the maximum value of **perimeter (P)** is 52.60 km in SW39, and the minimum is 12.85 km in SW14. **Basin length (L_b)** constitutes a basic input parameter to calculate many other morphometric parameters specially shape parameters. It is important in hydrological calculations and increases as the drainage increases (Patel et al. 2012). Basin length for the 44 sub-watersheds in YRB varies between 3.83 km for SW4 to 16.34 km for SW33. **The stream order (U)** describes the drainage network in quantitative terms. In this study, the stream order is derived based on the Strahler method (1952). The highest stream order in

the YRB sub-watershed is 4. **The number of streams (N_u)** of various orders for each sub-watershed was counted in YRB. SW41 has the greatest total number of streams (122 streams) and SW6 has the lowest total number of streams (5 streams). The numbers of first-order streams (N_1) vary from one sub-watershed to another. It ranges from 3 in SW6 to 64 in SW41. Among the 44 sub-watersheds, SW39 has the greatest total length of streams (101.09 km), whereas SW15 has the lowest total length of streams (4.98 km).

2. **Linear Parameters**

Bifurcation Ratio (R_b) and Mean Bifurcation Ratio (R_{bm})

The bifurcation ratio is an indicator of relief and dissection (Farhan and Anaba 2016). In general, bifurcation ratio values vary between 2 for flat or rolling drainage basins, and 6 for watersheds where the geological structure has distorted the drainage pattern (Strahler 1964). Watersheds with low structure disturbance or without any distortion of drainage pattern have low values of R_b (Strahler 1964). The bifurcation ratio has a direct relationship with erosion. YRB showed a variation in R_{bm} from 1.14 for SW13 indicating the lowest sensitivity to erosion to 11.07 for SW17. The highest values of R_{bm} were found in SWs 17, 23, 40, and 20, respectively. Whereas the lowest values of R_{bm} were found in SWs 13, 37, 2, and 21, respectively.

Drainage Density (D_d)

Drainage density depends on climatic conditions, vegetation, landscape properties (e.g., soil and rock), and relief (Kelson and Wells 1989; Moglen et al. 1998; Oguchi 1997). It is a measure of runoff potential (Chorley 1969), which yields sediment transportation and erosion susceptibility (Bates and Campbell 2001; Ozdemir and Bird 2009). Subsoil material that is highly permeable, and under dense vegetation, low relief, and low runoff develop low drainage density, whereas landscapes characterized by impermeable subsoil materials, sparse vegetation, higher runoff, and mountainous relief develop high drainage density (Macka 2001; Chow 1964).

The values of D_d for the 44 sub-watersheds in YRB are relatively low. The lowest value of D_d (0.66) was found for SW5, which is considered a well-drained basin because of its high infiltration capacity. SW35 has the highest value (1.61) and is considered a poorly drained basin because of its low infiltration capacity which implies the presence of highly dissected topography, steep slopes, and impermeable subsurface materials. Therefore, sub-watershed 35 has the highest susceptibility to erosion. The highest values of D_d were identified in SWs 35, 36, 30, and 34, respectively. The lowest values of D_d were found in SWs 5, 15, 11, and 14, respectively.

Length of Overland Flow (L_o)

Length of overland flow (L_o) refers to the length of the flow of water over the ground before it becomes concentrated into indefinite stream channels (Horton 1945). It has a significant impact on the amount of water needed to exceed a particular erosion threshold. It is dependent on the kind of rock, permeability, climatic conditions,

vegetation cover, relief, and the length of erosion (Schumm 1956). The length of overland flow (L_o) has a direct relation with erosion. L_o varies from 0.31 for SW35 to 0.76 for SW5. The lower value of L_o indicates quicker surface runoff and a well-developed drainage network, a higher slope, lowest susceptibility to erosion. The highest values of L_o were found in SWs 5, 15, 11, and 14, respectively. The lowest values of L_o were found in SWs 35, 36, 30, and 34, respectively.

Drainage Texture (D_t)

Drainage texture is determined by the underlying lithology, infiltration capacity, and relief aspect of the landscape (Farhan and Anaba 2016). The value of the drainage texture ranges between 0.34 (SW6) and 2.9 (SW36). These values imply very coarse to coarse texture. The highest values of D_t were found in SWs 36, 35, 41, and 40, respectively, indicating the highest sensitivity to erosion The lowest values of D_t were found in SWs 6, 15, 11, and 2, respectively.

Stream Frequency (F_s)

Stream frequency refers to the number of streams per unit of area (Horton 1945). This parameter has a direct correlation with erosion (Carlston 1963). The value of stream frequency (F_s) in YRB ranges from 0.94 (SW6) to 2.46 (SW7). The highest values of F_s were found for SWs 7, 24, 36, and 42, respectively. The lowest values of F_s were found for SWs 6, 2, 30, and 25, respectively. Hence, SW7 with the highest F_s has the highest susceptibility to erosion.

3. **Shape Parameters**

Elongation Ratio (R_e)

The values of R_e varies from 0 (highly elongated shape) to 1.0 (perfectly circular shape). Strahler (1964), classified drainage basins into five categories based on R_e: circular (0.9–1.0), oval (0.8–0.9), less elongated (0.7–0.8), elongated (0.5–0.7), and more elongated (< 0.5). YRB is an elongated basin with R_e value of 0.55. R_e has an inverse correlation with erosion. A circular basin leads to more discharge of runoff than an elongated basin (Singh and Singh 1997). SW9 has the highest R_e value (0.81) which indicates the least sensitivity to erosion, whereas SW29 has the lowest R_e (0.39) and indicates more susceptibility to erosion (Table 20.3).

Circularity Ratio (R_c)

The length and frequency of streams, geological structures, climate, roughness, and slope determine the Circularity Ratio (R_c) (Ameri et al. 2018). The circular shape of the watershed, high roughness, and permeability of the surface is represented by high values of R_c (Ameri et al. 2018). In a circular catchment, runoff often travels a similar distance and is therefore likely to arrive at the outflow at the same time (Abuzied et al. 2016). The outflow is located at one end of the primary axis in the elongated catchments, though, and as a result, the runoff is likely to disperse over

Table 20.3 Drainage basins categories of elongation ratio in YRB

Shape	Sub-watersheds
(0.9–1.0) Circular	None
(0.8–0.9) Oval	9
(0.7–0.8) Less elongated	4, 13, 17, 18, 20, 35, 40
(0.5–0.7) Elongated	1, 3, 5, 6, 7, 8, 10, 11, 14, 15, 19, 21, 22, 23, 24, 25, 26, 28, 30, 31, 32, 33, 34, 36, 37, 38, 39, 41, 42, 43, 44
(> 0.5) More elongated	2, 12, 16, 27, 29

time and produce a smaller flood peak (Schumm 1956). R_c and soil erosion are inversely correlated (Aher et al. 2014; Ameri et al. 2018). R_c value varies from 0, for a perfectly elongated shape, to 1 for perfect circular shape (Bisht et al. 2018). YRB has R_c value of 0.29, where it varies from 0.19 for SW29, indicating low permeability and high susceptibility to erosion, to 0.60 for SW9, indicating high permeability and low susceptibility to erosion. The lowest values of R_c were found in SWs 29, 12, 27, and 16, respectively, whereas, the highest values of R_c were found in SWs 9, 32, 1, and 4, respectively.

Shape Factor (B_s)

The shape factor is largely affected by the rate of sediment, water volume, and the length and roughness of the drainage network (Ameri et al. 2018). The shape factor has an inverse relationship with erosion (Farhan and Anaba 2016; Ameri et al. 2018). Strong relief and steep ground slopes yield low B_s values which indicate high potential runoff hazards. B_s values in YRB sub-watersheds vary between 1.92 for SW9 and 8.39 for SW29. Accordingly, SW29 has the least susceptibility to erosion. The lowest values of B_s were found in SWs 9, 4, 13, and 40, respectively, whereas the highest values of B_s were found in SWs 29, 27, 12, and 16, respectively.

Compactness Coefficient (C_c)

The Compactness Coefficient (C_c) has a direct relationship with the watershed penetration capacity and has an inverse relationship with soil erosion potentiality (Ameri et al. 2018). The lowest C_c in YRB sub-watersheds was found for SW9 with a value of 1.29, indicating that this sub-watershed has the lowest infiltration capacity and is highly susceptible to erosion. SW29 has the highest C_c with a value of 2.27, indicating that this sub-watershed has the highest infiltration capacity and thus the lowest sensitivity to erosion. The lowest values of C_c were found in SWs 9, 32, 1, and 4, respectively, whereas, the highest values of C_c were found in SWs 29, 12, 27, and 16, respectively.

4. **Relief Parameters**

Basin Relief (H)

The total slope of the drainage basin and the severity of erosion processes that operate on the slopes of a watershed are indicated by the Basin relief (H) (Ameri et al. 2018). Basin relief has a direct correlation with erosion (Ameri et al. 2018). It is found that the total basin relief of the YRB is 1400 m, while it varies from a minimum of 90 m (SW42) to a maximum of 645 m (SW1).

Relief Ratio (R_r)

Usually, runoff flow (R_r) in watersheds has a direct relationship with the relief ratio, the slope of the earth's surface, and the slope of the streams and consequently, the erosion of the watershed (Ameri et al. 2018; Abuzied et al. 2016). The highest value of R_r in YRB sub-watersheds was found for SW4 (0.13) and the lowest value was found for SWs 22 and 43 (0.008). SW4 has the highest susceptibility to erosion compared to other sub-watersheds. The highest values of R_r were found in SWs 4, 11, 14, and 5, respectively. The lowest values of R_r were found in SWs 43, 22, 44, and 42, respectively.

Basin Slope (S_w)

The slope refers to the angular inclination of terrain between hilltops and valley bottoms. The slope steepness influences the formation of drainage networks. The slope is controlled by the climatomorphogenic processes and rock resistance (Gouri Sankar Bhunia 2013; Magesh and Chandrasekar 2014). The slope of a basin affects the amount and the timing of runoff, where a higher slope degree causes rapid runoff and increased erosion rate (potential soil loss) with less groundwater recharge potential (Meraj et al. 2013). The maximum slope of 7.90° was found for SW4, indicating high sensitivity of this sub-watershed to erosion, whereas the lowest slope was found for SW43 with a value of 0.48°, indicating that this sub-watershed is less prone to erosion. The highest values of S_w were found in SWs 4, 11, 14, and 5, respectively. The lowest values of S_w were found in SWs 43, 22, 44, and 42, respectively.

Ruggedness Number (R_n)

According to Aher et al. (2014), areas of low relief but high drainage density are described as ruggedly textured, whereas areas of high relief have less dissection. R_n has a direct correlation with erodibility (Ameri et al. 2018). The highest value of R_n in YRB sub-watersheds was observed in SW30 (0.78), where both total relief and drainage density values are high, i.e., in this sub-watershed slope is very steep associated with its slope length, indicating that SW30 (0.78) has the highest sensitivity to erosion, SW21 (0.10) has the lowest sensitivity to erosion. The highest values of R_n were found in SWs 30, 27, 2, and 1, respectively, and the lowest values of R_n were found in SWs 21, 42, 23, and 43, respectively.

Based on the computed morphometric parameters, the compound factor (C_f) was calculated for each sub-watershed and then normalized in order to classify the sub-watersheds into five categories of soil erosion susceptibility. The lowest C_f (12.25) was found in SW1 and thus the highest degree of soil erosion risk. SWs 3 and 35 have the same C_f value (17.08) with a very high priority of soil erosion, and SW7 with C_f (17.50) also has a very high priority of soil erosion. SWs 17, 27, 33, 4, 20, 10, 36, 28, 40, 30, 14, 32, 9, and 11 have a high priority compared with other sub-watersheds. The highest C_f (27.67) was found for SW21 with the least degree of susceptibility to soil erosion.

Results revealed that eighteen sub-watersheds (41% of the total) are classified as a very high and high priority. This means less than half of the YRB is expected to suffer from very high and high soil erosion susceptibility. Sub-watersheds with very high and high priority are found in the central, southwestern, and northwestern parts of the basin (Fig. 20.5). The main morphometric parameters affecting the spatial distribution of the susceptibility to soil erosion in the YRB are stream frequency (F_s), ruggedness number (R_n), relief ratio (R_r), mean bifurcation ratio (R_{bm}), drainage density (D_d), drainage texture (D_t), and compactness coefficient (C_c).

20.4.2 *Prioritization Based on Land Use/Land Cover (LULC)*

Prioritization of sub-watersheds by LULC is given in Table 20.4. It revealed that thirty-nine sub-watersheds (88.6% of the total area) are classified as a very high and high priority. SWs 1, 2, 3, 4, 5, 11, 13, 14, 15, 19, 23, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, and 44 are expected to suffer from very high soil erosion susceptibility. SWs 6, 7, 8, 9, 10, 12, 18, 20, 21, 22, 24, 39, 40, 41, and 43 are expected to suffer from high soil erosion susceptibility (Fig. 20.6).

The results obtained from the morphometric analysis suggest that 18 sub-watersheds with 613.29 km^2 (44% of YRB area) have the highest susceptibility to soil erosion. According to LULC analysis, there are 39 sub-watersheds with 1262.27 km^2 (90.60% of YRB area) that are expected to suffer from high soil erosion susceptibility. A combination of both methods suggests that 1, 3, 4, 7, 9, 10, 11, 14, 20, 27, 28, 30, 32, 33, 35, 36, and 40 are the most sensitive sub-watersheds to get influenced by soil erosion. The matching in the classification of the sub-watersheds potential for soil erosion using morphometric analysis and LULC methods was 61.36% (Fig. 20.6).
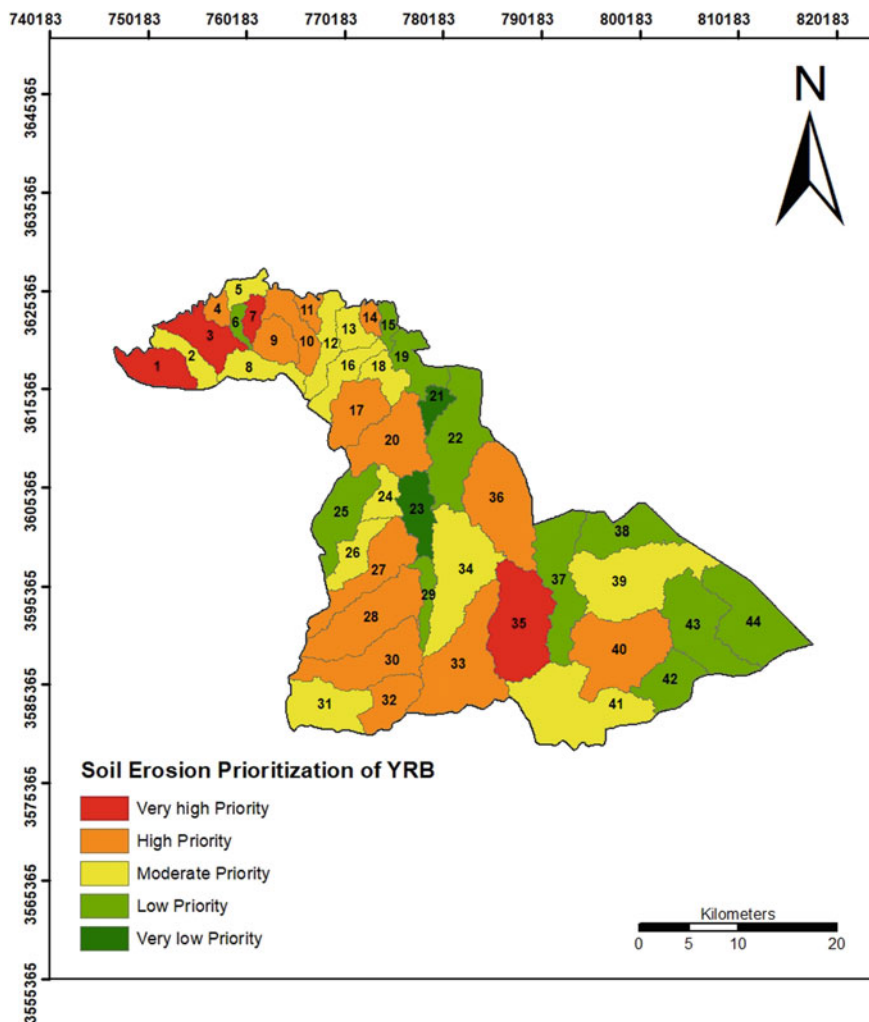
Fig. 20.5 Soil erosion susceptibility map for YRB sub-watersheds based on morphometric analysis

Table 20.4 Soil erosion susceptibility prioritization for YRB sub-watersheds based on LULC analysis

SW	Priority	SW	Priority	SW	Priority	SW	Priority
1	Very high	12	High	23	Very high	34	Very high
2	Very high	13	Very high	24	High	35	Very high
3	Very high	14	Very high	25	Very low	36	Very high
4	Very high	15	Very high	26	Very low	37	Very high
5	Very high	16	Moderate	27	Very high	38	Very high
6	High	17	Moderate	28	Very high	39	High
7	High	18	High	29	Very high	40	High
8	High	19	Very high	30	Very high	41	High
9	High	20	High	31	Very high	42	Moderate
10	High	21	High	32	Very high	43	High
11	Very high	22	High	33	Very high	44	Very high
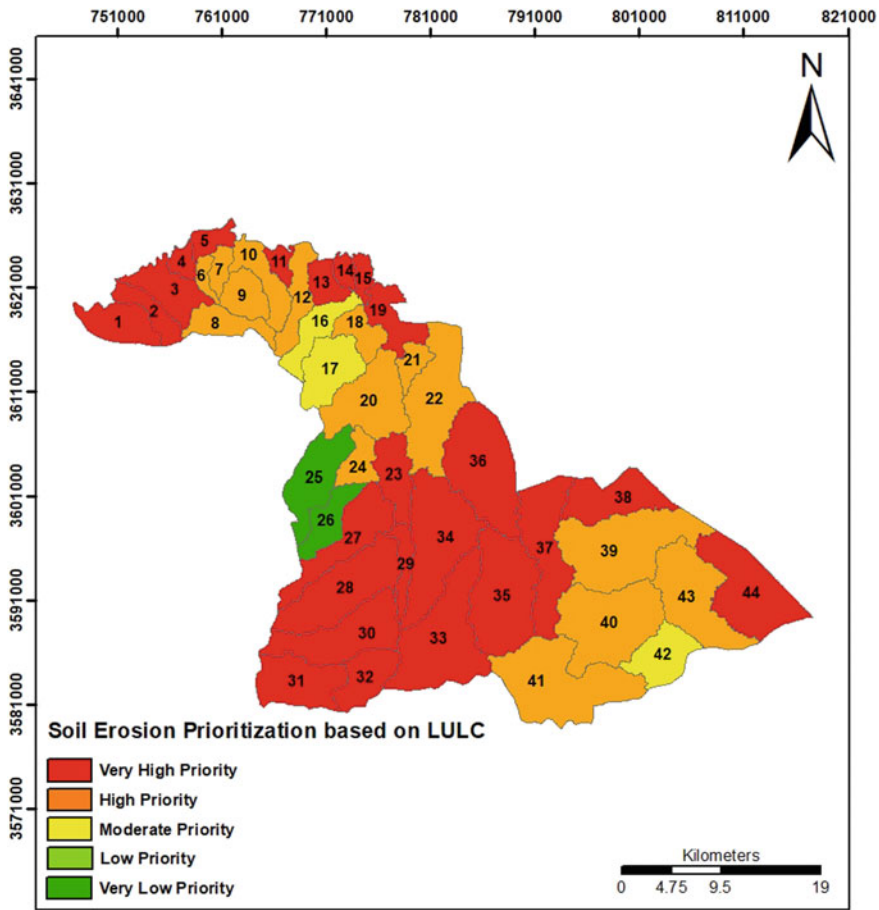
Fig. 20.6 Soil erosion susceptibility map for YRB sub-watersheds based on LULC analysis

20.5 Conclusions

Prioritization of sub-watersheds can be carried out by any one method, but in that case, the dependability of the result is low. Hence in this study, we adopted all two methods of prioritization so that the integration of these methods can provide more accurate and reliable results. The sub-watersheds with high susceptibility to erosion indicate that YRB is considerably affected by geologic structures (e.g., Sirhan Fault), which distorted the drainage pattern. The morphometric analysis points to many geometric distinctive features of the sub-watersheds of high soil erosion potential such as high drainage density, low permeability, sparse natural vegetation, and high relief. The elongated nature of the whole basin and its high stream frequency and density also contributed to the increased susceptibility to erosion. The multi-approach of sub-watershed prioritization decreases the uncertainty of results and hence makes

decisions of treatment simpler. Suitable erosion control measures are recommended strongly after field observations to preserve the land from further erosion.

Appendix 1: Methodology Adopted for Computation of Morphometric Parameters

Par. No.		Morphometric parameter	Formula/definition	References
Basic	1.	Basin area (A)	Plan area of the watershed (km^2)	Horton (1945)
	2.	Basin perimeter (P)	Perimeter of the watershed (km)	Horton (1945)
	3.	Basin length (L_b)	Length of the basin (km)	Horton (1945)
	4.	Stream order (U)	Hierarchical rank	Strahler (1952, 1964)
	5.	Total number of streams (N_u)	Total no. of streams of all orders	Strahler (1957)
	6.	Stream length (L_u)	Length of the stream (km)	Horton (1945)
	7.	Mean stream length (L_{sm})	$L_{sm} = L_u/N_u$ (km) where L_u = total stream length of all orders N_u = total no. of stream segments of order "u"	Horton (1945)
	8.	Stream length ratio (R_L)	$R_L = L_u/L_{u-1}$, where L_{u-1} = the total stream length of its next lower order	Horton (1945)
Linear	9.	Bifurcation ratio (R_b)	$R_b = N_u/N_{u+1}$, where N_{u+1} = no. of segments of the next higher order	Schumm (1956)
	10.	Mean bifurcation ratio (R_{bm})	R_{bm} = average of the bifurcation ratio of all orders	Strahler (1957)
	11.	Drainage density (D_d)	$D_d = L_u/A$, where L_u = total stream length of all orders (km) A = area of the watershed (km^2)	Horton (1945)
	12.	Length of overland flow (L_o)	$L_o = 1/(2 * D_d)$, where D_d = drainage density	Horton (1945)

(continued)

Par. No.		Morphometric parameter	Formula/definition	References
	13.	Drainage texture (D_t)	$D_t = N_u/P$, where N_u = total no. of stream segments of order "u" P = perimeter of the watershed (km)	Horton (1945)
	14.	Stream frequency (F_s)	$F_s = N_u/A$, where N_u = total no. of streams of all orders A = area of the basin (km^2)	Horton (1945)
Shape	15.	Elongation ratio (R_e)	$R_e = 1.128 * (A^{0.5})/L_b$, where A = area of the basin (km^2) L_b = basin length (km)	Schumm (1956)
	16.	Circularity ratio (R_c)	$R_c = 4 \times \pi \times A/P^2$, where $\pi = 3.14$ A = area of the basin (km^2) P = perimeter (km)	Miller (1953)
	17.	Shape factor (B_s)	$B_s = L_b^2/A$, where L_b = basin length (km) A = area of the basin (km^2)	Nooka Ratnam et al. (2005)
	18.	Compactness coefficient (C_c)	$C_c = 0.2812 * P/A^{0.5}$, where P = perimeter of the basin (km) A = area of the basin (km^2)	Horton (1945)
Relief	19.	Basin relief (H)	$H = h - h_1$, where h = maximum height (m) h_1 = minimum height (m)	Horton (1945)
	20.	Relief ratio (R_r)	$R_r = H/L_b$, where H = total relief (km) L_b = basin length (km)	Schumm (1956)
	21.	Relative relief ratio (R_v)	H/P, where H = total relief (km) P = perimeter of the basin (km)	Melton (1957)
	22.	Basin slope (S_w)	$H/L_b * 60$, where H = total relief (km) L_b = basin length (km)	Farhan and Anaba (2016)

(continued)

(continued)

Par. No.		Morphometric parameter	Formula/definition	References
	23.	Ruggedness number (R_n)	$R_n = D_d * H$, where H = basin relief (km) D_d = drainage density	Schumm (1956)
Hypsometric	24.	Hypsometric integral (HI)	$HI = (E_{mean} - E_{min})/(E_{max} - E_{min})$, where E_{mean} = the weighted mean elevation E_{max} = maximum elevation E_{min} = minimum elevation	Strahler (1952)

Appendix 2: Morphometric Parameters of YRB

Par. No.		Morphometric parameter					
Basic	1.	Basin area (A) (km^2)	1393.22				
	2.	Basin perimeter (P) (km)	247.70				
	3.	Basin length (L_b) (km)	76.94				
	4.	Stream order (U)	5	I	II	III	IV	V
	5.	Total number of streams (N_u)	2109	1092	519	307	85	106
	6.	Stream length (L_u) (km)	1854	890	493	315	78	79
	7.	Mean stream length (L_{sm}) (km)	0.88	0.82	0.95	1.03	0.91	0.74
	8.	Stream length ratio (R_L)			II/I	III/II	IV/III	V/IV
					0.55	0.64	0.25	1.02
Linear	9.	Bifurcation ratio (R_b)			I/II	II/III	III/IV	IV/V
					2.10	1.69	3.61	0.80
	10.	Mean bifurcation ratio (R_{bm})	2.052					
	11.	Drainage density (D_d) (km/km^2)	1.331					
	12.	Length of overland flow (L_o) (km)	0.376					

(continued)

(continued)

Par. No.		Morphometric parameter							
	13.	Drainage texture (D_t)	8.514						
	14.	Stream frequency (F_s)	1.514						
Shape	15.	Elongation ratio (R_e)	0.547						
	16.	Circularity ratio (R_c)	0.285						
	17.	Shape factor (B_s)	4.249						
	18.	Compactness coefficient (C_c)	1.866						
Relief	19.	Basin relief (H) (m)	1400						
	20.	Relief ratio (R_r)	18.195						
	21.	Relative relief ratio (R_v)	0.006						
	22.	Basin slope (S_w)	1.092						
	23.	Ruggedness number (R_n)	1.863						
Hypsometric	24.	Hypsometric integral (HI)	0.5858						

Appendix 3: The Morphometric Parameters of Sub-watersheds in YRB

SW	A	P	L_b	U	N_u	L_u	L_{sm}	R_{bm}	D_d	L_o	D_t	F_s	R_e	R_c	B_s	C_c	H	R_r	S_w	R_n	R_v	HI
1	23.77	23.45	9.27	3	38	27.13	0.71	4.14	1.14	0.44	1.62	1.62	0.59	0.54	3.61	1.35	645	0.070	4.18	0.74	0.57	0.028
2	14.58	23.22	8.76	2	14	17.02	1.22	1.33	1.17	0.43	0.60	0.96	0.49	0.34	5.26	1.71	636	0.073	4.36	0.74	0.61	0.027
3	25.25	31.44	9.93	3	44	29.10	0.66	1.70	1.15	0.43	1.40	1.74	0.57	0.32	3.90	1.76	620	0.062	3.75	0.71	0.58	0.020
4	6.85	13.04	3.83	2	9	7.89	0.88	2.00	1.15	0.43	0.69	1.31	0.77	0.51	2.14	1.40	504	0.132	7.90	0.58	0.68	0.039
5	9.47	17.30	5.55	2	11	6.23	0.57	2.67	0.66	0.76	0.64	1.16	0.63	0.40	3.25	1.58	452.2	0.082	4.89	0.30	0.58	0.026
6	5.31	14.87	5.06	2	5	5.3	1.07	1.50	1.01	0.50	0.34	0.94	0.51	0.30	4.82	1.81	401	0.079	4.75	0.40	0.73	0.027
7	7.72	15.93	5.31	3	19	7.75	0.41	1.83	1.00	0.50	1.19	2.46	0.59	0.38	3.65	1.61	391	0.074	4.42	0.39	0.67	0.025
8	17.86	27.53	9.21	3	25	19.10	0.76	1.63	1.07	0.47	0.91	1.40	0.52	0.30	4.75	1.83	378	0.041	2.46	0.40	0.63	0.014
9	17.16	18.96	5.74	3	24	22.51	0.94	1.68	1.31	0.38	1.27	1.40	0.81	0.60	1.92	1.29	336	0.058	3.51	0.44	0.64	0.018
10	20.80	31.44	10.08	3	28	21.18	0.76	4.10	1.02	0.49	0.89	1.35	0.51	0.26	4.88	1.94	587	0.058	3.49	0.60	0.70	0.019
11	6.96	16.32	4.57	2	9	5.84	0.65	2.00	0.84	0.60	0.55	1.29	0.65	0.33	3.00	1.74	484	0.106	6.35	0.41	0.68	0.030
12	19.94	32.47	11.34	3	23	22.05	0.96	1.83	1.11	0.45	0.71	1.15	0.44	0.24	6.44	2.05	544	0.048	2.88	0.60	0.69	0.017
13	12.37	18.66	5.16	2	15	13.02	0.87	1.14	1.05	0.48	0.80	1.21	0.77	0.45	2.15	1.49	397	0.077	4.62	0.42	0.64	0.021
14	6.00	12.85	4.02	2	10	5.27	0.53	1.50	0.88	0.57	0.78	1.67	0.69	0.46	2.70	1.47	349	0.087	5.20	0.31	0.82	0.027
15	6.92	16.24	5.22	2	8	4.98	0.62	3.00	0.72	0.69	0.49	1.16	0.57	0.33	3.94	1.74	313	0.060	3.60	0.23	0.83	0.019
16	19.68	31.47	10.18	3	29	22.12	0.76	1.63	1.12	0.45	0.92	1.47	0.49	0.25	5.27	2.00	414	0.041	2.44	0.47	0.73	0.013
17	30.10	27.47	8.56	3	46	37.55	0.82	11.07	1.25	0.40	1.68	1.53	0.72	0.50	2.43	1.41	308	0.036	2.16	0.38	0.68	0.011
18	14.81	22.17	5.85	3	21	16.35	0.78	1.60	1.10	0.45	0.95	1.42	0.74	0.38	2.31	1.62	326	0.056	3.35	0.36	0.66	0.015

(continued)

(continued)

SW	A	P	L_b	U	N_u	L_u	L_{sm}	R_{bm}	D_d	L_o	D_t	F_s	R_e	R_c	B_s	C_c	H	R_r	S_w	R_n	R_v	HI
19	21.19	32.25	7.83	3	25	22.44	0.90	2.94	1.06	0.47	0.78	1.18	0.66	0.26	2.90	1.97	227	0.029	1.74	0.24	0.77	0.007
20	45.00	38.35	10.74	4	69	54.06	0.78	5.43	1.20	0.42	1.80	1.53	0.70	0.38	2.57	1.61	292	0.027	1.63	0.35	0.72	0.008
21	9.66	17.98	5.30	2	12	10.43	0.87	1.40	1.08	0.46	0.67	1.24	0.66	0.38	2.90	1.63	94	0.018	1.07	0.10	0.30	0.005
22	57.84	48.78	15.05	3	82	71.60	0.87	1.75	1.24	0.40	1.68	1.42	0.57	0.31	3.92	1.80	122	0.008	0.49	0.15	0.55	0.003
23	23.17	30.62	9.31	3	27	26.14	0.97	6.18	1.13	0.44	0.88	1.17	0.58	0.31	3.74	1.79	124	0.013	0.80	0.14	0.48	0.004
24	14.09	21.97	6.40	3	31	19.31	0.62	1.67	1.37	0.37	1.41	2.20	0.66	0.37	2.90	1.65	136	0.021	1.28	0.19	0.43	0.006
25	35.27	36.20	12.86	3	40	42.65	1.07	1.64	1.21	0.41	1.11	1.13	0.52	0.34	4.69	1.71	393	0.031	1.83	0.48	0.31	0.011
26	19.45	27.60	9.85	3	24	24.25	1.01	1.80	1.25	0.40	0.87	1.23	0.51	0.32	4.99	1.76	364	0.037	2.22	0.45	0.37	0.013
27	37.68	44.33	15.76	4	57	52.16	0.92	4.07	1.38	0.36	1.29	1.51	0.44	0.24	6.60	2.03	546	0.035	2.08	0.76	0.29	0.012
28	55.25	44.14	14.92	3	79	71.25	0.90	1.69	1.29	0.39	1.79	1.43	0.56	0.36	4.03	1.67	547	0.037	2.20	0.71	0.35	0.012
29	11.65	27.60	9.88	3	17	14.46	0.85	4.14	1.24	0.40	0.62	1.46	0.39	0.19	8.39	2.27	220	0.022	1.34	0.27	0.30	0.008
30	46.93	41.53	14.21	4	51	67.90	1.33	4.46	1.45	0.35	1.23	1.09	0.54	0.34	4.30	1.71	539	0.038	2.28	0.78	0.41	0.013
31	35.49	29.94	9.65	3	42	42.90	1.02	1.67	1.21	0.41	1.40	1.18	0.70	0.50	2.62	1.41	343	0.036	2.13	0.42	0.58	0.011
32	23.82	23.41	8.08	3	32	29.34	0.92	2.15	1.23	0.41	1.37	1.34	0.68	0.55	2.74	1.35	337	0.042	2.50	0.42	0.46	0.014
33	69.01	48.87	16.34	4	104	95.13	0.92	2.08	1.38	0.36	2.13	1.51	0.57	0.36	3.87	1.65	438	0.027	1.61	0.60	0.47	0.009
34	65.23	50.96	15.92	3	84	91.49	1.09	1.79	1.40	0.36	1.65	1.29	0.57	0.32	3.89	1.77	280	0.018	1.06	0.39	0.27	0.005
35	62.31	41.28	12.64	4	106	100.32	0.95	2.27	1.61	0.31	2.57	1.70	0.71	0.46	2.56	1.47	367	0.029	1.74	0.59	0.34	0.009
36	63.59	40.75	14.13	4	118	100.05	0.85	2.24	1.57	0.32	2.90	1.86	0.64	0.48	3.14	1.44	238	0.017	1.01	0.37	0.24	0.006
37	49.50	49.73	15.81	3	75	63.25	0.84	1.25	1.28	0.39	1.518	1.52	0.50	0.25	5.05	1.99	191	0.012	0.73	0.24	0.42	0.004
38	33.84	33.93	11.50	3	49	43.69	0.89	1.86	1.29	0.39	1.44	1.45	0.57	0.37	3.91	1.64	168	0.015	0.88	0.22	0.29	0.005

(continued)

(continued)

SW	A	P	L_b	U	N_u	L_u	L_{sm}	R_{bm}	D_d	L_o	D_t	F_s	R_e	R_c	B_s	C_c	H	R_r	S_w	R_n	R_v	HI
39	73.59	52.61	15.61	4	110	101.09	0.92	4.61	1.37	0.36	2.09	1.50	0.62	0.33	3.31	1.72	182	0.012	0.70	0.25	0.29	0.003
40	65.08	44.11	12.11	4	103	89.38	0.87	5.98	1.37	0.36	2.34	1.58	0.75	0.42	2.26	1.54	208	0.017	1.03	0.29	0.40	0.005
41	74.34	50.12	15.72	3	122	93.22	0.76	1.65	1.25	0.40	2.43	1.64	0.62	0.37	3.33	1.64	247	0.016	0.94	0.31	0.44	0.005
42	26.45	27.69	8.31	3	47	34.19	0.73	1.67	1.29	0.39	1.70	1.78	0.70	0.43	2.61	1.51	90	0.011	0.65	0.12	0.28	0.003
43	52.30	46.68	13.24	3	75	71.62	0.96	1.76	1.37	0.37	1.61	1.43	0.62	0.30	3.35	1.82	106	0.008	0.48	0.15	0.52	0.002
44	55.94	41.47	13.49	3	80	71.39	0.89	1.82	1.28	0.39	1.93	1.43	0.63	0.41	3.25	1.56	122	0.009	0.54	0.16	0.48	0.003

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