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Delineating Groundwater Recharge Potential through Remote Sensing and Geographical Information Systems

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Abstract: Owing to the extensive global dependency on groundwater and associated increasing water demand, the global groundwater level is declining rapidly. In the case of Islamabad, Pakistan, the groundwater level has lowered five times over the past five years due to extensive pumping by various departments and residents to meet the local water requirements. To address this, water reservoirs and sources need to be delineated, and potential recharge zones are highlighted to assess the recharge potential. Therefore, the current study utilizes an integrated approach based on remote sensing (RS) and GIS using the influence factor (IF) technique to delineate potential groundwater recharge zones in Islamabad, Pakistan. Soil map of Pakistan, Landsat 8TM satellite data, digital elevation model (ASTER DEM), and local geological map were used in the study for the preparation of thematic maps of 15 key contributing factors considered in this study. To generate a combined groundwater recharge map, rate and weightage values were assigned to each factor representing their mutual influence and recharge capabilities. To analyze the final combined recharge map, five different assessment analogies were used in the study: poor, low, medium, high, and best. The final recharge potential map for Islamabad classifies 15% (136.8 km^2) of the region as the "best" zone for extracting groundwater. Furthermore, high, medium, low, and poor ranks were assigned to 21%, 24%, 27%, and 13% of the region with respective areas of 191.52 km^2, 218.88 km^2, 246.24 km^2, and 118.56 km^2. Overall, this research outlines the best to least favorable zones in Islamabad regarding groundwater recharge potentials. This can help the authorities devise mitigation strategies and preserve the natural terrain in the regions with the best groundwater recharge potential. This is aligned with the aims of the interior ministry of Pakistan for constructing small reservoirs and ponds in the existing natural streams and installing recharging wells to maintain the groundwater level in cities. Other countries can expand upon and adapt this study to delineate local groundwater recharge potentials.

Keywords: geographical information systems; groundwater assessment; groundwater recharge; remote sensing; Islamabad

1. Introduction and Background

Groundwater is necessary to sustain various forms of life [1]. It is defined as a form of water occupying all the voids within a geological stratum [2]. It is one of the important water sources for agriculture, industry, and domestic use worldwide [3]. The groundwater level is naturally maintained through precipitation that balances the water cycle, which is crucial for all multicellular life forms. The occurrence of groundwater in a geological formation and the scope for its exploitation primarily depend on the formation porosity [2]. The aquifers rely upon soil and fissured rocks as the medium of pores for the consistent flow between them [4]. In these complex networks of interconnected pores, fractures, cracks, joints, crushed zones (such as faults zones or shear zones), or solution cavities, rainwater can easily percolate through them and maintain groundwater tables [5].

In the past few decades, the greater reliance on groundwater has decreased groundwater table levels. Globally, more than 60% of agricultural practices depend on groundwater as a water source [6]. In developing countries in Asia, groundwater-based irrigation has grown up to 500% [7]. Moreover, due to the rapid increase in population, the demand for groundwater resources increases due to the inadequate availability of useable surface water resources. Furthermore, increased industrial and agricultural activities pollute water resources by directly releasing untreated waste into channels [8]. This eventually results in the unavailability of clean surface water, causing extreme dependency on the groundwater table. Therefore, the recharge of groundwater is of extreme importance to meet the global population's needs.

Groundwater/aquifer recharge is defined as water entry from the unsaturated zone to the saturated zone [9]. The degree of the recharge by natural means primarily depends on the amount of rainfall in a region that is considered a prime element for groundwater recharge [4]. The relationship between rainfall and the natural groundwater recharge is mainly governed by the region's topography, soil moisture content, rock structures, geology, the extent of fractures, elevation, slope, drainage patterns and density, landform, and land-use/land-cover and climatic conditions [3,4,10]. As a result of climate change, the overall global precipitation has decreased, resulting in a decrease in groundwater recharge [11,12]. Furthermore, the rapid worldwide urbanization also results in transforming once natural landscapes into urban water-impervious lands [12]. This limits the availability of freshwater resources but also causes hindrance in the recharge of the available water resources [13]. This puts tremendous pressure on the groundwater table considering the continuous use of groundwater to sustain essential life forms [10].

The aforementioned factors are resulting in water scarcity around the globe and are emerging as a major concern globally [14]. To temporarily maintain the groundwater levels and meet the ever-increasing water demand, artificial methods for recharging the aquifers have been employed. These methods are considered a prerequisite for sustainable groundwater management [3,15]. For this purpose, a new technique called managed aquifer recharge (MAR) has been gaining popularity lately. It is an efficient means of recycling storm water or treated sewage effluent for non-potable and indirect potable reuse in urban and rural areas [16]. Despite these artificial methods, a more sustainable approach must be adopted, and focus must be put on the natural means of groundwater recharge in line with the United Nations Sustainable Development Goals (UNSDGs).

In the case of Pakistan, the agriculture sector is the prime contributor to the country's GDP, with an overall contribution of 21% [17]. The surface water supplies are sufficient to irrigate 27% of the cultivable area, whereas the remaining 73% is directly or indirectly irrigated using groundwater. This is evident since out of Pakistan's total estimated annual groundwater extraction of 60 billion cubic meters [18,19], more than 85% is used for agricultural purposes compared to 40% in the rest of the world [20,21]. This makes Pakistan the third-largest user of groundwater for irrigation in the world [17]. Irrigation and agricultural usage have caused excessive groundwater abstraction in Pakistan, leading to water scarcity [7]. This growing deficiency of groundwater and ever-widening consumption for food production could weaken agriculture-dependent economies such as Pakistan [22,23]. In addition to the great agricultural and industrial demand for water, the increased urbanization [12] and overpopulation in Pakistan have also led to the overexploitation of ground and underground water. This, in turn, affects the water level/table and thus its availability [13].

Furthermore, the reduction of natural water pervious landscapes due to urbanization [13] and the natural reduction of precipitation due to climate change also prevent proper groundwater recharge [12]. Due to these facts, Pakistan is affected by acute groundwater shortages similarly to most developing countries [24,25]. As a result, the local groundwater levels are falling, increasing pumping costs and deteriorating groundwater quality. Thus, it is high time to carry out studies to delineate potential groundwater recharge zones in the country to use the resulting data to devise mitigation strategies [8].

Researchers have used different criteria for delineating potential groundwater zones in previous studies. Examples include the use of lineament and hydro geomorphology [26], geophysical data with geospatial information [27–33], delineation of artificial recharges sites using the use of remote sensing (RS) and geographic information system (GIS) [28,34,35], and the use of RS and GIS for geomorphic features and lineaments [36–42]. These techniques are important tools for enabling the appropriate management of crucial groundwater resources [43]. They are used to integrate various data to delineate potential groundwater zone and solve associated groundwater problems. Furthermore, these technologies are rapid and cost-effective in producing valuable data on geology, geomorphology, lineaments, slope, etc., which are important parameters for groundwater exploration, exploitation, and devising management strategy. Therefore, recent studies have used RS, satellite imagery, and GIS for hydrogeological and hydro-geomorphological investigations.

Several studies have also applied RS and GIS applications to delineate groundwater resources and potential recharge zones [8,34,44–58]. Some specific examples include a study by Saraf et al. [59], which used GIS technology to process and interpret groundwater quality data. In other studies, GIS and RS integrated with multi-criteria decision making (MCDM) have been successfully used to uncover potential recharge zones [60]. Such integration has also been used for district groundwater modeling [61], identification of water zones [62], climatic analysis for groundwater recharge [63], and aquifer analysis for recharge [64]. Selvam et al. [65] used similar techniques to decipher the groundwater recharge potential zones in a coastal area of India, which is geographically closer to our case study area. Other relevant studies using GIS have been described in Table 1 along with their respective limitations.

Table 1. Studies outlining techniques for groundwater recharge.

Technique Used	Usage and Findings	Key Factors/Parameters	Limitations	Ref
GIS and RS with fuzzy analytic hierarchy process (AHP)	Fuzzy AHP was used to delineate groundwater recharge zones. Several parameters were considered, and GIS and RS techniques were applied.	Drainage, Geomorphology, Geology, Land Use/Land Cover (LULC), Lineament, Permeability, Slope, Soil Texture, Soil Depth, Rainfall.	Fuzzy AHP brings more complexity and fuzziness to the decision-making process, thereby affecting outcomes.	[66,67]
GIS and RS with MCDM	MCDM was integrated with RS and GIS to delineate and map potential groundwater zones.	Density, Drainage Geology, Geomorphology, Lineament, LULC, Soil, Slope, Rainfall.	Various MCDM models can provide conflicting rankings of the alternatives for a common set of information.	[66,68]
GIS and RS with frequency ratio (FR)	FR, RS, and GIS were combined to delineate and map the potential groundwater zones.	Drainage Density, Soil Density, Geomorphology, Lineament Lithology, Land-use Pattern, Slope, Soil Texture, Rainfall.	The FR method utilizes past trends to predict the future outcome, making this approach depend on historical data that may not always be available.	[69–71]
Thermal infrared imagery	A thermal infrared multispectral scanner was used to delineate potential groundwater recharge zones.	Hydrogeology, Height, Thermal Parameters	Thermal activities around artificial structures such as power plants and industrial zones, clouds, and other distractions can lead to inaccurate data.	[68,72]

Table 1 shows various factors considered in respective studies for delineating groundwater resources. In this respect, a more accurate predicting model can be devised by increasing the number of influencing factors used and improving the data collection procedures. The current study uses an integrated RS and GIS technologies approach to delineate the potential recharge zones and categorize the study area into regions with high, moderate, low, and very low recharge potential. These techniques were employed in combination with the influencing factor (IF) technique, which has been previously used for studies related to semi-arid areas [10] and coastal areas [65]. However, it has not been employed in a noncoastal terrain such as the study area in the current research.

Moreover, compared to the previous studies, more factors have been introduced to increase the accuracy of the predicted results in the current study. The key assessment factors are overlaid with the spatial analysis tool of ArcGIS 9.3 to produce a combined thematic map uncovering the zones with their potential recharge. To further improve the model efficiency, more data were taken for the factors affected by temporal variations such as rainfall, etc. For other factors, data from a decade were taken and averaged before being used in the model development to nullify the effect of temporal variations. Further, thematic maps of larger spatial scales and the digital elevation model (DEM) data of a smaller resolution were used to study the targeted area comprehensively and accurately.

This study has practical applications for water management in developing and developed countries. For example, the groundwater delineation process paves the way for the relevant authorities to develop infrastructure and devise critical policies and committees to better manage the local groundwater sources. Furthermore, it can help policymakers, town planners, and construction stakeholders to plan future cities with a focus on sustainability and preserving the natural landscape required for proper groundwater recharge. Moreover, artificial structures could also be constructed to meet the associated groundwater demand and enable groundwater flow towards the region of lower concentration systematically. Such planned groundwater management will help meet the ever-increasing and widespread water demand among the country's residential, commercial, and agricultural zones. Moreover, sophisticated systems such as the one proposed in this study have lower costs and can easily interpret data to identify and suggest water contributing zones and factors. Accordingly, the applications in developing countries are numerous, which are usually concerned about the budgets of such projects. This provides incentives for developing countries such as Pakistan to use these sophisticated and integrated systems for groundwater delineation.

Further, this research contributes to the existing literature by providing an efficient integrated approach of RS and GIS coupled with the IF technique to identify the potential groundwater zones in a non-coastal study area. A similar approach was used to identify groundwater recharge zones in the coastal areas [73] and near the watershed [66]. However, such a study has not been conducted in non-coastal areas in a developing country. This presents a research gap that has been targeted in the current study. Moreover, a distinguishing element of this study is the introduction of more factors coupled with the use of more data (of a decade) for the temporal affected factors to nullify the temporal influence and variations. This was reported as a limitation in multiple similar studies. This study considers a larger spatial scale and finer resolution compared to other published works. This study can be extended to other non-coastal cities around the globe.

The main objective of this research is to identify the potential influencing factors that may impact groundwater recharge. Further, the potential groundwater recharge zones are determined by incorporating all influencing factors using the IF weightage technique. This will help the policymakers manage the groundwater resources and help researchers understand the utilization of remote sensing and GIS for groundwater analysis.

2. Study Area

The case study area of this research is Islamabad, the capital city of Pakistan, located at the edge of the Potohar plateau. It is located 14 km northeast of Rawalpindi in the province of Punjab. In terms of map reference, it is located at 33°49′ north and 72°24′ east of Greenwich [74,75]. Islamabad lies at an altitude range of 457–610 m and has 906.50 km^2 [76]. The climate of the area is humid and subtropical. May, June, and July are the warmest months, with average temperatures ranging from 36 °C to 42 °C, with temperatures sometimes as high as 48 °C. In comparison, the coldest months are December and January, with mean minimum temperatures ranging from 3 °C to 5.5 °C [77].

In Islamabad, groundwater is mainly used for drinking and agriculture purposes [78]. Since its announcement as the capital on 14 August 1967, the urbanization in and around Islamabad has been growing rapidly, leading to the development of multiple residential sectors (Sectors D to I) and more new ones being proposed, such as sectors A to C and sub-sectors I-14 to I-16 [74]. This is due to the increased migration of people in hopes of better facilities and high-end, luxurious lifestyles. According to the 2017 census, Islamabad recorded a population growth rate of 4.91 percent, and its population increased from 0.81 million in 1998 to 2.0 million in 2017 [79]. Such a mass-level migration to Islamabad increases the demand and reliance on groundwater to sustain life necessities [80].

Moreover, since Islamabad rests on the Potohar Plateau and consists of a hard rock terrain, its surface does not allow enough permeable surface for groundwater tables to be properly recharged [70]. As a result, the groundwater levels of Islamabad are depleting rapidly on an annual basis, as reported by the metropolitan corporation of Islamabad [80]. The Interior Ministry of Pakistan reported a 6 ft decrease in Islamabad groundwater in 2013, followed by a 10 ft, 16 ft, 23 ft, and 30ft from 2014 to 2017, respectively. It is estimated that groundwater levels in Islamabad have decreased by five times as of 2018 [80]. Therefore, it is imperative that new and reliable water sources must be found. Accordingly, it is necessary to carry out a study to delineate the potential groundwater zones in the city. This can help the policymakers and town planners to preserve such zones with permeable strata in the city to mitigate this groundwater recharge issue or alternatively better plan the construction activities around such areas.

Figure 1 shows the Islamabad map that is divided into five zones: zone 1 to zone 5 [74]. These zones are the administrative boundaries of the study area. They can be used as a reference for policymakers for decision making for each zone with respect to findings of this research. The city infrastructure has been planned in nine sectors in total, and an alphabet from A–I represents each sector. Every sector covers an area of approximately 2 km^2 and is further subdivided into four sub-sectors, each containing a central shopping mall, public park, and other amenities [74,81]. These sectors are the gridded divisions of the city to subdivide the capital into small units. It is similar to municipalities in developed countries and presents a grid division of the city. Out of the 5, zone 4 has the largest area, 282.5 km^2 [82], while zone 1 has the most developed residential area [83]. Zone 2 has an area of 9804 acres. Since CDA apportioned this zone to a private and cooperative housing scheme for improvement, zone 2 has become the city's most alluring space [83]. Zone 3 (203.9 km^2) is one of the most beautiful areas of Islamabad. Vacation spots such as Daman-e-Koh and Peer Sohawa are situated in this zone [84]. Zone 5 (157.9 km^2) is near the old airport and is one of the most populated zones [85].

Islamabad continues to experience expansion to accommodate the increasing population. The territorial limits of Islamabad have expanded by 87.31 km^2 from 1972 to 2009, with a significant reduction in the forest covers and other natural habitats [86]. As a result, Islamabad has registered the highest population growth rate of 4.91 percent, and the population has increased from 0.81 million in 1998 to 2.0 million in 2017 [79]. This rapid urbanization has led to many development projects being initiated within the city, including the extension of transportation systems, revision of the city master plan, and industrial and real estate development [12,75] that provide job opportunities to the residents [87,88].

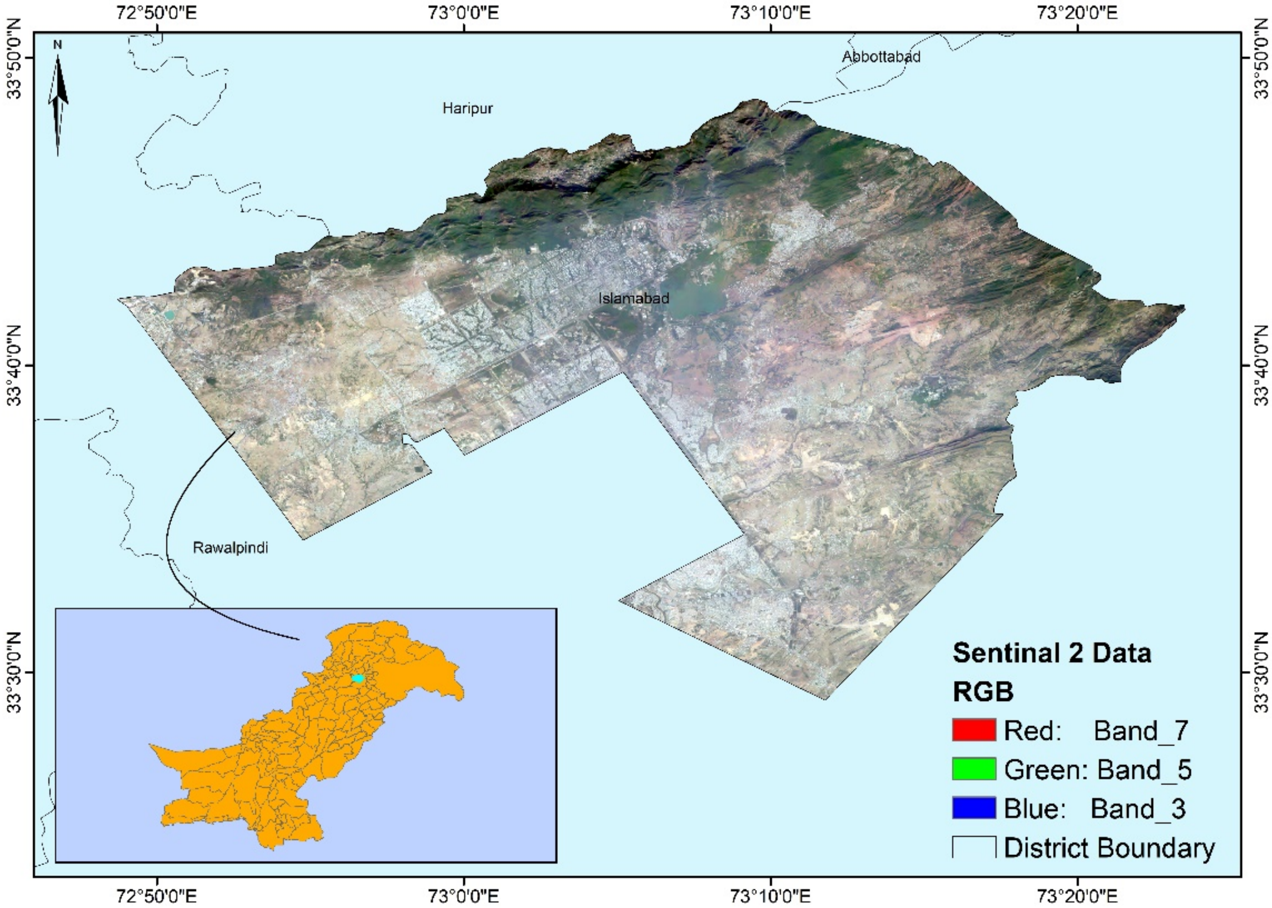

Figure 1. The study area (Islamabad) and its zones.

Due to this rapid increase in population, Islamabad has undergone many predicted and unpredictable changes [74]. One such change is the higher water demand in the region [80]. The main water resources for Islamabad are surface- and groundwater. Simli Dam and Khanpur Dam are major water resources for Islamabad. Along with the surface water, the Capital Development Authority (CDA) supplies groundwater extracted from 180 tube wells to Islamabad. Private and municipal wells are also used to fulfill the local water requirements [79]. Despite the aforementioned resources, the increased population has heightened the reliance on groundwater since it is one of the primary sources for domestic use [89]. The resulting extensive use of groundwater in the region leads to the depletion of natural groundwater resources [80].

Moreover, considering that the study area is situated in the Potohar Plateau, where the terrain is geologically composed of tertiary sandstone, limestone, and alluvial deposits [77], the recharge capacity of the region is not good. Thus, groundwater does not recharge properly, resulting in the depletion and unavailability of clean drinking water. The areas facing severe water shortage include sectors G6, G7, H8, G13, I-10, [90], and I-8/1 [91]. Thus, it is important to manage the regional groundwater resources [78]. For this purpose, the current study delineates Islamabad's potential groundwater recharge zones. The obtained potential recharge map provides the information to help improve the local management of groundwater resources. Such an assessment is important for future planning and development policies in the area and devising strategies for efficiently utilizing natural resources such as groundwater.

3. Factors Affecting Groundwater Recharge Potential

Groundwater is affected by multiple factors such as land use, slope, and lineament [92]. In addition, the study area's rainfall, soil conditions, and soil types also influence the groundwater [93]. In this study, 15 influencing factors (Ifs) were identified and used to develop potential zones to produce an error-free diverse outcome instead of a single influencing factor outcome, which provides a limited outcome in terms of accuracy [65]. Broadly, these factors can be grouped into four key groups: (1) elevation and slope, (2) rainfall and drainage, (3) land-use/land-cover and soil characteristics, and (4) faults, as listed in Table 2. The influencing factors (IFs) are the factors that can affect some features of the target object, system, or phenomenon [94]. IFs can be used as control variables to determine the key influencing factors of an object, system, or phenomenon. These have been used in various studies. In water-related studies, IFs have been used to assess the seasonal changes in water quality [95], water transport through cracks in concrete [96], distribution characteristics of microplastics in urban tap water [97], comprehensive evaluation and urban agglomeration water resources carrying capacity [98], and others. Accordingly, in the current study, IFs are used to delineate potential groundwater recharge zones in Islamabad, Pakistan. These 15 key factors are listed in Table 2 and discussed subsequently.

Table 2. Factors influencing groundwater recharge classified criteria.

Group	Key Factors	Source of Categorization	Selected Ref
Elevation and slope	Elevation	Height value	[99]
	Slope	Slope gradient	[100]
	Slope length	Measurement of slope lengthwise	[100]
	Aspect	Aspects of area	[70]
Rainfall and drainage	Total wetness index	Runoff collection and infiltration	[101]
	Rainfall	Zones with rainfall recement	[93]
	Drainage distance	Distance to drainage networks	[102]
	Drainage density	Density values for drainage	[103]
Land use/land cover and soil characteristics	Land use/land cover	Satellite imageries	[104]
	Soil	Textures	[72]
	Lithology	Rock type details	[105]
	Plan curvature	Detailed area curvature	[70]
	Profile curvature	Flow categorization	[61]
Faults	Distance to faults	Lineament distance	[106]
	Fault density	Density for lineaments	[107]

3.1. Elevation

Surface elevation plays an important part in groundwater recharge. It is the primary source for triggering the water flow under gravity [99]. Elevation studies highlight the regions contributing to the groundwater flow; i.e., higher slopes allow less water infiltration. Islamabad has variable elevation, as it is composed of both mountainous regions and flat surfaces. The mountainous regions have higher slopes that transfer water from higher elevation to lower elevation. A similar study found designated slope as a very important factor in groundwater recharge [108]. Previous research has indicated that gentle slopes and flat surfaces have higher recharge potential compared to inclined surfaces and higher slopes [100]. Therefore, the inclusion of surface elevation signifies the groundwater flow and determines the flow direction as it induces the flow under gravity [108–110]. A major part of the current study area consists of mountainous regions with high surface elevations. Therefore, it is used as a key factor in the current study.

3.2. Slope

Slope defines the extent to which groundwater can be recharged with the precipitated water [100]. The regions with higher slopes experience rapid water running over the surface, hindering the absorption of precipitated water into the groundwater [65]. Conversely, in areas involving lower slopes and vegetation, the water cannot run off the surface rapidly, and thus, more of it is absorbed in between the pores and adds to the groundwater table [100]. In relevant studies, it has been established that the topographical feature of the slope impacts the directional flow of water and indicates its accumulation. Further, the flat surfaces with gentle slopes displayed the highest infiltration capacity [109,111], thus contributing to an increase in the groundwater table. Our study area, Islamabad, comprises high-slope areas, as the northern outskirt is predominant with the mountain region, making the slope one of the important factors for the current study. Accordingly, the slope has been included as one of the key factors in this study.

3.3. Slope Length

Slope length indicates the physical characteristic of the slope in terms of its extension and magnitude. It helps determine the flow and highlight possible regions of groundwater retention [100]. Being a primary factor for groundwater contribution, slope length determines runoff strength and the groundwater flow direction. Slope length also indicates the amount of rainfall that would reach the groundwater table through infiltration [100,108,109]. Gentle slopes have greater infiltration capacity, displaying greater groundwater recharge potential and vice versa [100]. Slope lengths help understand the flow of precipitation as the water runs off from higher elevation towards the lower elevation. Considering that our study area is predominantly sloped in the northern parts due to mountain ranges, this is an important factor in this research.

3.4. Aspect

The front-facing side of a slope, or generally the face of the slope, is defined as the aspect [109]. When combined with the slope and slope length maps, the aspect can indicate the extension of a particular slope in a specified direction to unveil the potential flow of groundwater [70]. The aspect proceeded by flat surfaces or gentle slopes allows the precipitated water to flow smoothly and streamlined, thereby maximizing the area's infiltration capacity, leading to greater recharge [70,109]. Islamabad is composed of higher elevations at the northern outskirt that stretches predominantly towards the east. The aspect is proceeded by the gentle and flat surfaces containing the residential zone of Islamabad. The aspect can indicate the flow of precipitation and groundwater accumulation towards the inner zones in Islamabad. Therefore, it is used as a key factor in the current study.

3.5. Topographic Wetness Index (TWI)

The topographic wetness index (TWI) is a steady-state wetness index used to quantify topographic control on hydrological processes [101]. TWI indicates control over the groundwater processes, such as flow and retention in a specified zone. Several studies have been published explaining the process to calculate the TWI [101,111]. TWI provides detail about the flow of groundwater considering the effect of the slope. TWI can impact groundwater flow and its occurrence in a varied elevation areas such as Islamabad. Numerous studies have linked TWI, slope, and elevation effects to the water recharge potential [65,100,109]. TWI gives an indirect indication of water moisture availability and potential recharge zones. Therefore, this has been used as a key factor in the current study.

3.6. Rainfall

Rainfall or precipitation positively affects the groundwater table because of larger water infiltration [93]. Rainfall has always been a reliable source of freshwater [65]. Previous research has linked both the movement and occurrence of ground and surface water to mainly depend upon rainfall [108,111]. Considering that the rainfall quantities of the study area can indicate the movement of groundwater and can depict the flow and accumulation of water bodies, it is important to include this factor while investigating groundwater recharge zones [109]. Therefore, it is considered significant for Islamabad as well and used in the current study as a key factor. Further, since Islamabad is a rainy area, and some mountainous regions in the area receive more rainfall than other parts of Pakistan, rainfall is a key factor dictating the local climate and recharging the water sources.

3.7. Drainage Distance

Drainage distance is crucial for water studies, such as its occurrence and flow assessments. Drainage distance highlights the geological distance between successful drainage zones. The drainage density indicates the drainage condition of the water shed [109]. Groundwater movement beneath the surface can be unfolded by uncovering the drainage networks according to lineaments such as underground fractures and faults. Lineaments impact groundwater movement within the surface [65,102]. For studies relating to groundwater recharge, the inclusion of drainage distance is crucial because of its relationship with permeability which is the property that describes the flow of water bodies beneath the earth's surface [108]. A similar study prioritized areas comprising more considerable drainage distances for the groundwater recharge potential and vice versa [109]. Accordingly, drainage distance has been shortlisted as a key factor in the current study for the study area of Islamabad.

3.8. Drainage Density

Drainage density is the ratio of all the streams over the area to the total area [65]. It indicates the drainage capacity and measures the drainage over a particular watershed [103]. A higher drainage density region indicates a well-distributed water flow area with multiple streams contributing to the flow and recharge and vice versa. A similar study has linked higher drainage density to greater groundwater recharge potential [108]. According to the previous research, the drainage density contributes toward the groundwater recharge as it describes the flow pattern and the occurrence of water beneath the surface [65,109]. As Islamabad receives higher rainfall towards the northern outskirts, and the density of the drainage network would greatly influence the flow and occurrence of groundwater in the region, drainage density is selected as a key factor for this study.

3.9. Land Use/Land Cover

Land use/land cover involves several elements, including soils, human settlements, vegetation cover, waste lands, etc. [112]. The settlement in an area affects the groundwater due to the human-made structures. The land vegetation covering is one of the major groundwater factors used for retaining water [65]. Depending upon the porosity and permeability, the soil conditions of an area also control groundwater seepage through the surface. RS and GIS usage for land mapping has gained popularity recently [6,104]. With the help of land use/land cover, a similar study has linked the best and most abundant agricultural practices with groundwater availability over the study region [109]. For Islamabad, the regions should be studied based on their demand for groundwater, thereby necessitating the inclusion of land use/land cover in this study.

3.10. Soil

Soil is one of the most important factors for groundwater recharge since groundwater movement through the surface is controlled by soil type and properties [65]. Accordingly, parameters such as porosity and permeability are of utmost importance and are crucial to groundwater flow [72]. Moreover, the soil is also responsible for the filtering or buffering activities between the atmosphere and the groundwater in the biosphere [65]. Therefore, it is considered one of the prime influencing factors in groundwater recharge analysis. Considering that soil properties vary in each region, large-scale test data of the soil type might be required. In previous research consisting of a variable soil type for groundwater recharge, higher weightage has been allocated to the soil as a contributing factor. Accordingly, it has been declared as one of the high IF [109,111]. Furthermore, greater variations of the soil types were seen influencing the groundwater recharge potential in relevant studies [108]. In the current study area, the terrain has high soil variation; the northern outskirts are predominant with mountainous soil, and the southern outskirts are predominant with loamy soils. Thus, soil type is selected as a key factor in this study.

3.11. Lithology

Lithology refers to the physical appearance of rocks. Rock characteristics impact the movement of water beneath the surface [105]. In smaller rocks, the water finds more passage for movement and vice versa. If the grains are arranged in a well-graded manner, there is no passageway for water and vice versa [65]. Lithology plays an important part in dictating groundwater flow via channels, permeability, and occurrence [104]. This factor has been considered in a similar groundwater recharge study outlining the influence of rock type, soil type, and the higher permeability on groundwater movement and occurrence [105,109]. Several other factors may influence the lithological characterization and its impact on groundwater recharge. However, this research is limited to lithological information and does not have permeability, porosity, or grain size information. Further, it is based on a literature review for assigning weightages of lithologies. The terrain is composed of various rock types in our study area, including tertiary sandstone, limestone, and alluvial deposits [84]. Lithology contributes to groundwater flow and is included in the current study [105].

3.12. Plan Curvature

Plan curvature explains the geometry of a particular region. It helps understand the way contours intersect the horizontal region and their impact on the slope inclination of a particular zone [70]. It explains the flow of groundwater and helps establish a generalized flow pattern. Plan curvature approximates the inclination of various zones that impacts groundwater recharge through topographical influence [111]. The inclination of the area is marked with a slope that runs from the region of higher inclination towards the lower inclination, thus indicating groundwater flow [100,109]. The region of Islamabad is higher in inclination towards the northern region that goes down towards the southern zones. This is because the northern area is comprised of mountainous regions, and the southern zone consists of high-populous flat regions, establishing a generalized pattern of inclination decrease [111]. The inclination and gentle slopes and the presence of flat surfaces greatly influence groundwater recharge [108]. Therefore, plan curvature has been included as a key factor in this study.

3.13. Profile Curvature

Profile curvatures define the nature of the ground zones under study: linear, concave, and convex. It is defined as the line parallel to the direction of the maximum slope. Patterns might indicate a general linear formation with a defined value approaching zero. A positive value indicates an upward concave profile, while the negative region represents an upward convex profile [70]. The profile curvature helps classify the area into lower or higher water-retention zones depending upon its convexity and concavity. Accordingly, the regions comprising elevated convex profiles within center zones are regarded as less water holding and vice versa [110]. The curvature of the study area is included in this study to assess its effect on the water-retention capability of the zone following related studies [109,110]. Considering the variability of Islamabad's surface in terms of slope and elevation, it is important to consider the influence of profile curvature on groundwater recharge in this region. Therefore, this factor has been used in the current study.

3.14. Distance to Fault

Faults describe the change in geological composition in a particular zone [106]. These indicate the movement and change a particular rock surface has undergone in a specified period. For example, earthquake-induced faults can indicate rapid geological movement beneath the surface. The parameters of faults can have vast ranges. Distance to faults impacts the flow and occurrence of groundwater [108]. It is important, as it indicates groundwater flow and can highlight the zones contributing to underground-water flow [106,109]. In our study area, Islamabad and nearby regions have more faults that influence the groundwater recharge. Thus, this factor is included in the current study.

3.15. Fault Density

The magnitude of faults (density) indicates the potential groundwater regions. In a similar study, lineaments such as faults have been reported to impact the groundwater recharge potential zones and are considered key IF [108]. Fault density helps determine the occurrence and movement of groundwater beneath the surface. Many relevant studies have included fault density as a key factor in assessing groundwater recharge potentials [60,65,66]. As previously discussed, Islamabad has higher faults than the rest of the country. Therefore, fault density is included as a key factor in the study.

4. Methodology

The current study follows a four-step approach. In the first step, the relevant thematic layers are identified. First, the thematic layers used for the study were extracted that act as input data for the eventual delineation of recharge zones. These thematic maps present the geographical map of the study region in accordance with the subject matter. The current study utilizes thematic maps for 15 hydrological factors. These include distance to faults, land use, lithology, drainage density, slope, soil, rainfall, plan curvature, fault density, profile curvature, TWI, elevation, aspect (the front-facing direction of a slope), drainage distance, and slope length. These factors were extracted from previous literature [60,66,87,103,113] considering the geological properties of the study area as listed and are discussed in Section 3 of the study.

The thematic maps used in the research were generated at a 1:200,000 scale considering that this would eventually increase accuracy. In addition, the majority of the data sets were available at this scale. The differing scales were later normalized for the sake of uniformity. The digital elevation model (DEM) data are used on a global scale at 30 m $\times$ 30 m resolution for topographic analysis. This resolution is highly important, as it contributes to how sharply the objects can be seen in an image. It represents the size of the tiniest feature captured by a satellite sensor or portrayed in a satellite photo. It is commonly expressed as a single number representing the length of one of the sides of a square (grid) [12]. In addition to the normalization of the input data, uniformity is ensured in their format for easy integration of these thematic maps into the GIS platform. For this purpose, the acquired maps are converted into raster form before integration with the GIS.

In the second step, the pre-processing of the thematic layers was performed to ensure uniform projection and resolution. This is followed by the assignment of scores and suitable weightage to each factor. During weightage overlay analysis, the ranking was given for each parameter of each thematic map, and weights were assigned according to the influences (following IF technique) of the feature on the hydrogeological environment of the area coupled with that parameter's contribution toward the groundwater recharge as shown in previous researches [65,108,109].

The IF technique was used to assign scores and get a diverse and error-free outcome. A diversely produced thematic map considers the input from multiple hydrological procedures, thus not relying on a single hydrological process where the outcome can be manipulated and is prone to error. Moreover, due to finer resolution, any errors in the weighted overlay analysis within the ArcGIS were eliminated since such resolutions result in finer interpretation.

The third step involves using ArcGIS to deploy the thematic layers to get the processed images containing the potential zones. In this step, all the scored thematic maps along are integrated by employing the "Spatial Analysis tool" in ArcGIS 9.3, whereby rankings are assigned to all the thematic maps. Then, these weighted thematic maps are overlaid using ArcGIS to highlight the potential recharge zones. In the fourth (last) step, the study area was categorized based on the potential groundwater rechargeability into five different classes: poor, low, medium, high, and best in terms of their capability for the groundwater recharge potential.

Figure 2 shows a flowchart summarizing the methodology used in this study. The associated steps include acquiring the data, converting to raster, preprocessing (confirming projection and resolution coupled with assigning scores and weights), integrating GIS for final output, and categorizing the study area based on groundwater recharge capability. Figure 2 also shows the source of the acquired data. Accordingly, the thematic maps are acquired from Landsat-8 TM Satellite, Aster DEM, and soil and geological maps of Pakistan. The following sections explain the IFs used in this study in detail, their sources, and the procedure for assigning weights to each of these factors.

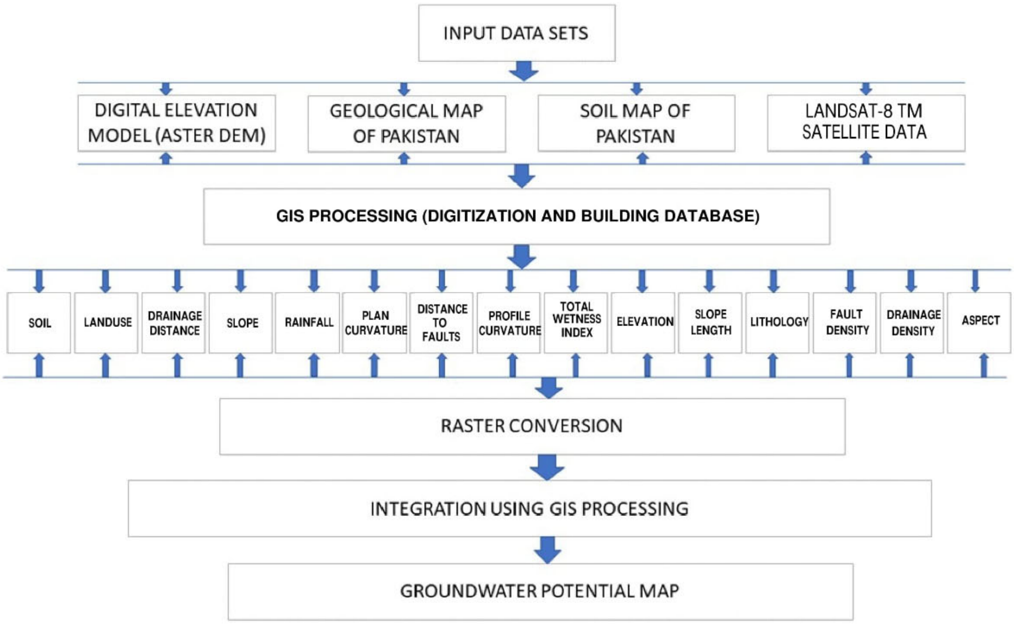

Figure 2. Flowchart for potential groundwater assessment using integrated remote sensing and GIS techniques.

4.1. Acquisition of Thematic Maps for Contributing Factors

Table 3 below enlists the sources for acquiring thematic maps for all the contributing factors. The soil thematic map was generated using the Soil Map of Pakistan [114]. Land use, rainfall, and TWI thematic maps were generated using Landsat 8TM satellite data. Drainage distance, slope, plan curvature, profile curvature, slope length, elevation, drainage density, and aspect thematic maps were generated using ASTER global DEM. Finally, distance to faults, lithology, and fault density thematic maps were generated using data from the geological map of Pakistan on a scale of 1:200,000 [115].

Table 3. Acquisition of Thematic Maps for Contributing Factors.

Factors (units)	Sources of Acquisition for Thematic Maps
Soil	Soil map of Pakistan
Land use, TWI, Rainfall (mm/y)	Landsat-8 TM satellite data
Drainage distance (m), Slope (degree), Plan curvature, Profile curvature, Slope length (m), Elevation (m), Drainage density, Aspect	ASTER GDEM
Distance to faults (m), Lithology, Fault density	Geological map of Pakistan

These thematic map data were cross-checked using ground surveys for cross-validation. The imagery was visually interpreted to delineate rainfall, land use, and other factors with the help of slandered characteristic image-interpretation elements such as tone, texture, shape, size, pattern, and association using the Landsat 8 satellite data products. These data sets are used for assessing groundwater recharge potential [65,109,111].

4.2. Weightage Assignment via IF Technique

Weights and rates were assigned to the factors to obtain a final combined recharge potential map. Using the IF technique, the influence of various factors was taken into account, and the level of impact they have on the hydrological aspect of groundwater flow and its occurrence was assessed. A weightage approach was included as used by [65] to assign weightage to the factors that would ultimately define the control they can assert over the groundwater recharge of the study area. The current study follows a similar approach. In assigning weights to the considered factors, five major descriptive levels were plotted for each factor ranging from very high to very low, including some interrelated levels. These weightage values range from 10 to 1 point, i.e., a very high range is assigned a score of 10, and the minimum level is 1 following relevant groundwater studies [113,116]. These weights for each factor were assigned based on their degree of impact on groundwater recharge as extracted from relevant literature [6,10,63,113].

5. Results and Discussions

This section presents the results and discussions in line with the adopted method.

5.1. Spatial Analysis of Considered Key Factors

Figure 3 represent the resulting thematic maps of the 15 considered factors for the current study area. Figure 3a highlights the wells or water extraction points in the study area. These are primarily located in the residential zones and plain areas of Islamabad. Figure 3b shows the thematic map of rainfall for Islamabad. The resulting map highlights that Islamabad receives ample rainfall. Further, it shows a rhythmic increase in rainfall volume from south to north. The northeast outskirts receive the highest rainfall, consisting of regions from Rawat to Crore Village. Low-rainfall regions are evident in the southwest. Considering the high rainfall in the northeastern regions, there are more chances for more groundwater recharge and high groundwater levels in alluvial plains [64], thus displaying a higher potential for groundwater recharge. Moreover, the map shows that around 44% of the area receives less than 882 mm of rainfall, 16% area receives rainfall between 882–999 mm, 10% area receives rainfall between 999–1116 mm, 9% area receives rainfall between 1116–1233 mm, while 21% of the area receives most rainfall ranging between 1233–1350 mm. This shows that around 40% of Islamabad receives good rainfall. This assessment can help policymakers preserve the natural terrain in the region receiving more rainfall and utilize it for groundwater recharge.

Figure 3c shows Islamabad's thematic layer of plan curvature data. The figure categorizes the regions based on concavity and convexity. The map shows that the northeast region of Islamabad is composed of higher convexity, whereas a systematic decrease in convexity is observed from north to south. This indicates a higher surface and altitude in the north and a gradual decrease towards the south. This heavily contributes to the groundwater flow from north to south, where a gentler slope and plain area can accumulate this water and get recharged. A similar study accounted for alluvial plain and gentle slopes to be more promising for groundwater potential due to large infiltration rates, high porosity, and permeability [116].

Figure 3d shows the thematic layer of soil data for Islamabad, where the region is classified based on soil composition. Soil types impact groundwater flow directly, but they also impact other important phenomena, such as infiltration [117], which ultimately impact groundwater recharge. The soil conditions define permeability, which impacts groundwater infiltration and soil porosity. For example, the calcareous loamy soil is abundant in arid and densely populated areas. Figure 3d shows that the mountainous soil forms the northern edge of Islamabad that receive a decent amount of rainfall. Such soil helps infiltration, enabling the groundwater to flow towards the inner zones. While no definite pattern exists throughout the study area, calcareous soils are mostly reported for various regions.

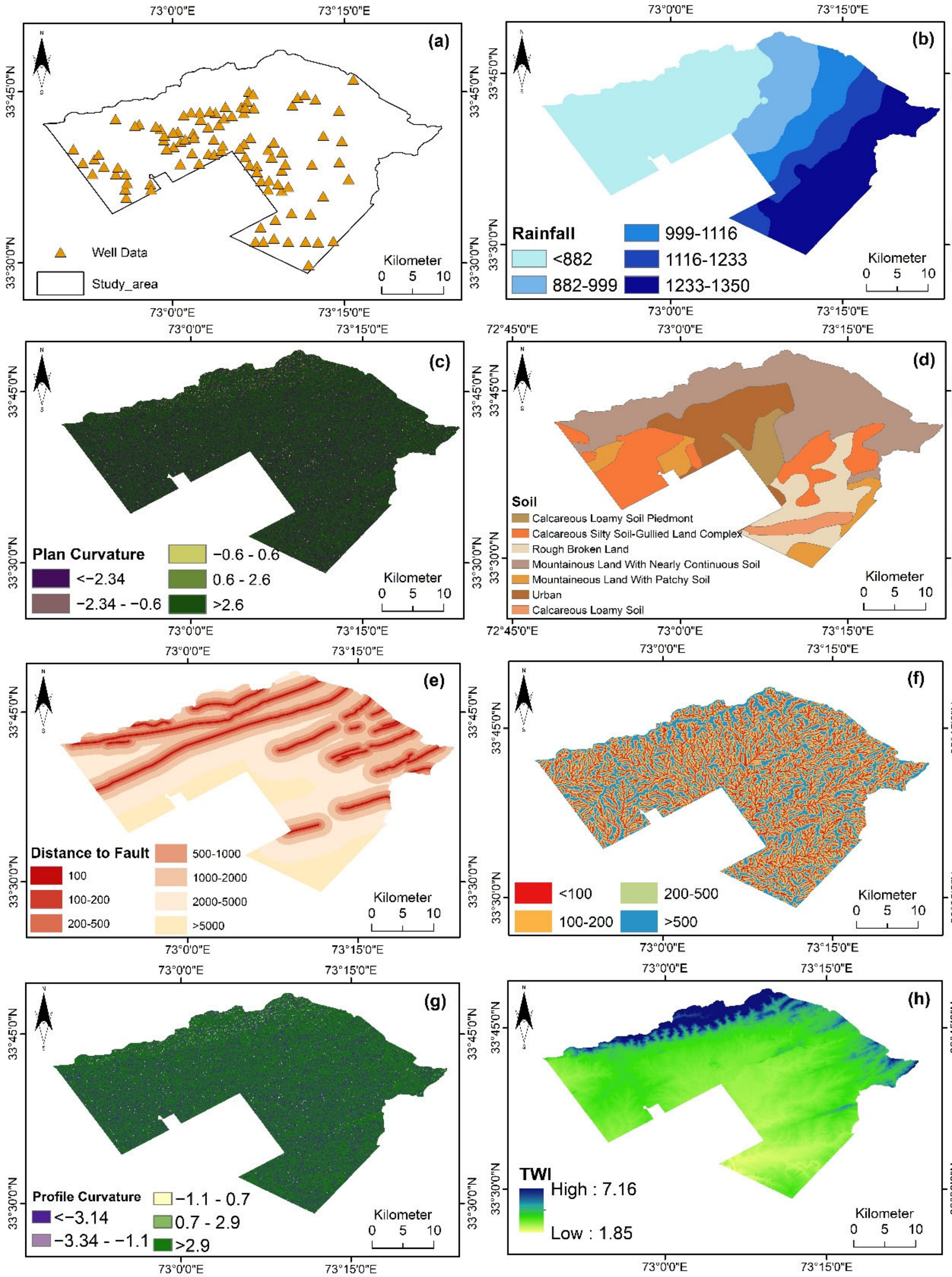

Figure 3. *Cont.*

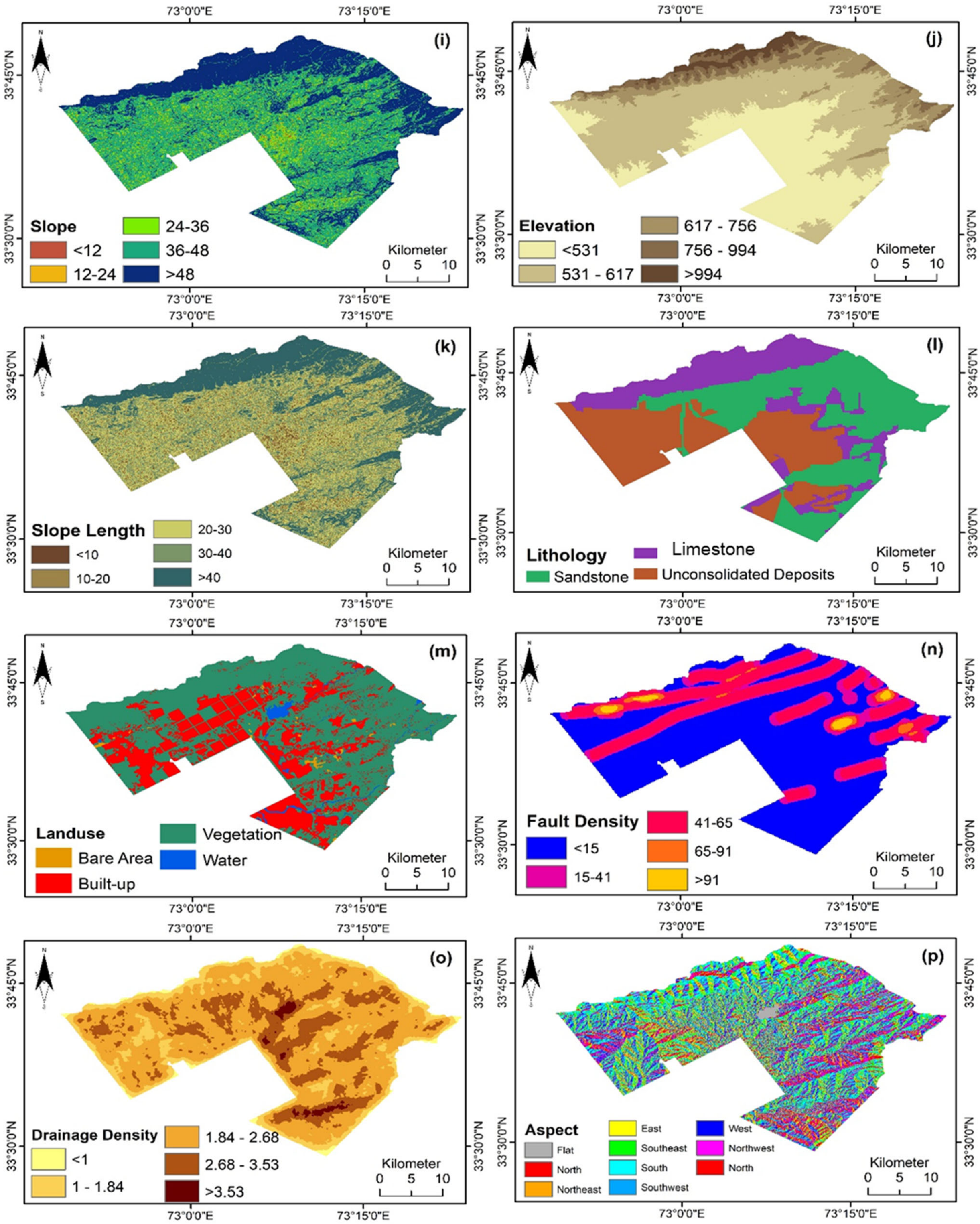

Figure 3. Thematic layers of selected factors for Islamabad's data (part 1), (**a**) well data, (**b**) rainfall data, (**c**) plan curvature, (**d**) soil data, (**e**) distance to fault, (**f**) drainage distance, (**g**) profile curvature, (**h**) TWI, (**i**) slope, (**j**) elevation, (**k**) slope length, (**l**) lithology, (**m**) land use, (**n**) fault density, (**o**) drainage density, (**p**) aspect.

Figure 3e shows the thematic layer map of distance to fault for Islamabad. This map categorizes regions with respect to distances to faults. Considering that the faults act as points with more recharge capability, more distance from faults implies less recharge capability and vice versa. In this respect, Figure 3e shows that the major faults are all located on the outskirts of Islamabad. The zones comprising convex geological features and landscapes have nearby faults, whereas the southern regions comprising more land use and less geological convexity comprise low distances to faults. This aligns with several studies that have established patterns with lineaments and groundwater recharge potential [10,118]. Overall, the southern regions with less distance to faults display more recharge potential in the current study area.

Figure 3f shows the thematic layer of drainage distance for Islamabad. It categorizes the study area based on the distance of various zones from the drainage networks. Figure 3f shows that the study area comprises abundant and closely located drainage networks. However, there is no defined pattern for the drainage distances in the study area. Considering that a lesser distance from the drainage pathway displays higher groundwater recharge potential [119], the drainage distance thematic map suggests that the study area has a larger potential for groundwater recharge. Further, there is a well-distributed groundwater flow throughout the region. Figure 3g shows the thematic layer of profile curvature for Islamabad. It highlights the geological characteristics of Islamabad and depicts the concavity and convexity of the region. It is indicated that the outskirts of the northern region are higher in altitude and contribute to the groundwater flow under gravity. A higher profile value indicates a rising elevation, ensuring a systematic flow towards the inner edges with the highest and densest land use in Islamabad. This is in line with a previous study's findings that suggest a higher potential of gentle slopes for groundwater recharge [116].

Figure 3h shows the thematic layer of TWI for Islamabad. The TWI map shows the impact of geology on the hydrological aspects. The outskirts, shaded in deep blue in Figure 3h, show the zones with geological makeup that impact regional hydrology. Following our thematic maps for the land use, well data, and rainfall, the TWI highlights Islamabad's northern outskirts as the areas directly reaching the groundwater. The inner edges with lower index value contribute little to the groundwater flow, while the geological makeup of the outermost skirts contributes greatly to the groundwater flow towards the center, housing the area with the highest and densest land use. A direct relationship between the higher TWI value was also established by another study [120]. Following our findings, a higher TWI value suggests a better groundwater recharge potential in the Islamabad region.

Figure 3i shows the thematic layer of slope data for Islamabad, showing that the northern outskirts of Islamabad have the highest slope. The slope plays an important part in determining the runoff direction of groundwater. The thematic map indicates that 23% of the region has a slope greater than 48 degrees, 38% has a slope ranging from 36 to 48, 16% has a slope ranging from 24 to 36, 9% has a slope ranging from 12 to 24, and 4% of the region has a slope less than 12 degrees. The figure shows that the outskirts of Islamabad in the northern region comprise the highest slopes due to mountains that promote a rapid runoff towards the south. While some water is lost during the runoff, infiltration takes water to the deep soil layers, contributing to recharging the local groundwater table.

Islamabad's outskirts comprise Attock, Wah Cantt, and Taxila in the west; Murree in the northeast; Haripur in the north; Gujar Khan, Rawat, Mandrah, and Kahuta in the southeast; Rawalpindi to the south and southwest; and other Punjab regions in the east. The greater slope in the northern region ensures a flow of water towards the south with the highest settlement and greatest water recharge potential.

Figure 3j shows the thematic layer of elevation data for Islamabad. Islamabad is high on the northern edge due to the mountains that decrease towards the south. The area with residential zones, i.e., the inner edges, and that towards Rawalpindi has higher population density and low elevation. This systematic decrease of elevation contributes directly to the groundwater flow as the water flows under the action of gravity. The higher elevation area also receives greater rainfall, as shown in our rainfall thematic map, ensuring infiltration and surface runoff towards the inner edge. Thus, the area with higher elevation retains rainwater for a lesser time duration and generates more runoff towards the residential areas in Islamabad, in line with published studies [64].

Figure 3k shows the thematic layer of slope length data for Islamabad that highlights the lengths of slopes in the region. Longer slope lengths are evident on the northern outskirts, while a rhythmic slope length decrease can be observed towards the south. The area with the highest land use comprises regions with lower slope length values. The groundwater flows from the northern sides with the highest slope lengths promoting recharge potentials and infiltration. The gradually decreasing slopes towards the center help with groundwater recharge to meet the requirements of the local population.

Figure 3l shows the thematic layer of lithology data for Islamabad that shows regions with limestone and unconsolidated deposits to be abundant in the area. However, there is no defined pattern, and the data are scattered throughout the region. The concentrated regions are highlighted in red, green, and purple colors in Figure 3l. There is a presence of sandstone in the northeastern region along the dense mountainous regions that continues towards the northwestern region.

Further sandstone and unconsolidated deposits are seen within the areas of highest land use towards the southwest. Past glacial activity has contributed to the unconsolidated deposits in the region due to the weathering of rocks. A previous study also established a pattern between the weathering of rocks towards the increased groundwater recharge potential [121]. An increased recharge was also observed in the area of higher unconsolidated deposits in another study [120]. Accordingly, there is a greater potential for groundwater recharge in the study area.

Figure 3m shows the thematic layer of land-use data for Islamabad, showing areas such as bare land, water bodies, built up, and vegetative regions. Such a map displays the variation of population density and associated water demand throughout the study area [10]. The thematic map for Islamabad indicates that 4% of the region comprises bare land, 36% is built-up region, 51% is vegetative, while 9% of the study area is composed of water bodies. Further, it can be observed that most of the built-up region is around the inner region of Islamabad. This region falls towards the city of Rawalpindi, which has a far greater population density than Islamabad. The runoff from the northern region infiltrates into the groundwater table around these internal regions, where there is a greater need for water.

Figure 3n shows the thematic layer of fault density for Islamabad that highlights geological features induced by the movement of rock bodies. These faults govern groundwater flow following their complex and favorable topography. Accordingly, the fault densities for the area include 43 % area with less than 15 fault density, 6% area ranging from 15 to 41, 35% ranging from 41 to 65, 7% ranging from 65–91, while 9% of the study area has fault density greater than 91. The map indicates that the northeastern edges of Islamabad consist of lower-density faults than the northwestern region, where there are more mountains. The maximum land use is towards the internal regions with no major geological faults. Previous studies have linked fault-dense regions with higher groundwater recharge potential [10]. Thus, there is a higher recharge potential in the northwestern areas of Islamabad.

Figure 3o shows the thematic layer of drainage density for Islamabad that highlights the northeastern regions to have streams or rivers with relatively long lengths. This ensures a deep-water flow towards the inner edges of Islamabad. Thus, the northeastern region contributes majorly towards the groundwater flow in the areas of highest land use. Further, a flow from the northern to the southern edge is seen with the major contribution from the northeastern region. A previous study showed that high-density drainage regions have greater groundwater recharge potential [122]. This is in line with the current study where major water sources contribute to the water recharge. The same has been highlighted by the rainfall thematic map, where the northeastern region receives most of the rainfall and has a high drainage density, thus contributing to the groundwater flow and recharge.

Figure 3p shows the thematic layer of aspect data for Islamabad that categorizes regions based on their compass directions. The aspect map lists out the front-facing direction of regions along with the compass. For example, the major constituting region in the northeast contains southeastern front-facing regions that align with thematic maps of land use and wells in the study region. The dense regions with most residential and commercial zones are in the southeast. The flow from the north region is ensured towards the southeast region. The southeastern compass front directions of the geological regions act as a gentle slope that promotes groundwater recharge in Islamabad [116].

These influencing factors were considered based on a literature review and classified based on their impact on groundwater recharge contribution, i.e., the class at which lesser the groundwater recharge potential would rank lower and vice versa. For example, a higher slope would have lesser groundwater potential, or a lower TWI would mean low water moisture and low groundwater recharge potential; hence, these classes would have lesser weightage.

5.2. Weightage Calculation for Influence Factor (IF) Techniques

After obtaining the individual thematic maps for each of the contributing factors, these factors were integrated to obtain a potential holistic map that highlights the recharge potential of Islamabad. Accordingly, weights and rates were assigned to the 15 key factors. For incorporating the mutual influence of the factors, rate values were assigned to them. Two points were given for every major effect, while one point was given to the corresponding factor for each minor effect. The cumulative weightage of both major and minor effects was considered for calculating the relative rate, as shown in Table 4. Table 4 shows that factors such as lithology influence six of its fellow factors majorly. It has a noticeable impact on the lineament, drainage, land/use, slope, and soil types. Thus, it has been assigned a value of 2 six times (2 × 6 factors).

Table 4. Relative rates and scores for each potential factor.

Factors	Major Effect (*A*)	Minor Effect (*B*)	Proposed Relative Rates (*A* + *B*)	Normalized Relative Rates (*Y*) in %
Distance to Faults	2 + 2 + 2 + 2	1 + 1 + 1	11	**6.875**
Land use/Land cover	2 + 2 + 2 + 2 + 2 + 2	1 + 1 + 1 + 1	16	**10.000**
Lithology	2 + 2 + 2 + 2 + 2 + 2	1 + 1 + 1 + 1	16	**10.000**
Drainage Density	2 + 2 + 2 + 2 + 2 + 2	1 + 1 + 1	15	**9.375**
Slope	2 + 2 + 2 + 2 + 2	1 + 1 + 1	13	**8.125**
Soil	2 + 2 + 2 + 2 + 2	1 + 1 + 1	13	**8.125**
Rainfall	2 + 2 + 2 + 2 + 2	1 + 1 + 1	13	**8.125**
Plan Curvature	2 + 2	1	5	**3.125**
Fault Density	2 + 2 + 2 + 2	1 + 1	10	**6.250**
Profile Curvature	2 + 2	1	5	**3.125**
TWI	2 + 2 + 2	1 + 1	8	**5.000**
Elevation	2 + 2 + 2 + 2	1 + 1 + 1	11	**6.875**
Aspect	2 + 2 + 2	1 + 1	8	**5.000**
Drainage Distance	2 + 2 + 2 + 2	1 + 1	10	**6.250**
Slope Length	2 + 2	1 + 1	6	**3.750**
			Σ = 160	Σ = 100
			160	100

Similarly, other factors have also been assigned their respective rate values using the same approach. Overall, the major effect (*A*) and minor effect (*B*) are summed for all factors, and their cumulative sums are calculated for each factor to get the proposed relative rates. The cumulative proposed relative rates sum up to 160. Using this value, the normalized relative rates are calculated, where the proposed relative rate of each factor is divided by the cumulative proposed related rates and multiplied by 100 using Equation (1). The values are rounded off to the nearest integer.

$$Normalized\ relative\ rates\ (Y) = \frac{Proposed\ relative\ rates\ (A+B)}{Commulative\ Proposed\ relative\ rates\ (\Sigma(A+B))} \times 100 \quad (1)$$

After the assignment of rate values, the next step is to assign weights. In this process, five major descriptive levels are plotted for each factor ranging from very high to very low, including some interrelated levels as shown in Table 5. Factors contributing majorly, such as rainfall, can be seen as very dominant in relevant studies [108,109] and in abundance in the southeastern regions of the study area and thus were assigned higher weights. In contrast, factors such as profile curvature were assigned a lower weightage, as the area followed a rhythmic curvature, and the influence of curvature was not dominant in terms of groundwater flow, as evident from Figure 3 (previously shown).

With a weightage of 8.1%, rainfall is a dominant factor in the southeastern parts of the study area. Plan curvature data indicate a slight shift in curvature as seen from the thematic map and thus were assigned a weightage of 3.1%. The higher curvature would result in a greater flow of water beneath the surface [66]. Soil is the primary factor that controls seepage and the associated groundwater recharge [117]. Thereby, it was assigned the highest weightage (8.1%). Likewise, faults being the primary indicator of geographical movement (earthquakes or tectonic) over the years indicate a weaker and vulnerable zone suspectable to the greater flow of groundwater channels beneath the surface. It adds greatly to the groundwater recharge and was hence assigned a weightage of 6.8%. Drainage distance, profile curvature, and TWI were assigned weights of 6.2%, 3.1%, and 5%, respectively.

The data obtained from thematic maps do not indicate an abrupt or dominant effect of these considered geographical features (key factors) over the study area, thus acquiring a lower weightage in our study area. The slope indicating the natural flow of water towards the lower altitude area was assigned a weightage of 8.1%. Elevation and slope length were assigned the weightage of 6.8% and 3.7%, indicating the flow towards lower-elevated areas and the flow speed. Accordingly, the lower the speed, the greater the infiltration and vice versa [122]. Lithology has been assigned a weightage of 10%. It indicates the rock characteristics that dictate the water flow beneath the surface in channels and streams. Land use is another primary factor that was assigned 10% weightage. It has been utilized by several related studies [60,66]. Finally, fault and drainage densities and aspects indicated the magnitude of faults, drainage networks, and front-facing direction of slopes signifying the flow of groundwater beneath the surface and were assigned weights of 6.2%, 9.3%, and 5%, respectively, in this study.

After the assignment of rates and weights, the % influencing score was calculated using Equation (2). The % influencing score is defined as the percentage of factor effect on recharge potential (%) and is shown in Table 5 for each factor, where X is the normalized weight from 1 to 10, and Y is the rate from 1 to 10.

$$\%\ influencing\ score = \frac{Total\ Weightage\ \Sigma(X \times Y)}{Grand\ Total\ Weight\ (GTW)} \times 100 \quad (2)$$

Table 5. Weight evaluations of factors influencing potential recharge capacity.

Factors	Categories	Effect	Normalized Weight (X) (1–10)	Normalized Relative Rates (Y) Based on Table 4 (1–10)	Weighted Rating (X × Y)	Total Weightage max(X) × Y	MAX Effect on Recharge Potential (%)
Rainfall	<882	Very Low	2	8.125	16.25	81.25	**8.125**
	882–999	Low	4		32.50		
	999–1116	Medium	6		48.75		
	1116–1233	High	8		65.00		
	1233–1350	Very High	10		81.25		
Plan curvature	<−2.34	Very Low	2	3.125	6.25	31.25	**3.125**
	−1.74	Low	4		12.50		
	−1.2	Medium	6		18.75		
	0.6–2.6	High	8		25.00		
	>2.6	Very High	10		31.25		
Soil	Calcareous Loamy Soil Piedmont	Very High	10	8.125	81.25	81.25	**8.125**
	Calcareous Silty Soil Gullied Land Complex	High	8		65.00		
	Rough Broken Land	High	8		65.00		
	Mountainous land with nearly continuous soil	Medium	6		48.75		
	Mountainous land with patchy soil	Medium	6		48.75		
	Urban	Very Low	4		32.50		
	Calcareous Loamy Soil	Low	2		16.25		
Distance to fault	<100	Very High	10	6.875	68.75	68.75	**6.875**
	100–200	High	8		55.00		
	200–500	High	8		55.00		
	500–1000	Medium	6		41.25		
	1000–2000	Medium	6		41.25		
	2000–5000	Very Low	4		27.50		
	>5000	Low	2		13.75		

Table 5. *Cont.*

Factors	Categories	Effect	Normalized Weight (X) (1–10)	Normalized Relative Rates (Y) Based on Table 4 (1–10)	Weighted Rating ($X \times Y$)	Total Weightage max(X) $\times$ Y	MAX Effect on Recharge Potential (%)
Drainage distance	<100	Very High	10	6.250	62.50	62.50	**6.250**
	100–200	High	8		50.00		
	200–500	Medium	6		37.50		
	>500	Low	4		25.00		
Profile Curvature	<−3.14	Very Low	2	3.125	6.25	31.25	**3.125**
	−2.24	Low	4		12.50		
	−1.8	Medium	6		18.75		
	0.7–2.9	High	8		25.00		
	>2.9	Very High	10		31.25		
TWI	<2	Very Low	2	5.000	10.00	50.00	**5.000**
	2–4	Low	4		20.00		
	4–6	Medium	6		30.00		
	>6	High or very high	10		50.00		
Slope	<12	Very High	10	8.125	81.25	81.25	**8.125**
	12–24	High	8		65.00		
	24–36	Medium	6		48.75		
	36–48	Low	4		32.50		
	>48	Very Low	2		16.25		
Elevation	<531	Very High	10	6.875	68.75	68.75	**6.875**
	531–617	High	8		55.00		
	617–756	Medium	6		41.25		
	756–994	Low	4		27.50		
	>994	Very Low	2		13.75		
Slope length	<10	Very High	10	3.750	37.50	37.50	**3.750**
	10–20	High	8		30.00		
	20–30	Medium	6		22.50		
	30–40	Low	4		15.00		
	>40	Very Low	2		7.50		
Lithology	Limestone	High	10	10.000	100.00	100.00	**10.000**
	Sandstone	Medium	6		60.00		
	Unconsolidated deposit	Low	4		40.00		

Table 5. *Cont.*

Factors	Categories	Effect	Normalized Weight (*X*) (1–10)	Normalized Relative Rates (*Y*) Based on Table 4 (1–10)	Weighted Rating ($X \times Y$)	Total Weightage $\max(X) \times Y$	MAX Effect on Recharge Potential (%)
Land use	Bare area	Low	4	10.000	40.00	100.00	**10.000**
	Vegetation	High	8		80.00		
	Water	Very High	10		100.00		
	Built-up	Medium	6		60.00		
Fault density	<15	Very Low	2	6.250	12.50	62.50	**6.250**
	15–41	Low	4		25.00		
	41–65	Medium	6		37.50		
	65–91	High	8		50.00		
	>91	Very High	10		62.50		
Drainage density	<1	Very Low	2	9.375	18.75	93.75	**9.375**
	01/01/1984	Low	4		37.50		
	1.84–2.68	Medium	6		56.25		
	2.68–3.53	High	8		75.00		
	>3.53	Very High	10		93.75		
Aspect	Flat	Very High	10	5.000	50.00	50.00	**5.000**
	North	Very High	10		50.00		
	Northeast	High	8		40.00		
	East	High	8		40.00		
	Southwest	Medium	6		30.00		
	Southeast	Medium	6		30.00		
	South	Low	4		20.00		
	West	Low	4		20.00		
	Northwest	Very Low	2		10.00		
						GTW: $\Sigma = 3118$	$\Sigma = 100$

5.3. Final Combined Recharge Potential Map

After considering rate assessment, different layers of recharge potential were superimposed in the ArcGIS tool. As a result of the integration of the 15 contributing factors, the final combined potential map was generated, which highlights the overall recharge potential of Islamabad, as shown in Figure 4. The resulting map generated with the help of influencing factors' relative rates categorizes the region into five descriptive levels based on the rechargeability. These descriptive levels include "best", "high", "medium", "low", and "poor", each with a distinctive color.

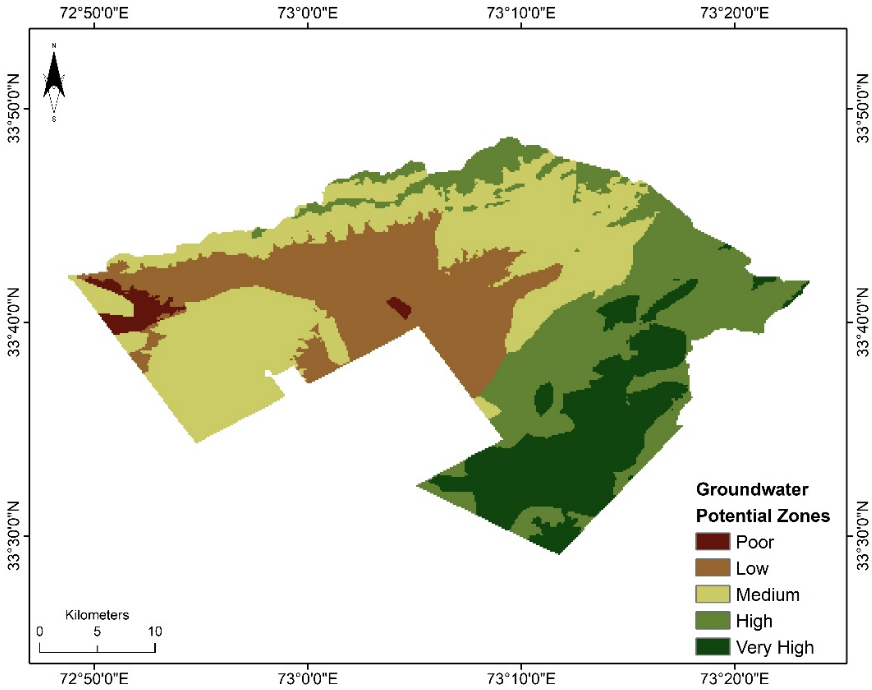

Figure 4. Potential groundwater recharge zones in the study area.

From the output thematic map (Figure 4), it is evident that the eastern region of the study area is the most suitable for groundwater recharge. Accordingly, it is highlighted to be the "best" region. This region received the highest rainfall as per the previously presented maps. This is in line with previous studies that argued that the higher the rainfall, the greater the groundwater recharge and vice versa [116,123]. Moreover, it can be observed from Figure 4 that the groundwater recharge potential decreases as we head towards the western side of Islamabad. A decreasing pattern for groundwater recharge is seen as we move from east to west in the study area. Most of the mountainous region is located towards the northeast of Islamabad, receiving the highest rainfall and having higher slopes, inducing rapid runoff. Towards the center and to the west, the slope length decreases, thus indicating a higher recharge potential, as gentle slopes were attributed to higher recharge potential [122].

Table 6 presents the data of each category shown in graphical form in Figure 4 and gives the exact portions of the study area having best to worst recharge capability. It shows that the area labeled under the "best" comprises 136.8 km^2, covering 15% of the study area. Similarly, an area of 191.52 km^2 falls under our map's "high" classification, covering 21% of the study area. Another 35% of the region collectively serves as a competent region (preferred) for groundwater recharge. The moderate zone covers 218.88 km^2 of area, covering 24% of the study area. In contrast, the potentially poor and low zones make up 13% and 27% of the area, i.e., 118.56 km^2 and 246.24 km^2, respectively.

Table 6. Classification of potential recharge areas.

Recharge Potential Category	Average %	Area Extant (km^2)
Very High	15%	136.8
High	21%	191.52
Medium	24%	218.88
Low	27%	246.24
Poor	13%	118.56

The results show that around more than half (51%) of the total area of Islamabad does not have sufficient recharge capability, and the city is dependent on only 35% of the total area to fulfill the city's demand for groundwater for daily life usage. This can be taken into consideration by local authorities when planning to meet the local water requirements and groundwater recharge. The city planners and policymakers should take mitigation steps and devise strategies to preserve most of this 35% of the land to avoid any further damage to the already fragile water condition of the city. The information devised from this final groundwater potential zones map can help resolve the long due water shortage issues in various sectors of Islamabad and nearby areas through efficient management and preservation of groundwater resources in the area. Compared to the previous studies [36–42], this study addresses the research gap of applying this methodology in a non-coastal region and modifies it by using thematic maps of larger spatial scale and the DEM data of smaller resolution to refine the accuracy of the process. All the previous published research used the one-time dataset and map the output. However, these do not depict the true representation of the groundwater recharge. This is because the considered datasets may change temporally, needing more datasets to overcome this limitation. Hence, this study used the annual mean for all datasets, which change with respect to season or time. Secondly, previously published research used limitedly influencing datasets that might not present the actual situation of the study. In the current research, all the contributing factors were analyzed and used to consider the entire situation. Accordingly, the model gives reliable actual output. Moreover, the study also considers more contributing factors than the previous studies to further enhance the accuracy of the output. The research presents a holistic approach that gives comparatively improved results and can be applied to other regions as and when required.

6. Conclusions

Considering the constant increase in groundwater demand in Islamabad with increasing population growth, the decreasing groundwater level has become a matter of concern for the local authorities. This study attempts to develop a groundwater potential recharge zone map of the study area of Islamabad, Pakistan, to help the policymakers devise efficient policies for mitigating this problem.

The methodology involves the integration of RS and GIS to develop a map that highlights the groundwater recharge potential in the study area. In our scenario, 15 key factors were selected based on their contribution to the recharge. These include soil, land use/land cover, drainage distance, slope, rainfall, plan curvature, distance to faults, profile curvature, TWI, elevation, slope length, lithology, fault density, drainage density, and aspect. Thematic maps were generated and overlayed using GIS. A holistic map was devised at the end, comprising input from 15 of the influencing factors and their weights to produce a weighted map. The resulting map categorizes the region into five different descriptive levels, namely poor, low, medium, high, and best, based on the groundwater recharge potential. The results showed that 13% of the area falls in the poor-recharge-potential category, 27% area has a low potential, 24% has medium potential, 21% has high potential, and 15% has the best chance of recharging the groundwater table. Overall, around 35% of the study area is suitable for groundwater recharge, and more than half is unsuitable for such purposes.

This study provides a holistic model with more accurate results than the previous studies by introducing a comparatively greater number of factors and employing the thematic maps of larger spatial scale and DEM data of a smaller resolution. The current study paves the way for future infrastructure development by the concerned authorities to meet the water demand of Islamabad and preserve the precious natural terrain with high recharge potential.

The study is limited in terms of the factors considered. Further, it is restricted to a single region in a developing country for testing purposes. Moreover, considering that this study was limited in terms of the unavailability of geophysical data for the case study area, future researchers can conduct further research by including the geophysical and field data from multiple regions. This can help in carrying out the subsurface groundwater modeling as well as 3D modeling of the targeted study area. Further, similar studies can be conducted for larger nearby regions and developed countries to help move toward global sustainability goals and tackle climate change effects. The effects of vegetation on recharge can also be investigated in the future.

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References

1. Megdal, S.B. Invisible Water: The Importance of Good Groundwater Governance and Management. *NPJ Clean Water* **2018**, *1*, 15. [CrossRef]
2. Ganapuram, S.; Kumar, G.V.; Krishna, I.M.; Kahya, E.; Demirel, M.C. Mapping of Groundwater Potential Zones in the Musi Basin Using Remote Sensing Data and Gis. *Adv. Eng. Softw.* **2009**, *40*, 506–518. [CrossRef]
3. Singh, S.K.; Zeddies, M.; Shankar, U.; Griffiths, G.A. Potential Groundwater Recharge Zones within New Zealand. *Geosci. Front.* **2019**, *10*, 1065–1072. [CrossRef]
4. Bear, J. *Hydraulics of Groundwater*; Courier Corporation: North Chelmsford, MA, USA, 2012.
5. Todd, D.K.; Mays, L.W. *Groundwater Hydrology*; John Wiley & Sons: Hoboken, NJ, USA, 2004.
6. Thakur, D.; Bartarya, S.K.; Nainwal, H.C. Mapping Groundwater Prospect Zones in an Intermontane Basin of the Outer Himalaya in India Using Gis and Remote Sensing Techniques. *Environ. Earth Sci.* **2018**, *77*, 368. [CrossRef]
7. Wang, X.J.; Zhang, J.Y.; Shahid, S.; Guan, E.H.; Wu, Y.X.; Gao, J.; He, R.M. Adaptation to Climate Change Impacts on Water Demand. *Mitig. Adapt. Strateg. Glob. Chang.* **2016**, *21*, 81–99. [CrossRef]
8. Rao, Y.S.; Jugran, D.K. Delineation of Groundwater Potential Zones and Zones of Groundwater Quality Suitable for Domestic Purposes Using Remote Sensing and Gis. *Hydrol. Sci. J.* **2003**, *48*, 821–833.
9. Cherry, J.A.; Freeze, R.A. *Groundwater*; Prentice-Hall: Hoboken, NJ, USA, 1979.
10. Shao, Z.; Huq, M.E.; Cai, B.; Altan, O.; Li, Y. Integrated Remote Sensing and Gis Approach Using Fuzzy-Ahp to Delineate and Identify Groundwater Potential Zones in Semi-Arid Shanxi Province, China. *Environ. Model. Softw.* **2020**, *134*, 104868. [CrossRef]
11. Huang, T.; Ma, B.; Pang, Z.; Li, Z.; Li, Z.; Long, Y. How Does Precipitation Recharge Groundwater in Loess Aquifers? Evidence from Multiple Environmental Tracers. *J. Hydrol.* **2020**, *583*, 124532. [CrossRef]

12. Aslam, B.; Maqsoom, A.; Khalid, N.; Ullah, F.; Sepasgozar, S. Urban Overheating Assessment through Prediction of Surface Temperatures: A Case Study of Karachi, Pakistan. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 539. [CrossRef]
13. Okello, C.; Tomasello, B.; Greggio, N.; Wambiji, N.; Antonellini, M. Impact of Population Growth and Climate Change on the Freshwater Resources of Lamu Island, Kenya. *Water* **2015**, *7*, 1264–1290. [CrossRef]
14. Atif, S.; Umar, M.; Ullah, F. Investigating the Flood Damages in Lower Indus Basin since 2000: Spatiotemporal Analyses of the Major Flood Events. *Nat. Hazards* **2021**, *108*, 2357–2383. [CrossRef]
15. Page, D.; Bekele, E.; Vanderzalm, J.; Sidhu, J. Managed Aquifer Recharge (Mar) in Sustainable Urban Water Management. *Water* **2018**, *10*, 239. [CrossRef]
16. Dillon, P.; Toze, S.; Page, D.; Vanderzalm, J.; Bekele, E.; Sidhu, J.; Rinck-Pfeiffer, S. Managed Aquifer Recharge: Rediscovering Nature as a Leading Edge Technology. *Water Sci. Technol.* **2010**, *62*, 2338–2345. [CrossRef]
17. Bhatti, M.T.; Anwar, A.A.; Aslam, M. Groundwater Monitoring and Management: Status and Options in Pakistan. *Comput. Electron. Agric.* **2017**, *135*, 143–153. [CrossRef]
18. Subhadra, B. Water: Halt India's Groundwater Loss. *Nature* **2015**, *521*, 289. [CrossRef]
19. Qureshi, A.S. Improving Food Security and Livelihood Resilience through Groundwater Management in Pakistan. *Glob. Adv. Res. J. Agric. Sci.* **2015**, *4*, 687–710.
20. Siebert, S.; Kummu, M.; Porkka, M.; Döll, P.; Ramankutty, N.; Scanlon, B.R. A Global Data Set of the Extent of Irrigated Land from 1900 to 2005. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 1521–1545. [CrossRef]
21. Chindarkar, N.; Grafton, R.Q. India's Depleting Groundwater: When Science Meets Policy. *Asia Pac. Policy Stud.* **2019**, *6*, 108–124. [CrossRef]
22. Mancosu, N.; Snyder, R.L.; Kyriakakis, G.; Spano, D. Water Scarcity and Future Challenges for Food Production. *Water* **2015**, *7*, 975–992. [CrossRef]
23. Schneider, U.; Havlík, P.; Schmid, E.; Valin, H.; Mosnier, A.; Obersteiner, M.; Böttcher, H.; Skalský, R.; Balkovič, J.; Sauer, T.; et al. Impacts of Population Growth, Economic Development, and Technical Change on Global Food Production and Consumption. *Agric. Syst.* **2011**, *104*, 204–215. [CrossRef]
24. Iqbal, N.; Hossain, F.; Lee, H.; Akhter, G. Satellite Gravimetric Estimation of Groundwater Storage Variations over Indus Basin in Pakistan. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2016**, *9*, 3524–3534. [CrossRef]
25. Van Steenbergen, F.; Kaisarani, A.B.; Khan, N.U.; Gohar, M.S. A Case of Groundwater Depletion in Balochistan, Pakistan: Enter into the Void. *J. Hydrol. Reg. Stud.* **2015**, *4*, 36–47. [CrossRef]
26. Nag, S.K. Application of Lineament Density and Hydrogeomorphology to Delineate Groundwater Potential Zones of Baghmundi Block in Purulia District, West Bengal. *J. Indian Soc. Remote Sens.* **2005**, *33*, 521–529. [CrossRef]
27. Ravindran, A.A.; Selvam, S. Coastal Disaster Damage and Neotectonic Subsidence Study Using 2d Eri Technique in Dhanushkodi, Rameshwaram Island, Tamilnadu, India. *Middle-East J. Sci. Res.* **2014**, *19*, 1117–1122.
28. Jasrotia, A.S.; Kumar, R.; Saraf, A.K. Delineation of Groundwater Recharge Sites Using Integrated Remote Sensing and Gis in Jammu District, India. *Int. J. Remote Sens.* **2007**, *28*, 5019–5036. [CrossRef]
29. Kumar, P.K.D.; Gopinath, G.; Seralathan, P. Application of Remote Sensing and Gis for the Demarcation of Groundwater Potential Zones of a River Basin in Kerala, Southwest Coast of India. *Int. J. Remote Sens.* **2007**, *28*, 5583–5601. [CrossRef]
30. Rodell, M.; Velicogna, I.; Famiglietti, J.S. Satellite-Based Estimates of Groundwater Depletion in India. *Nature* **2009**, *460*, 999–1002. [CrossRef]
31. Srivastava, P.K.; Bhattacharya, A.K. Groundwater Assessment through an Integrated Approach Using Remote Sensing, Gis and Resistivity Techniques: A Case Study from a Hard Rock Terrain. *Int. J. Remote Sens.* **2006**, *27*, 4599–4620. [CrossRef]
32. Selvam, S.; Sivasubramanian, P. Groundwater Potential Zone Identification Using Geoelectrical Survey: A Case Study from Medak District, Andhra Pradesh, India. *Int. J. Geomat. Geosci.* **2012**, *3*, 55–62.
33. Selvam, S. Use of Remote Sensing and Gis Techniques for Land Use and Land Cover Mapping of Tuticorin Coast, Tamilnadu. *Univers. J. Environ. Res. Technol.* **2012**, *2*, 233–241.
34. Saraf, A.K.; Choudhury, P.R. Integrated Remote Sensing and Gis for Groundwater Exploration and Identification of Artificial Recharge Sites. *Int. J. Remote Sens.* **1998**, *19*, 1825–1841. [CrossRef]
35. Chenini, I.; Ben Mammou, A.; El May, M. Groundwater Recharge Zone Mapping Using Gis-Based Multi-Criteria Analysis: A Case Study in Central Tunisia (Maknassy Basin). *Water Resour. Manag.* **2010**, *24*, 921–939. [CrossRef]
36. Kamal, A.M.; Midorikawa, S. Gis-Based Geomorphological Mapping Using Remote Sensing Data and Supplementary Geoinformation: A Case Study of the Dhaka City Area, Bangladesh. *Int. J. Appl. Earth Obs. Geoinf.* **2004**, *6*, 111–125.
37. Gustavsson, M.; Kolstrup, E.; Seijmonsbergen, H. A New Symbol-and-Gis Based Detailed Geomorphological Mapping System: Renewal of a Scientific Discipline for Understanding Landscape Development. *Geomorphology* **2006**, *77*, 90–111. [CrossRef]
38. Singh, A.K.; Parkash, B.; Choudhury, P.R. Integrated Use of Srm, Landsat Etm+ Data and 3d Perspective Views to Identify the Tectonic Geomorphology of Dehradun Valley, India. *Int. J. Remote Sens.* **2007**, *28*, 2403–2414. [CrossRef]
39. Selvam, S.I.J.D.; Mala, R.I.J.D.; Muthukakshmi, V. A Hydrochemical Analysis and Evaluation of Groundwater Quality Index in Thoothukudi District, Tamilnadu, South India. *Int. J. Adv. Eng. Appl.* **2013**, *2*, 25–37.
40. Selvam, S.; Manimaran, G.; Sivasubramanian, P. Hydrochemical Characteristics and Gis-Based Assessment of Groundwater Quality in the Coastal Aquifers of Tuticorin Corporation, Tamilnadu, India. *Appl. Water Sci.* **2013**, *3*, 145–159. [CrossRef]

41. Selvam, S.; Manimaran, G.; Sivasubramanian, P. Cumulative Effects of Septic System Disposal and Evolution of Nitrate Contamination Impact on Coastal Groundwater in Tuticorin, South Tamilnadu, India. *Res. J. Pharm. Biol. Chem. Sci.* **2013**, *4*, 1207–1218.
42. Singaraja, C.; Chidambaram, S.; Srinivasamoorthy, K.; Anandhan, P.; Selvam, S. A Study on Assessment of Credible Sources of Heavy Metal Pollution Vulnerability in Groundwater of Thoothukudi Districts, Tamilnadu, India. *Water Qual. Expo. Health* **2015**, *7*, 459–467. [CrossRef]
43. Machiwal, D.; Jha, M.K.; Mal, B.C. Assessment of Groundwater Potential in a Semi-Arid Region of India Using Remote Sensing, Gis and Mcdm Techniques. *Water Resour. Manag.* **2011**, *25*, 1359–1386. [CrossRef]
44. Saraf, A.K.; Jain, S.K. Integrated Use of Remote Sensing and Geographical Information System Methods for Groundwater Exploration in Parts of Lalitpur District, Up. In Proceedings of the International Conference on Hydrology and Water Resources, New Delhi, India, 20–22 December 1993; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1994.
45. Krishnamurthy, J.; Srinivas, G. Role of Geological and Geomorphological Factors in Ground Water Exploration: A Study Using Irs Liss Data. *Int. J. Remote Sens.* **1995**, *16*, 2595–2618. [CrossRef]
46. Krishnamurthy, J.; Kumar, N.V.; Jayaraman, V.; Manivel, M. An Approach to Demarcate Ground Water Potential Zones through Remote Sensing and a Geographical Information System. *Int. J. Remote Sens.* **1996**, *17*, 1867–1884. [CrossRef]
47. Kamaraju, M.; Bhattacharya, A.; Reddy, G.S.; Rao, G.C.; Murthy, G.S.; Rao, T.C.M. Ground-Water Potential Evaluation of West Godavari District, Andhra Pradesh State, India—a Gis Approach. *Groundwater* **1996**, *34*, 318–325. [CrossRef]
48. Ravindran, K.V. Drainage Morphometry Analysis and Its Correlation with Geology, Geomorphology and Groundwater Prospects in Zuvari Basin, South Goa: Using Remote Sensing and Gis. In Proceedings of the National Symposium on Remote Sensing for Natural Resources with Special Emphasis on Water Management, Pune, India, 4–6 December 1996.
49. Kumar, A. Sustainable Utilisation of Water Resource in Watershed Perspective-a Case Study in Alaunja Watershed, Hazaribagh, Bihar. *J. Indian Soc. Remote Sens.* **1999**, *27*, 13–22. [CrossRef]
50. Krishnamurthy, J.; Mani, A.; Jayaraman, V.; Manivel, M. Groundwater Resources Development in Hard Rock Terrain-an Approach Using Remote Sensing and Gis Techniques. *Int. J. Appl. Earth Obs. Geoinf.* **2000**, *2*, 204–215. [CrossRef]
51. Srivastava, P.K.; Bhattacharya, A.K. Delineation of Ground Water Potential Zones in a Hard Rock Terrain of Bargarh District, Orissa Using Irs Data. *J. Indian Soc. Remote Sens.* **2000**, *28*, 129–140. [CrossRef]
52. Shahid, S.; Nath, S.K.; Roy, J. Groundwater Potential Modelling in a Soft Rock Area Using a Gis. *Int. J. Remote Sens.* **2000**, *21*, 1919–1924. [CrossRef]
53. Khan, M.A.; Moharana, P.C. Use of Remote Sensing and Geographical Information System in the Delineation and Characterization of Ground Water Prospect Zones. *J. Indian Soc. Remote Sens.* **2002**, *30*, 131–141. [CrossRef]
54. Karanth, K.R.; Seshubabu, K. Identification of Major Lineaments on Satellite Imagery and on Aerial Photographs for Delineation for Possible Potential Groundwater Zones in Penukonda and Dharmavaram Taluks of Anantapur Ditrict. In Proceedings of the Joint Indo-US Workshop on Remote Sensing of Water Resources, National Remote Sensing Agency (NRSA), Hyderabad, India, 10–14 April 1978.
55. Raju, K.C.B.; Rao, P.N.; Rao, G.V.K.; Kumar, B.J. Analytical Aspects of Remote Sensing Techniques for Ground Water Prospection in Hard Rocks. In Proceedings of the 6th Asian Conference on Remote Sensing, Hyderabad, India, 21–26 November 1986.
56. Palanivel, S.; Ganesh, A.; Kumaran, T.V. Geohydrological Evaluation of Upper Agniar and Vellar Basins, Tamil Nadu: An Integrated Approach Using Remote Sensing, Geophysical and Well Inventory Data. *J. Indian Soc. Remote Sens.* **1996**, *24*, 153–168. [CrossRef]
57. Sankar, K. Evaluation of Groundwater Potential Zones Using Remote Sensing Data in Upper Vaigai River Basin, Tamil Nadu, India. *J. Indian Soc. Remote Sens.* **2002**, *30*, 119–129. [CrossRef]
58. Devi, P.S.; Srinivasulu, S.; Raju, K.K. Hydrogeomorphological and Groundwater Prospects of the Pageru River Basin by Using Remote Sensing Data. *Environ. Geol.* **2001**, *40*, 1088–1094. [CrossRef]
59. Saraf, A.K.; Gupta, R.P.; Jain, R.K.; Srivastava, N.K. Gis Based Processing and Interpretation of Ground Water Quality Data. In Proceedings of the Regional Workshop on Environmental Aspects of Ground Water Development, Kurukshetra, India, 17–19 October 1994.
60. Achu, A.L.; Thomas, J.; Reghunath, R. Multi-Criteria Decision Analysis for Delineation of Groundwater Potential Zones in a Tropical River Basin Using Remote Sensing, Gis and Analytical Hierarchy Process (Ahp). *Groundw. Sustain. Dev.* **2020**, *10*, 100365. [CrossRef]
61. Das, B.; Pal, S.C.; Malik, S.; Chakrabortty, R. Modeling Groundwater Potential Zones of Puruliya District, West Bengal, India Using Remote Sensing and Gis Techniques. *Geol. Ecol. Landsc.* **2019**, *3*, 223–237. [CrossRef]
62. Lakshmi, S.V.; Reddy, Y.V.K. Identification of Groundwater Potential Zones Using Gis and Remote Sensing. *Int. J. Pure Appl. Math.* **2018**, *119*, 3195–3210.
63. Roy, A.; Keesari, T.; Sinha, U.K.; Sabarathinam, C. Delineating Groundwater Prospect Zones in a Region with Extreme Climatic Conditions Using Gis and Remote Sensing Techniques: A Case Study from Central India. *J. Earth Syst. Sci.* **2019**, *128*, 201. [CrossRef]
64. Kaur, L.; Rishi, M.S.; Singh, G.; Thakur, S.N. Groundwater Potential Assessment of an Alluvial Aquifer in Yamuna Sub-Basin (Panipat Region) Using Remote Sensing and Gis Techniques in Conjunction with Analytical Hierarchy Process (Ahp) and Catastrophe Theory (Ct). *Ecol. Indic.* **2020**, *110*, 105850. [CrossRef]

65. Selvam, S.; Dar, F.A.; Magesh, N.S.; Singaraja, C.; Venkatramanan, S.; Chung, S.Y. Application of Remote Sensing and Gis for Delineating Groundwater Recharge Potential Zones of Kovilpatti Municipality, Tamil Nadu Using If Technique. *Earth Sci. Inform.* **2016**, *9*, 137–150. [CrossRef]
66. Abijith, D.; Saravanan, S.; Singh, L.; Jennifer, J.J.; Saranya, T.; Parthasarathy, K. Gis-Based Multi-Criteria Analysis for Identification of Potential Groundwater Recharge Zones-a Case Study from Ponnaniyaru Watershed, Tamil Nadu, India. *HydroResearch* **2020**, *3*, 1–14. [CrossRef]
67. Kaliraj, S.; Chandrasekar, N.; Magesh, N.S. Identification of Potential Groundwater Recharge Zones in Vaigai Upper Basin, Tamil Nadu, Using Gis-Based Analytical Hierarchical Process (Ahp) Technique. *Arab. J. Geosci.* **2014**, *7*, 1385–1401. [CrossRef]
68. Banks, W.S.; Paylor, R.L.; Hughes, W.B. Using Thermal-Infrared Imagery to Delineate Ground-Water Discharge D. *Groundwater* **1996**, *34*, 434–443. [CrossRef]
69. Aslam, B.; Maqsoom, A.; Tahir, M.D.; Ullah, F.; Rehman, M.S.U.; Albattah, M. Identifying and Ranking Landfill Sites for Municipal Solid Waste Management: An Integrated Remote Sensing and GIS Approach. *Buildings* **2022**, *12*, 605. [CrossRef]
70. Gilani, H.; Ahmad, S.; Qazi, W.A.; Abubakar, S.M.; Khalid, M. Monitoring of Urban Landscape Ecology Dynamics of Islamabad Capital Territory (Ict), Pakistan, over Four Decades (1976–2016). *Land* **2020**, *9*, 123. [CrossRef]
71. Das, S.; Pardeshi, S.D. Integration of Different Influencing Factors in Gis to Delineate Groundwater Potential Areas Using If and Fr Techniques: A Study of Pravara Basin, Maharashtra, India. *Appl. Water Sci.* **2018**, *8*, 197. [CrossRef]
72. Juandi, M.; Syahril, S. Empirical Relationship between Soil Permeability and Resistivity, and Its Application for Determining the Groundwater Gross Recharge in Marpoyan Damai, Pekanbaru, Indonesia. *Water Pract. Technol.* **2017**, *12*, 660–666. [CrossRef]
73. Arkoprovo, B.; Adarsa, J.; Animesh, M. Application of Remote Sensing, Gis and Mif Technique for Elucidation of Groundwater Potential Zones from a Part of Orissa Coastal Tract, Eastern India. *Res. J. Recent Sci.* **2013**, *2277*, 2502.
74. Butt, M.J.; Waqas, A.; Iqbal, M.F.; Muhammad, G.; Lodhi, M.A.K. Assessment of Urban Sprawl of Islamabad Metropolitan Area Using Multi-Sensor and Multi-Temporal Satellite Data. *Arab. J. Sci. Eng.* **2012**, *37*, 101–114. [CrossRef]
75. Shaheen, N.; Baig, M.A.; Mahboob, M.A.; Akbar, S.; Khokar, M.F.; Wwf-Pakistan, G. Application of Remote Sensing Technologies to Detect the Vegetation Changes During Past Two Decades in Islamabad, Pakistan. *J. Soc. Sci.* **2015**, *4*, 886–900. [CrossRef]
76. Hassan, Z.; Shabbir, R.; Ahmad, S.S.; Malik, A.H.; Aziz, N.; Butt, A.; Erum, S. Dynamics of Land Use and Land Cover Change (Lulcc) Using Geospatial Techniques: A Case Study of Islamabad Pakistan. *SpringerPlus* **2016**, *5*, 812. [CrossRef]
77. Butt, A.; Shabbir, R.; Ahmad, S.S.; Aziz, N. Land Use Change Mapping and Analysis Using Remote Sensing and Gis: A Case Study of Simly Watershed, Islamabad, Pakistan. *Egypt. J. Remote Sens. Space Sci.* **2015**, *18*, 251–259. [CrossRef]
78. Shabbir, R.; Ahmad, S.S. Water Resource Vulnerability Assessment in Rawalpindi and Islamabad, Pakistan Using Analytic Hierarchy Process (Ahp). *J. King Saud Univ.-Sci.* **2016**, *28*, 293–299. [CrossRef]
79. Shah, A.; Ali, K.; Nizami, S.M. Spatio-Temporal Analysis of Urban Sprawl in Islamabad, Pakistan During 1979–2019, Using Remote Sensing. *GeoJournal* **2021**, 1–14. [CrossRef]
80. Abbasi, K. Islamabad's Groundwater Has Lowered by Five Times over Last Five Years: Minister. *DAWN News*. 20 December 2018. Available online: https://www.dawn.com/news/1452462/islamabads-groundwater-has-lowered-by-five-times-over-last-five-years-minister (accessed on 18 April 2022).
81. Doxiadis, C.A. Islamabad: The Creation of a New Capital. *Town Plan. Rev.* **1965**, *36*, 1–35. [CrossRef]
82. Adeel, M. Methodology for Identifying Urban Growth Potential Using Land Use and Population Data: A Case Study of Islamabad Zone Iv. *Procedia Environ. Sci.* **2010**, *2*, 32–41. [CrossRef]
83. Aslam, A.; Rana, I.A.; Bhatti, S.S. The Spatiotemporal Dynamics of Urbanisation and Local Climate: A Case Study of Islamabad, Pakistan. *Environ. Impact Assess. Rev.* **2021**, *91*, 106666. [CrossRef]
84. Sandhu, G.S.; Naeem, M.A. A Case Study of Innovative Businesses Involved with Efficient Municipal Solid Waste Management in Islamabad, Pakistan. *WIT Trans. Ecol. Environ.* **2017**, *223*, 529–538.
85. Maria, S.I.; Imran, M. Planning of Islamabad and Rawalpindi: What Went Wrong. In Proceedings of the 42nd ISoCaRP Congress, Istanbul, Turkey, 14–18 September 2006.
86. Arribas-Bel, D.; Nijkamp, P.; Scholten, H. Multidimensional Urban Sprawl in Europe: A Self-Organizing Map Approach. *Comput. Environ. Urban Syst.* **2011**, *35*, 263–275. [CrossRef]
87. Liu, Y.; Din, S.U.; Jiang, Y. Urban Growth Sustainability of Islamabad, Pakistan, over the Last 3 Decades: A Perspective Based on Object-Based Backdating Change Detection. *GeoJournal* **2020**, *86*, 2035–2055. [CrossRef]
88. Ghalib, H.; Elkhorazaty, M.T.; Serag, Y. New Capital Cities: A Timeless Mega-Project of Intercontinental Presence. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Chennai, India, 16–17 September 2020.
89. Sohail, M.T.; Mahfooz, Y.; Azam, K.; Yat, Y.; Genfu, L.; Fahad, S. Impacts of Urbanization and Land Cover Dynamics on Underground Water in Islamabad, Pakistan. *Desalin Water Treat.* **2019**, *159*, 402–411. [CrossRef]
90. Yaseen, H. People in Islamabad Facing Extreme Water Crisis. *MM News*, 4 February 2020; p. 1.
91. APP. Water Shortage Puts Islamabad's I-8/1 Residents at Risk. *The Express Tribune*. 13 April 2020. p. 2013. Available online: https://tribune.com.pk/story/2196636/water-shortage-puts-islamabads-81-residents-risk (accessed on 18 April 2022).
92. Bishop, J.M.; Glenn, C.R.; Amato, D.W.; Dulai, H. Effect of Land Use and Groundwater Flow Path on Submarine Groundwater Discharge Nutrient Flux. *J. Hydrol. Reg. Stud.* **2017**, *11*, 194–218. [CrossRef]

93. Kotchoni, D.O.V.; Vouillamoz, J.-M.; Lawson, F.M.A.; Adjomayi, P.; Boukari, M.; Taylor, R.G. Relationships between Rainfall and Groundwater Recharge in Seasonally Humid Benin: A Comparative Analysis of Long-Term Hydrographs in Sedimentary and Crystalline Aquifers. *Hydrogeol. J.* **2019**, *27*, 447–457. [CrossRef]
94. Lei, M.; Liu, W.; Gao, Y.; Zhu, T. Mobile User Behaviors in China. In *Encyclopedia of Mobile Phone Behavior*; IGI Global: Hershey, PA, USA, 2015; pp. 1110–1128.
95. Xu, G.; Li, P.; Lu, K.; Tantai, Z.; Zhang, J.; Ren, Z.; Wang, X.; Yu, K.; Shi, P.; Cheng, Y. Seasonal Changes in Water Quality and Its Main Influencing Factors in the Dan River Basin. *Catena* **2019**, *173*, 131–140. [CrossRef]
96. Mengel, L.; Krauss, H.-W.; Lowke, D. Water Transport through Cracks in Plain and Reinforced Concrete–Influencing Factors and Open Questions. *Constr. Build. Mater.* **2020**, *254*, 118990. [CrossRef]
97. Zhang, M.; Li, J.; Ding, H.; Ding, J.; Jiang, F.; Ding, N.X.; Sun, C. Distribution Characteristics and Influencing Factors of Microplastics in Urban Tap Water and Water Sources in Qingdao, China. *Anal. Lett.* **2020**, *53*, 1312–1327. [CrossRef]
98. Zhao, Y.; Wang, Y.; Wang, Y. Comprehensive Evaluation and Influencing Factors of Urban Agglomeration Water Resources Carrying Capacity. *J. Clean. Prod.* **2021**, *288*, 125097. [CrossRef]
99. Gebreyohannes, T.; De Smedt, F.; Walraevens, K.; Gebresilassie, S.; Hussien, A.; Hagos, M.; Amare, K.; Deckers, J.; Gebrehiwot, K. Regional Groundwater Flow Modeling of the Geba Basin, Northern Ethiopia. *Hydrogeol. J.* **2017**, *25*, 639–655. [CrossRef]
100. Liu, J.; Gao, G.; Wang, S.; Jiao, L.; Wu, X.; Fu, B. The Effects of Vegetation on Runoff and Soil Loss: Multidimensional Structure Analysis and Scale Characteristics. *J. Geogr. Sci.* **2018**, *28*, 59–78. [CrossRef]
101. Raduła, M.W.; Szymura, T.; Szymura, M. Topographic Wetness Index Explains Soil Moisture Better Than Bioindication with Ellenberg's Indicator Values. *Ecol. Indic.* **2018**, *85*, 172–179. [CrossRef]
102. Akinluyi, F.O.; Olorunfemi, M.O.; Bayowa, O.G. Investigation of the Influence of Lineaments, Lineament Intersections and Geology on Groundwater Yield in the Basement Complex Terrain of Ondo State, Southwestern Nigeria. *Appl. Water Sci.* **2018**, *8*, 49. [CrossRef]
103. Akter, A.; Uddin, A.M.H.; Ben Wahid, K.; Ahmed, S. Predicting Groundwater Recharge Potential Zones Using Geospatial Technique. *Sustain. Water Resour. Manag.* **2020**, *6*, 24. [CrossRef]
104. Gnanachandrasamy, G.; Zhou, Y.; Bagyaraj, M.; Venkatramanan, S.; Ramkumar, T.; Wang, S. Remote Sensing and Gis Based Groundwater Potential Zone Mapping in Ariyalur District, Tamil Nadu. *J. Geol. Soc. India* **2018**, *92*, 484–490. [CrossRef]
105. Jerbi, H.; Massuel, S.; Leduc, C.; Tarhouni, J. Assessing Groundwater Storage in the Kairouan Plain Aquifer Using a 3d Lithology Model (Central Tunisia). *Arab. J. Geosci.* **2018**, *11*, 236. [CrossRef]
106. Torabi, A.; Alaei, B.; Ellingsen, T. Faults and Fractures in Basement Rocks, Their Architecture, Petrophysical and Mechanical Properties. *J. Struct. Geol.* **2018**, *117*, 256–263. [CrossRef]
107. Daryono, M.R.; Natawidjaja, D.H.; Sapiie, B.; Cummins, P. Earthquake Geology of the Lembang Fault, West Java, Indonesia. *Tectonophysics* **2019**, *751*, 180–191. [CrossRef]
108. Ahmed, R.; Sajjad, H. Analyzing Factors of Groundwater Potential and Its Relation with Population in the Lower Barpani Watershed, Assam, India. *Nat. Resour. Res.* **2018**, *27*, 503–515. [CrossRef]
109. Khan, A.; Govil, H.; Taloor, A.K.; Kumar, G. Identification of Artificial Groundwater Recharge Sites in Parts of Yamuna River Basin India Based on Remote Sensing and Geographical Information System. *Groundw. Sustain. Dev.* **2020**, *11*, 100415. [CrossRef]
110. Thapa, R.; Gupta, S.; Gupta, A.; Reddy, D.V.; Kaur, H. Use of Geospatial Technology for Delineating Groundwater Potential Zones with an Emphasis on Water-Table Analysis in Dwarka River Basin, Birbhum, India. *Hydrogeol. J.* **2018**, *26*, 899–922. [CrossRef]
111. Magesh, N.S.; Chandrasekar, N.; Soundranayagam, J.P. Delineation of Groundwater Potential Zones in Theni District, Tamil Nadu, Using Remote Sensing, Gis and Mif Techniques. *Geosci. Front.* **2012**, *3*, 189–196. [CrossRef]
112. Shaban, A.; Khawlie, M.; Abdallah, C. Use of Remote Sensing and Gis to Determine Recharge Potential Zones: The Case of Occidental Lebanon. *Hydrogeol. J.* **2006**, *14*, 433–443. [CrossRef]
113. Ahirwar, S.; Malik, M.S.; Ahirwar, R.; Shukla, J.P. Application of Remote Sensing and Gis for Groundwater Recharge Potential Zone Mapping in Upper Betwa Watershed. *J. Geol. Soc. India* **2020**, *95*, 308–314. [CrossRef]
114. Pakistan. Generalized Soil Map. Soil Survey of Pakistan. Lahore. Available online: https://esdac.jrc.ec.europa.eu/content/pakistan-generalized-soil-map (accessed on 18 April 2022).
115. Bakr, M.U. Geological Map of Pakistan. (East and West Pakistan). Direction of N.M. Khan. Director General. Geological Survey of Pakistan. Available online: https://esdac.jrc.ec.europa.eu/content/geological-map-pakistan-east-and-west-pakistan (accessed on 18 April 2022).
116. Dar, T.; Rai, N.; Bhat, A. Delineation of Potential Groundwater Recharge Zones Using Analytical Hierarchy Process (Ahp). *Geol. Ecol. Landsc.* **2020**, *5*, 292–307. [CrossRef]
117. Lehmann, P.; Berli, M.; Koonce, J.E.; Or, D. Surface Evaporation in Arid Regions: Insights from Lysimeter Decadal Record and Global Application of a Surface Evaporation Capacitor (Sec) Model. *Geophys. Res. Lett.* **2019**, *46*, 9648–9657. [CrossRef]
118. Igwe, O.; Ifediegwu, S.I.; Onwuka, O.S. Determining the Occurrence of Potential Groundwater Zones Using Integrated Hydro-Geomorphic Parameters, Gis and Remote Sensing in Enugu State, Southeastern, Nigeria. *Sustain. Water Resour. Manag.* **2020**, *6*, 39. [CrossRef]
119. Kumar, V.A.; Mondal, N.C.; Ahmed, S. Identification of Groundwater Potential Zones Using Rs, Gis and Ahp Techniques: A Case Study in a Part of Deccan Volcanic Province (Dvp), Maharashtra, India. *J. Indian Soc. Remote Sens.* **2020**, *48*, 497–511. [CrossRef]

120. Moeck, C.; Grech-Cumbo, N.; Podgorski, J.; Bretzler, A.; Gurdak, J.J.; Berg, M.; Schirmer, M. A Global-Scale Dataset of Direct Natural Groundwater Recharge Rates: A Review of Variables, Processes and Relationships. *Sci. Total Environ.* **2020**, *717*, 137042. [CrossRef] [PubMed]
121. Martos-Rosillo, S.; Ruiz-Constán, A.; González-Ramón, A.; Mediavilla, R.; Martín-Civantos, J.M.; Martínez-Moreno, F.J.; Jódar, J.; Marín-Lechado, C.; Medialdea, A.; Galindo-Zaldívar, J.; et al. The Oldest Managed Aquifer Recharge System in Europe: New Insights from the Espino Recharge Channel (Sierra Nevada, Southern Spain). *J. Hydrol.* **2019**, *578*, 124047. [CrossRef]
122. Lentswe, G.B.; Molwalefhe, L. Delineation of Potential Groundwater Recharge Zones Using Analytic Hierarchy Process-Guided Gis in the Semi-Arid Motloutse Watershed, Eastern Botswana. *J. Hydrol. Reg. Stud.* **2020**, *28*, 100674. [CrossRef]
123. Kolli, M.K.; Opp, C.; Groll, M. Mapping of Potential Groundwater Recharge Zones in the Kolleru Lake Catchment, India, by Using Remote Sensing and Gis Techniques. *Nat. Resour.* **2020**, *11*, 127. [CrossRef]