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Research Article:

Evaluating Sediment-Induced Storage Loss in Centralized and Decentralized Dam Systems: A Case Study of Proposed Bekhma Dam and Its Alternative

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Abstract

This research studies the sediment transport developments and their impact on reservoir sustainability in the Greater Zab Basin in the Kurdistan Region of Iraq, focusing on the proposed Bekhma dam and upstream alternatives of it. This study uses Digital Elevation Model (DEM) analysis, spatial modeling along with geographic information systems (GIS) and empirical sediment transport modeling by means of the Shields principle and the Ackers-White equation to assess the sediment transport dynamics under varying scheme designs. Alternative scenarios comprise a single, centralized reservoir (baseline) and a distributed arrangement with multiple upstream reservoirs. The results reveal that, under normal conditions, sediment transport is highly concentrated towards Proposed Bekhma reservoir, resulting in a centralized pattern of sediment storage and a greater risk of rapid storage loss. However, the existence of upstream reservoirs modifies sediment transport pattern (the alternative), can create multiple interception points in upstream pattern (the alternative), can create the flux of sediments to the single reservoir of proposed Bekhma dam. The results show that distributed reservoir systems can significantly improve sediment management by disrupting basin-scale sediment transport and helping system permanency. This transition from transport to capture offers a promising perception for the sustainable design of reservoirs in sediment-laden basins. This study stresses the necessity to consider sediment transport in strategic planning of dam construction and offers a template for associating different reservoir configurations in other river basins.

1. Introduction

In semi-arid and mountainous areas, the risk of reservoir unsustainability is growing, in which sediment transport is more significant than we have thought. River systems such as the Greater Zab River are prone to high sediment yields, due to steep terrain, unstable geology and changing hydrologic conditions. This makes large storage reservoirs, particularly single and centralised dams, very vulnerable to storage loss (Kondolf et al., 2014; Schleiss et al., 2016). Historically, dam design has focused on storage volume and water yield, with a subsidiary concern for sediment problems. Today, many studies show that sediment inflow is a variable constraint that is constantly reducing effective storage, and impacting on the hydraulic function and lifespan of reservoirs (Morris & Fan, 1998; Annandale, 2013). Previous studies have shown that reservoirs located in Sediment storage losses are likely to be substantial over time in sediment-rich catchments caused by sediment accumulation, specifically when erosion rates are high and sediment-management strategies are imperfect (Morris and Fan, 1998; Schleiss et al., 2016). especially in catchments with high sediment yields and seasonal flooding. This is especially true in the case of the Bekhma Dam, one of the largest proposed water projects in the Kurdistan Region of Iraq. The proposed Bekhma Reservoir is the most important downstream storage facility in the study area, and it is likely to receive sediment from a large part of the catchment area via the river system. Thus, long-term sustainability of sediment storage in the reservoir may become a significant constraint, especially if sediment supply continues from upstream sources (Kondolf et al., 2014; Schleiss et al., 2016). This inevitably leads to downstream trapping of sediment at a single location, which means a more rapid expansion of dead storage and loss in system efficiency with time. As has been found in other large systems, this can result in a reduced flexibility and higher maintenance costs (Basson & Rooseboom, 1997; Kondolf et al., 2014). On the other hand, recent developments in integrated water resources management (IWRM) indicate the merits of dispersed storage. This includes the distribution of storage among multiple reservoirs upstream, which can help trap sediment upstream, reducing the sediment load downstream. This helps alleviate sediment-related issues, and enhances system resilience through risk diversification and adaptation to climate change (Grill et al., 2019; Lehner et al., 2011). While these advances have been made, there is a lack of research in the quantitative evaluation of sediment redistribution in multiple-reservoir systems, particularly in semi-arid areas such as the Greater Zab basin. While several studies have addressed storage and water yield optimization, limited studies have addressed the sediment transport processes in comparative studies of single and multiple reservoir systems. This study aims to address this issue and provide a sediment transport and reservoir sustainability assessment of the Proposed Bekhma Dam and the proposed upstream dams. This study compares the current situation (Bekhma as a single reservoir) and a multiple reservoir system approach in terms of sediment inflow, redistribution and performance. This involves spatial modeling using GIS, sediment transport calculation using empirical formulae and hydrologic interpretation to estimate sediment transport parameters. A special emphasis is put on locating high inflow sub-catchments, determining the efficiency of upstream sediment trapping, and quantifying the impact on downstream reservoir management. As shown later in the Results section the proposed upstream alternatives result in a major shift in sediment transport, from a point-source accumulation system to a distributed sediment management system.Moreover, the quantitative analysis reveals a significant decrease in sediment inflow to the Proposed Bekhma Reservoir under the multiple-dam scenario. In summary, this research helps to transform the traditional approach to dam design and planning processes by highlighting the need to consider sediment transport analysis in the early stages of design and planning. It offers a practical and quantitative approach to assess the long-term sustainability of reservoirs in sediment-laden basins, with implications for strategic water resource planning in the Kurdistan Region and elsewhere. The upstream alternatives assessed in this study are not presented merely as replacements for the proposed Bekhma Dam. Rather, they epitomize alternative and complementary storage configurations previously developed within an integrated water resources management framework for the Greater Zab Basin. Depending on future water-resource necessities, these reservoirs may function as independent storage systems, as mechanism of a distributed reservoir network, or in combination with a reduced-height Bekhma Dam. The present study efforts specifically on evaluating the sediment-management inferences of these alternative storage configurations. The novelty of this study is to combine sediment-transport assessment with previously developed alternative reservoir configurations for the Greater Zab Basin. Previous studies were mainly concerned with the storage capacity, water resources management and strategic reservoir planning, whereas the present study examines the impact of various reservoir configurations on sediment redistribution and reservoir sustainability. The study uses DEM-based reservoir analysis, GIS spatial assessment, and empirical sediment-transport modelling to make a comparative assessment of the sediment-management performance of the two different storage scenarios (centralised and distributed) within the Greater Zab Basin. To the authors' knowledge, no earlier study has quantitatively associated sediment redistribution and reservoir sustainability between centralized and distributed reservoir conformations within the Greater Zab Basin. The upstream alternatives were initially presented in an overall integrated water resources management plan for the Greater Zab Basin but the main aim of the current study is to assess their consequences on sediment transport, sediment redistribution, and reservoir sustainability. The analysis thus concentrates on the effect of the various storage configurations on the sediment behaviour in the basin and the implications for the long-term performance of the reservoir.

2. Study Area

This work is centred on the Greater Zab River Basin, a key water resource system of northern Iraq and the Kurdistan Region. The basin is a typical mountainous catchment with a significant spatial variability in topography, climate and hydrologic response. This makes it an excellent site for sediment transport model assessment and reservoir sustainability under various storage scenarios. The Greater Zab River rises in the mountains of southeastern Turkey, and traverses the Kurdistan Region before emptying into the Tigris River. The river traverses a rugged landscape, via deep and narrow valleys, of high mountain ranges and low flat regions. This complexity is a key in regulating runoff and sediment generation (Al-Ansari, 2013; Sissakian et al., 2014). In this basin, the Proposed Bekhma Dam site is located downstream, in a relatively broad valley section, where a large reservoir can be formed. But this geomorphological condition also facilitates significant lateral reservoir development, which expands the area where sediment can accumulate, and decreases the reservoir efficiency in the long term. On the other hand, the alternative sites are proposed in narrower valley segments, where topographic characteristics are more suitable for efficient storage and trapping of sediments. As can be seen in Figure 1 the upstream alternatives are located in tributaries and tight river reaches. This is significant as it allows sediment to be retained near the source, thus reducing sediment transport into the Proposed Bekhma Reservoir. This arrangement exemplifies a more decentralised storage strategy, in line with current basin-wide water control practices. The basin's hydrology is heavily affected by seasonal rainfall, which peaks in winter and early spring. The meltwater from the mountains also contributes to peak discharges, often resulting in high-energy events that mobilise sediment. This enhances erosion, especially in vegetation-poor and sloping areas, resulting in substantial sediment inputs to the river system (UN-ESCWA, 2013; Issa et al., 2015). The basin is a combination of bed load and suspended load transport in terms of sediment transport, depending on the flow and particle sizes. Coarse particles are moved along the riverbed in upstream steep gradient regions, whereas finer particles are transported further downstream (in suspension) towards reservoirs. This combination results in complex sediment deposition, particularly in large reservoirs such as Bekhma, where the flow velocity is low. Further, sediment yield is influenced by land use and soil types in the catchment. Areas with high farming, bare soil and less vegetation cover are more prone to erosion, and thus, have higher sediment yield. Such variations are essential for identifying the sources of sediment and so were incorporated in the analysis through mapping of the basin using GIS.These maps show that the erosion potential is not uniform in the basin. It is mainly limited to headwater regions at higher altitudes, due to steeper slopes, poor soil structure and/or low vegetation cover, which enhance sediment production. These areas are therefore significant sediment sources, which impact on sediment transport. The main hydrological unit of this study, the Eski Kalak watershed, is the source of the Bekhma Dam. This micro-watershed is a small-scale unit that combines climatic, topographic and land surface characteristics, and is a suitable unit for examining sediment inflow and dam responses under different scenarios. In a nutshell, the study basin presents a typical and representative case study to investigate the interaction between hydrology, sediment yield and reservoir operations. The basin's complexity and sediment yield provide a comprehensive view of the trade-offs between centralised and decentralised options for water and sediment storage, particularly in an uncertain environment and climate. The Greater Zab Basin (upstream of the proposed Bekhma Dam) is one of the largest water-resource systems in northern Iraq. The basin is mountainous, with large reliefs, irregular rainfall, and steep slopes and active erosion processes, which are conducive to sediment production. The basin has these features that make it especially suitable for testing reservoir sustainability under various storage scenarios. The hydrological and environmental conditions used in this study are represented by the DEM, land-use, soil, and sediment data, which are described in the following methodology section. The hydrological analysis conducted in this study is for the Eski Kalak watershed and the sediment transport process of the proposed Bekhma reservoir and the upstream alternatives. The information on rainfall, discharges, and sediment characteristics given in the text are based on the data and analyses provided in the relevant section of the study, and do not stem from a basin-wide inventory of hydrology.

3. Methodology

This study adopts an approach to quantify the effects of sediment transport on reservoir sustainability under different reservoir storage scenarios in the Greater Zab Basin. This approach integrates terrain-based hydrologic modeling, GIS-based spatial data and empirical equations of sediment transport. This makes it possible to assess the system under various reservoir storage options (centralized and decentralized) while synchronizing process and spatial interactions. The research began with a Digital Elevation Model (DEM) with a resolution of 30 m from Shuttle Radar Topography Mission (SRTM). The DEM is the key data for terrain and hydrologic modelling. The DEM was preprocessed by filling sinks and surface-conditioning to remove spurious depressions and ensure physically valid flow direction, respectively, prior to extraction of hydrologic features. This process is required to eliminate spurious flow accumulation, and to maintain the integrity of the extracted drainage networks, particularly in the hills (Tarboton, 1997; Maidment, 2002). Using the preprocessed DEM, flow direction and flow accumulation were calculated as grids using a D8 method, which routes flow from each cell to the steepest downslope cell. The latter were then used to delineate the river network and the watershed of the Proposed Bekhma Dam. The watershed outlines the extent of the analyses, and connects the topographic features to the sediment generation processes. Figure 1 shows the spatial distribution of the Proposed Bekhma Dam and the proposed upstream alternative sites, which gives an indication of their location within the basin and along the main river. The properties of reservoir storage were estimated from the DEM through an elevation-based volumetric analysis. The elevation surface was progressively assessed at incremental levels to calculate the associated area and volume. This approach permits the construction of elevation-area-volume (E-A-V) relationships that capture the actual shape of the reservoir without making simplifying assumptions. The methodology was thus designed to assess the performance of alternative reservoir configurations in terms of sediment-related issues, but not necessarily the general viability of the proposed reservoir system from a water resources management standpoint. For this study, the baseline scenario of a centralized reservoir with the proposed Bekhma Dam was adopted. The design data published indicates that the dam has a proposed height of 230 m, a crest length of 530 m, a total storage capacity of 17 BCM, a dead storage capacity of 4 BCM and an installed hydropower capacity of ~ 1,500 MW (Table 1). These design features are the engineering foundation for assessing the sustainability of sediment redistribution and storage with different reservoir configurations.

In this study, the centralized storage scenario investigated is the proposed Bekhma Dam. Ibrahim and Abdulla (2026) however, have shown that sustainable management of water resources in the Greater Zab Basin is possible by using an integrated water storage system composed of the four water store alternatives (D2–D5) either alone or in combination with a lowered height of the Bekhma Dam. The multi-reservoir idea was first conceived to maximize water storage efficiency, flood control, system resilience, and minimize reliance on a single large reservoir. The results of Ibrahim and Abdulla (2026) also indicated that the upstream reservoirs may allow for a more viable configuration of the Bekhma with a lower height. On this basis, the current research study investigates the impact of the distributed storage system on sediment redistribution, sediment interception and the sustainability of sediment storage in the proposed Bekhma Reservoir in the long term. Ibrahim and Abdulla (2026) have already assessed the technical feasibility, storage capacity and performance of water resources management of D2–D5 alternatives. Thus, in the present study, their hydrological feasibility is not re-evaluated, and instead the impact on sediment redistribution and reservoir sustainability is examined.

In the Greater Zab Basin, four alternative reservoirs upstream (D2–D5) were evaluated, namely Derana (D2), Sheladiz (D3), Deraluk (D4), and Dore (D5). These sites were chosen for their topographic suitability, storage potential, watershed characteristics and their strategic location in the basin. The spatial distribution of them in relation to the planned Bekhma Dam is presented in Figure 1 and their main storage properties are summarized in Table 2. The spatial features and topographic conditions of the proposed Bekhma Reservoir and the four alternatives upstream of it are shown in Figure 2. The figure emphasizes the variability of geometry, catchment configuration and the setting of the reservoir at the various sites assessed. The resulting relationship for the Proposed Bekhma Reservoir is shown in Figure 6. The validity of this approach was tested by comparing estimated values with reported design values, where the DEM-based estimate (~17.9 km^3) was found to be consistent with literature values (Lehner et al., 2011; Messager et al., 2016, ~17 km^3), thus suggesting that the resolution of the DEM is sufficient for regional-scale analysis. To consider the spatial distribution of sediment production, we also included other environmental data that affect erosion, using a GIS approach. These include land use/land cover (LULC), soil properties, and slope (figure 5). The elevation–volume relationship shown in Figure 6 is a geometric assessment derived from the DEM that was used to compare with other reservoirs and for screening. It should not be taken as the designed capacity of the proposed Bekhma Dam. While the published engineering studies report a total storage of ~17 BCM for the proposed Bekhma Dam, the DEM-based analysis is designed to explore the relative storage properties for various dam elevations and to facilitate comparison to the proposed alternatives upstream. The elevation–volume relationship in Figure 6 was developed from the DEM analysis and applied in comparative assessment of the reservoirs. The geometric estimates obtained were compared with published design parameters of proposed Bekhma dam presented in table 1. The reliability of the DEM analysis of the reservoir was checked by comparing the estimated storage capacity of the proposed Bekhma Reservoir with the published engineering design values. The comparison results indicated that the estimated storage capacity from the DEM is in good agreement with the reported storage capacity, thus giving confidence in the applicability of the methodology for comparative reservoir assessment. The validation results suggest that the approach is satisfactory for assessing relative differences between different reservoir configurations, though uncertainties remain due to the resolution of the DEM and the empirical sediment-transport relationships used. The elevation–volume relationships obtained from the DEM were used to calculate the dead-storage elevations for the proposed reservoirs. The chosen elevations are in the lower portion of the reservoir area for long-term sediment storage with adequate active storage above the dead-storage. Instead of using a single dead storage depth, the values were determined individually for each reservoir in accordance with the topographic conditions and reservoir geometry in the respective area. LULC was used to locate regions vulnerable to runoff and erosion, and soil properties were used to determine erodibility. Slope, which is derived from the DEM, is a major factor influencing water runoff velocity and erosion. The spatial distribution of these controls is shown in Figures 3, 4 and 5, which together represent the main controls on sediment generation. This approach is commonly used in basin sediment studies to represent the effects of terrain and surface properties on erosion (Morgan, 2005; Nearing et al., 2017). Sediment transport processes within the basin were assessed using a mix of theoretical and empirical methods. Sediment entrainment was evaluated using the Shields parameter, which represents the dimensionless critical shear stress for particle entrainment. The Shields criterion can be expressed as in equation 1:

$$\theta = \frac{\tau}{(\rho_s - \rho)gd} \qquad (1)$$

In the present study, the Shields criterion was applied as a screening tool for comparative sediment-mobility valuation rather than for comprehensive site-specific calibration. The objective was to classify relative variances in sediment transport potential between the assessed reservoir arrangements. where τ is the bed shear stress, ρ_s and ρ are sediment and fluid densities, g is gravitational acceleration, and d is the characteristic sediment diameter. The bed shear stress was estimated based on hydraulic parameters including flow depth, hydraulic radius, and channel slope, allowing identification of zones where sediment motion is likely to occur (Shields, 1936; Julien, 2010). As well as threshold analysis, sediment transport rates were calculated using the Ackers-White equation, which offers a semi-empirical formula to calculate total load transport in alluvial channels. This equation considers flow velocity, particle size, fluid viscosity and relative density as the main governing factors and is expressed in a dimensionless form which relates the transport rate to mobility parameters (Ackers & White, 1973).

The Ackers–White equation has been reported to be an overestimate for sediment transport rates under fine sand conditions in certain instances, especially when the particle size is low (Julien, 2010), but the equation is still widely used for comparative sediment transport assessments for alluvial rivers. The equation was used mainly for the purpose of this present study, to compare the relative differences between the various reservoir configurations, rather than to determine accurate sediment loads. The same sediment transport assumptions were used for all scenarios, which gave a solid foundation for comparison of the patterns of sediment redistribution in the basin. Input data were based on a combination of hydrologic data measured at the Eski Kalak gauging station, spatial features derived from the GIS, and a combination of regional studies that provide typical sediment properties. The combination of empirical sediment transport equations with spatially explicit parameters derived from a geographic information system (GIS) facilitates the assessment of sediment yield at the basin scale, taking into account the variability of terrain, land use (figure 3) and soil (figure 4). This method has been demonstrated to yield satisfactory results when used for comparative analysis, especially when evaluating differences between alternative system configurations, rather than absolute magnitudes of sediment loads (Kondolf et al., 2014; Schleiss et al., 2016). In order to assess the effects of reservoir configuration on sediment yield, two scenarios were considered. The first scenario is the "business as usual" scenario in which the Bekhma Dam is the only reservoir in the basin in a "centralized" configuration. The second scenario is a distributed configuration, with upstream reservoirs (D2-D5) introduced to trap sediment. Such a scenario comparison enables the impact of upstream sediment management on sediment transport and downstream redistribution to be assessed. Sediment patterns were mapped for the scenarios using GIS. In the case of the baseline scenario, sediment transport is mainly towards the downstream Proposed Bekhma Reservoir, resulting in a centralised pattern of sediment accumulation. But the upstream reservoirs redistribute sediment, resulting in a decentralized sediment trapping pattern. Finally, the system is evaluated by calculating the potential sediment reduction, redistribution and inflow for various scenarios. The findings are summarized Tables 4 and 5 showing sediment reduction and system efficiency of the decentralized system. The analysis is based on some assumptions to make it practical and physically sound. Sediment transport was assumed to be steady for typical flow conditions and sediment was assumed to be uniform in the sub-catchment. This simplifies the analysis, but these assumptions are consistent with large-scale sediment analyses and are appropriate for comparative analyses (Morris & Fan, 1998). It needs to be acknowledged that there are certain limitations. The use of empirical sediment transport formulae may be questionable outside of the range of conditions used for their calibrations and the DEM analysis may not capture fully the micro-topographic complexities. However, the integrated approach provides a reasonable basis for assessing relative differences among reservoir designs, which is the focus of this paper. The aim of the present study is not to create a completely calibrated sedimentation model for the Greater Zab Basin. Instead, the approach was developed to allow for a comparative evaluation of sediment redistribution at the basin level for different reservoir configurations. The Ackers–White Sediment transport rates were estimated using the widely-used Ackers–White formulation see table 3, which is applicable to alluvial rivers and offers a practical framework to identify relative differences in sediment transport and interception potential among the scenarios evaluated (Ackers and White, 1973).equation were selected because they provide a practical framework to identify relative differences in sediment transport and interception potential among the scenarios evaluated (Ackers and White, 1973). The approach taken is deemed suitable for initial comparative analysis and strategic planning, although more detailed physical sediment transport models can be used. In this study, the downstream control section of the Greater Zab River was represented by the Eski Kalak reach where the parameters used in the Shields and Ackers–White calculations were selected to represent the hydraulic and sediment conditions of the Eski Kalak reach. The medium sediment diameter

(D50) was chosen because the fine sand fraction was used for the sediment classification and the specific gravity of the sediment was considered to be 2.65, which is typical for quartz-dominated natural river sediments. The river reach geometry was analyzed to obtain water depth, channel slope, hydraulic radius and river width. The kinematic viscosity was assigned based on the water temperature conditions around 10°C. These parameters were used for all comparative scenarios in order to compare their sediment transport behaviour rather than to make a full site calibration for a site specific sediment transport prediction. Representative hydraulic and sediment characteristics were used in the sediment-transport assessment based on available hydrological records see table 4, basin characteristics derived from GIS data, and published regional studies. In order to be able to compare the results of the investigation in a basin-wide scale, representative sediment properties were used. The goal was not to duplicate the exact sediment response at specific sites, but to compare the sediment transport and interception capability of the various reservoir designs. To allow for the comparability of the results the same assumptions and input parameters were used throughout all the analysed scenarios. Therefore, the analysis is to be interpreted as a comparative analysis, not a prediction of sedimentation at the design level, at the basin scale. The aim is to compare the relative sediment interception characteristics of different storage configurations with the same set of assumptions, not to predict exact future sedimentation rates.

4. Results and Discussion

This study provides information about the sediment transport and the effect on the sustainability of the reservoirs in the Greater Zab Basin. The evaluation involves the baseline condition (the Proposed Bekhma Dam is used as the main reservoir) and a modified condition which allows for upstream reservoirs. It should be emphasized that the proposed Bekhma The aim of the Dam is to be multipurpose, with water storage, hydropower generation, flood regulation and water security for the region being the goals. This study does not seek to supplant these more general functions with sediment management. Rather, the study addresses only the sedimentary impacts of different storage configurations and how they may affect the sustainability of reservoirs over time. The findings show that the sediment transport and deposition in the basin are strongly influenced by the spatial variability in the basin's terrain and the reservoir's structure. The distribution of sediment transport in the baseline condition is illustrated in Figure 7. The patterns of sediment transport for the centralized and distributed storage cases are illustrated in Figures 7 and 8, respectively. Figure 7 shows how sediment pathways converge towards the proposed Bekhma Reservoir under the centralized configuration, whereas, Figure 8 shows how the introduction of upstream reservoirs changes sediment pathways with multiple interception points throughout the basin. These implications of the redistribution are quantified in Tables 2 and 3. The results show that sediment production is highly concentrated in the upstream mountainous regions with steep slopes and low vegetation. These areas are important sediment sources, contributing a significant portion of the total sediment load. At the downstream end, the sediment transport pathways converge at the Proposed Bekhma Reservoir, resulting in a high level of sediment convergence at the reservoir. This implies that the Proposed Bekhma Reservoir is a major sediment sink. This finding is consistent with observations from large reservoir systems where upstream reservoirs with large catchments contribute to downstream reservoirs (Kondolf et al., 2014). This pattern is significant as it suggests that the sedimentation in the Proposed Bekhma Reservoir is likely to be high, leading to a rapid decrease in the effective storage capacity and creation of dead storage. The control of landscape properties on sediment yield is also indicated by the results of the spatial analysis shown in Figures 2, 3, and 4. Regions with steep terrain and sparse vegetation cover have a greater potential for erosion, and as a result, generate more sediment. This confirms the fact that sediment generation within the basin is not even but is influenced by local terrain features. The use of upstream alternative reservoirs leads to a significant change in sediment transport. As illustrated in Figure 8, the upstream reservoirs will change the spatial distribution of sediment from a concentrated regime to an interference system. Several upstream points of the basin intercept the flow of sediment that would eventually reach the Proposed Bekhma Reservoir, presumably modifying the sediment balance of the basin. This is a change in system behaviour. In the first case, the sediment transport regime is governed by hydrologic connectivity, allowing sediment to be transported far distances. But the multiple-reservoir alternative introduces multiple storage points in the river and thus the connectivity is interrupted, allowing local sediment storage and reducing transport. This shift from a transport- to an interception-dominated regime is a key factor in improving reservoir sustainability. The magnitude of this redistribution is quantified in Table 6, which shows the sediment inflow to the Proposed Bekhma Reservoir in both scenarios. It shows a substantial reduction in sediment inflow to the reservoir after the introduction of upstream options. Table 6 shows the results of the analysis, which shows that sediment interception takes place across the upstream reservoirs, rather than being stored in a single downstream reservoir. This re-distribution decreases the sediment load on the proposed Bekhma Reservoir and helps to provide a more even sediment storage distribution throughout the basin. This demonstrates the ability of upstream reservoirs to intercept sediment, thereby reducing the sediment load on downstream reservoirs. The sediment reduction achieved in this study is in line with previous studies that demonstrate the advantages of distributed sediment control systems (Schleiss et al., 2016). The system, by trapping sediment at several points, decreases the rate of sediment buildup in the main reservoir, thus increasing the useful lifespan and efficiency of the reservoir. The percentage reduction was computed based on the estimated sediment inflow to the proposed Bekhma Reservoir, both for the baseline scenario (Bekhma only) and the distributed-storage scenario (Bekhma with D2–D5), as follows:

$$\mathrm{Reduction}(\%) = \frac{S_{\text{baseline}} - S_{\text{alternative}}}{S_{\text{baseline}}} \times 100 \quad (2)$$

Additional assessment can be found in Table 6., which presents the overall reduction in basin-scale sediment load. Based on the values given in Table 6, the reduction is ~82.9%. Table 6 shows the reduction values, supporting the spatial patterns shown in Figures 6 and 7. These results indicate that the distributed-storage configuration changes the sediment transport response of the basin at this basin scale and decreases the amount of sediment delivered to the downstream reservoir

The results show that the distributed system provides a large percentage reduction in total sediment inflow, suggesting a major improvement in sediment management efficiency. The quantitative results in this study verify the influence of the upstream alternatives on sediment transport, which is not solely based on conceptual considerations. The addition of the upstream reservoirs changes sediment transport paths with the creation of multiple interception points across the basin (see Figure 8). This redistribution effect is also illustrated on Tables 2 and 3, which show significant decreases in the sediment delivery to the proposed Bekhma Reservoir in the distributed-storage situation. The results above suggest that the upstream options may offer benefits beyond distributed water storage, including sediment management and improving the long-term sustainability of the reservoir. The results of this study should not be interpreted as an indication that the upstream alternatives necessarily are substitutes for the proposed Bekhma Dam. Instead, the findings show how the sediment transport and sediment redistribution in the Greater Zab Basin are affected by different reservoir configurations. The upstream alternatives were initially suggested as part of an integrated water resources management framework for enhancing water storage distribution, water resource flexibility and long-term water security. The present analysis reveals another possible advantage of that configuration, which is sediment delivery to the downstream reservoir and the resulting enhancement of the sustainability of the reservoir. The results of this study correspond to the work of Ibrahim and Abdulla (2026) that assessed the hydrological and storage-management consequences of the upstream alternatives and a lower Bekhma configuration. The current study investigates the sediment aspects of the same reservoir system. These results have significant implications for engineering design and water resources management. Centralized and large reservoirs are attractive from a capacity standpoint, but are highly vulnerable to transport is dominant. This research has shown that upstream sediment interception structures can help "break" this barrier, and provide a more sustainable design alternative to conventional approaches. However, consideration needs to be given to the complexity of multiple reservoir systems. There are multiple structures to manage and monitor, which may be more complex than a single reservoir. However, the benefits of less sediment and greater sustainability far outweigh these complexities, particularly in systems where sediment transport plays an important role in the system. In summary, the results demonstrate sediment transport is an important factor to consider in the design of reservoir systems. The findings of the centralized and decentralized scenarios clearly demonstrate that upstream sediment interception can be an effective way to improve the long-term sustainability of reservoirs, and offer a viable solution to the sediment issues in large river systems. The influence of the upstream alternatives on sediment transport is not simply hypothesized based on conceptual considerations, but is backed up by the quantitative results from this study. The addition of the upstream reservoirs changes sediment transport pathways as shown in Figure 8, by introducing a number of interception points along the basin. The results shown in Tables 2 and 3 demonstrate significant decreases in sediment delivery under the distributed storage scenario, but should be considered in the context of the methodology used. The present study has relied on the empirical sediment-transport relationships, the GIS-based spatial assessment and the reservoir analysis carried out using DEM. The dead-storage elevations assigned to the alternative reservoirs were selected as preliminary design assumptions for comparative evaluation purposes. A dead-storage depth of 5 m was adopted for most reservoirs to represent a minimum sediment-retention zone below the active storage level. For the Sheladiz (D3) reservoir, a larger dead-storage depth of 10 m was assumed because of its local topographic characteristics and the need to provide additional sediment accommodation within the reservoir. These values were not intended as final engineering design criteria but were used to ensure consistent comparison among alternative storage configurations. The results are therefore meant to give a comparative assessment of the different reservoir configurations, not a detailed operational sedimentation forecast. More accurate sedimentation predictions would be possible with future studies that include long-term field measurements, reservoir operation scenarios, and physically based sediment-transport models. It is important to note that the sediment properties could vary from place to place in the Greater Zab Basin. Therefore, the estimated sediment loads are only comparative measures of system behavior, not absolute measures of sediment deposition volumes. However, if the same assumptions are applied to all scenarios, comparisons of the relative performance of the reservoir configurations evaluated are meaningful.

5. Conclusion

This study mainly assesses the sediment transport and reservoir sustainability under different storage configurations in the Greater Zab Basin. The analysis is not intended to establish a new water-resources management plan for the basin, rather it examines an element of that management plan, namely its effect on sediment redistribution and reservoir sustainability.

The present study provides an integrated evaluation of sediment transport processes and effects on reservoir sustainability in the Greater Zab Basin, with particular emphasis on the proposed Bekhma dam and the upstream options. The results indicate that the sediment transport processes in the basin are extremely sensitive to the spatial variability in topography, land surface and water connectivity, which leads to different responses of the system to a single large reservoir and multiple smaller reservoirs. The results also indicate that the conventional design of a large downstream reservoir, with a single sediment interceptor, forms a highly concentrated sediment storage. This leads to more rapid storage loss and dead storage filling in the proposed Bekhma reservoir. This highlights a problem with traditional dam design in rivers with high sediment loads, where sediment inputs can limit the life of the dam. But the introduction of the alternative, upstream reservoirs, affected sediment transport by intercepting them. This configuration leads to a decrease in the sediment flux to the main reservoir and a buildup of the sediment in multiple locations. This shift in transport to interception is a major improvement of the sediment management strategy, with impact on reservoir life and efficiency. Indeed, the findings suggest that from an engineering perspective, when planning a reservoir, it is not only necessary to consider the volume of the reservoir, but also the sediment transport processes as a design element. The integration of spatial analysis for sediment transport modeling is a useful approach to evaluate alternative system options and can be used in reservoir design and water resources planning. It should be noted that the approach in this study is based on assumptions, especially regarding the representation of the basin characteristics and flow. While these simplifications are necessary to perform basin-scale analyses, they have implications for the uncertainty of the findings, which should be addressed in future research by field observations and model simulations. Also, the challenges of multiple reservoir management should be investigated for improved management. The results should therefore be viewed as a comparative study of the sedimentation processes in the basin and not as a detailed sedimentation prediction for the individual reservoirs. The validation results indicate that the methodology adopted can be applied to the Greater Zab Basin for comparative analysis of reservoir alternatives, albeit with associated uncertainty, in the region. Notwithstanding the limitations, the study convincingly demonstrates that multiple storage systems can be a useful approach to tackle problems associated with sediment in large river systems. It shows clear evidence of the benefits of upstream sediment trapping on the sustainability of reservoirs, particularly in regions with high sediment yields and changing hydrologic regimes. Overall, this study contributes to the paradigm shift in dam design and construction by taking into account the sediment transport in the initial design and assessment stage. The approach offers a way to develop a more sustainable and resilient water resources development, not only in the Kurdistan Region, but also in other parts of the world.

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تقييم فقدان السعة الخزنية الناتج عن الترسبات في أنظمة السدود المركزية واللامركزية: دراسة حالة لسد بخمة وبدائله

المستخلص

تتناول هذه الدراسة تطورات نقل الرسوبيات وتأثيرها على استدامة الخزانات المائية في حوض الزاب الكبير في إقليم كردستان العراق، مع التركيز على سد بخمة وبدائله الواقعة في أعالي النهر. تعتمد الدراسة على تحليل نموذج الارتفاعات الرقمية(DEM) ، والنمذجة المكانية باستخدام نظم المعلومات الجغرافية(GIS) ، بالإضافة إلى نمذجة نقل الرسوبيات التجريبية باستخدام مبدأ شيلدز ومعادلة آكرز–وايت لتقييم ديناميكية نقل الرسوبيات تحت تصاميم إنشائية مختلفة. وتشمل السيناريوهات المدروسة خزاناً مركزياً واحداً (السيناريو الأساسي) ونظاماً موزعاً يضم عدة خزانات في المناطق العليا من الحوض . أظهرت النتائج أنه في الظروف الطبيعية يتركز نقل الرسوبيات بشكل كبير باتجاه خزان سد بخمة، مما يؤدي إلى نمط مركزي لتخزين الرسوبيات وزيادة خطر فقدان السعة الخزنية بسرعة. إلا أن وجود خزانات في المناطق العليا يغيّر أنماط نقل الرسوبيات، من خلال توفير نقاط اعتراض متعددة داخل الأحواض الفرعية وتقليل تدفق الرسوبيات نحو الخزان الرئيسي لسد بخمة. كما أوضحت النتائج أن أنظمة الخزانات الموزعة يمكن أن تحسن إدارة الرسوبيات بشكل ملحوظ من خلال تعطيل نقل الرسوبيات على مستوى الحوض والمساهمة في زيادة استدامة النظام المائي. ويقدم هذا التحول من النقل إلى الاحتجاز تصوراً واعداً للتصميم المستدام للخزانات في الأحواض الغنية بالرسوبيات .وتؤكد الدراسة على ضرورة أخذ نقل الرسوبيات بعين الاعتبار في التخطيط الاستراتيجي لإنشاء السدود، كما توفر نموذجاً يمكن تطبيقه لربط تكوينات الخزانات المختلفة في أحواض نهرية أخرى.

الكلمات المفتاحية:

نقل الرسوبيات؛ استدامة الخزانات؛ سد بخمة؛ تحليل نظم المعلومات الجغرافية؛ نموذج آكرز–وايت؛ السدود اللامركزية؛ حوض الزاب الكبير.

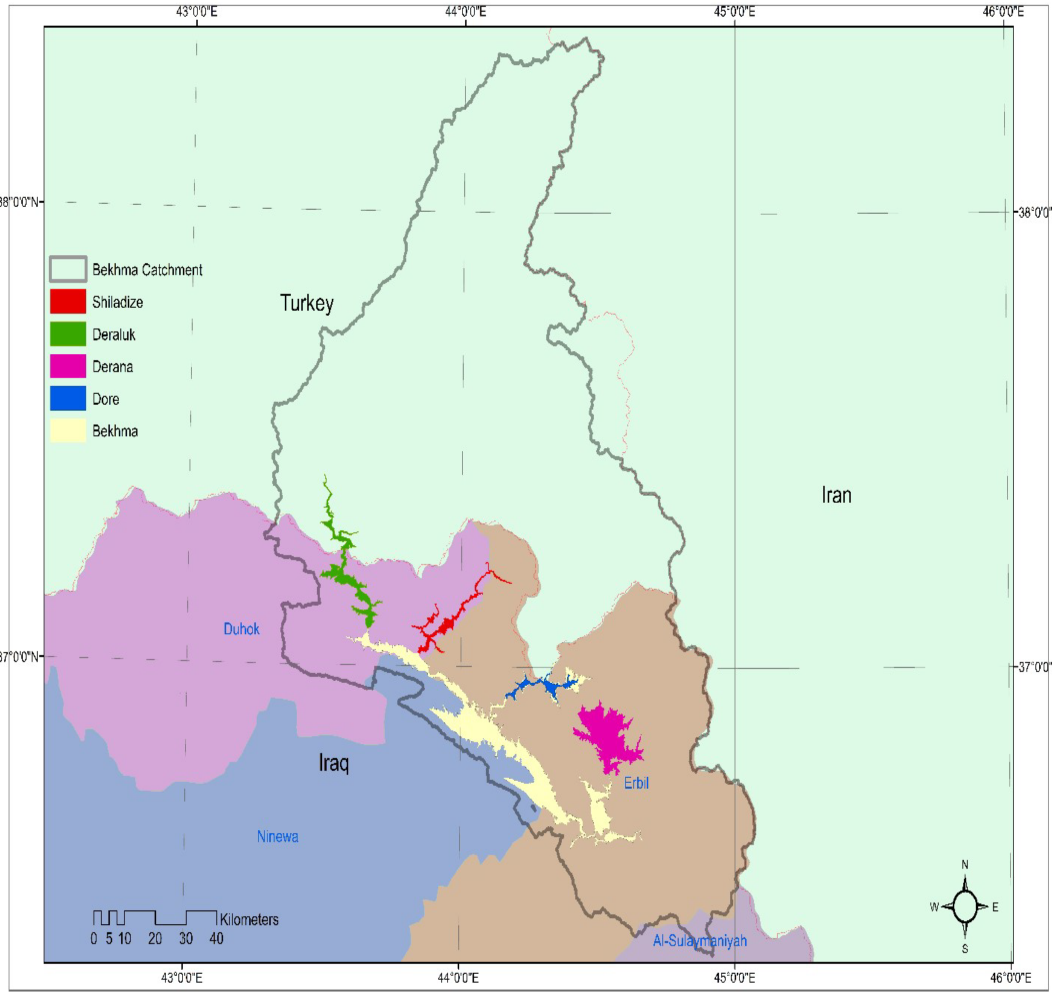

Figure 1. Spatial distribution of Proposed Bekhma Dam and selected upstream alternative sites within the Greater Zab Basin.

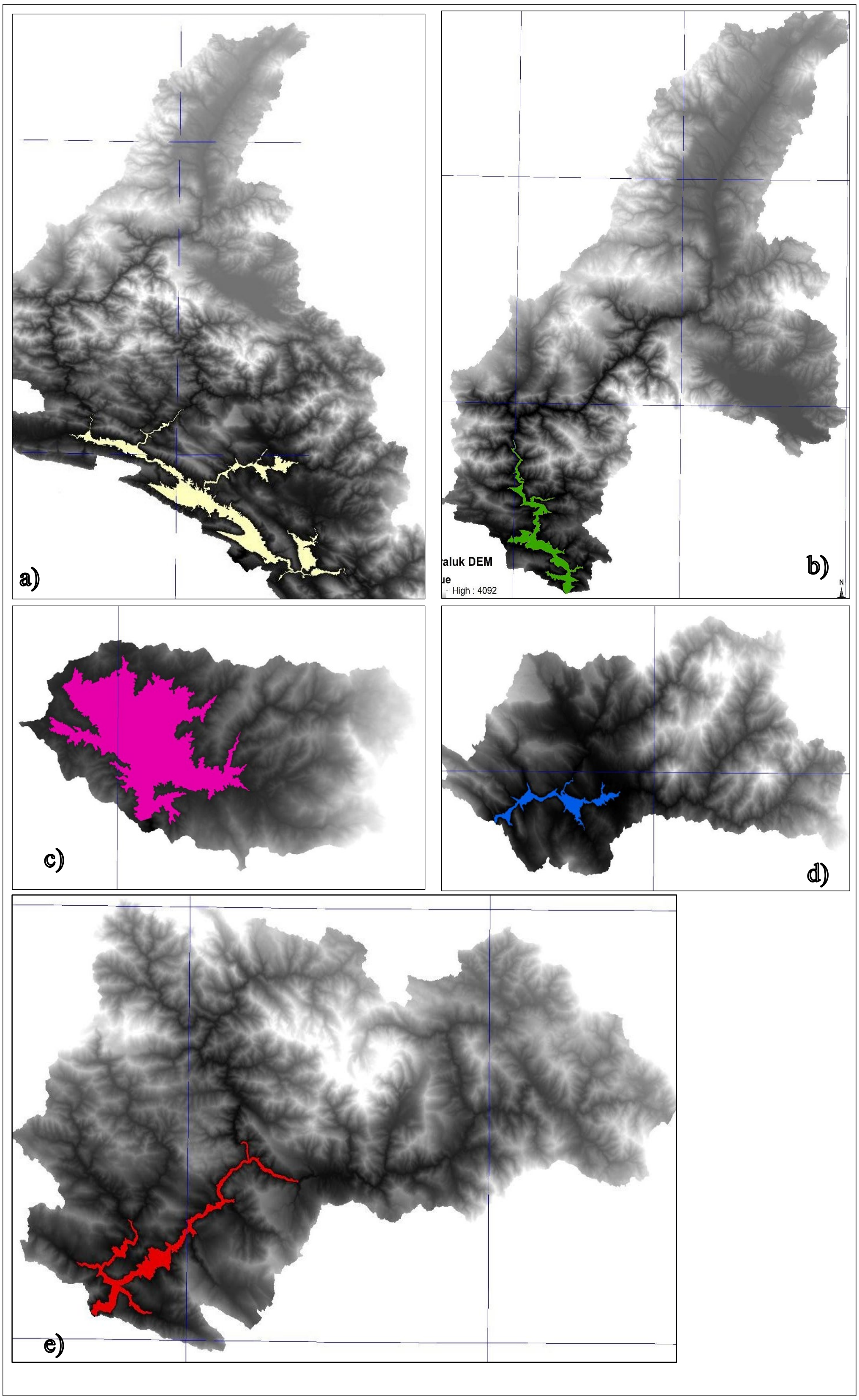

Figure 2. DEM-based representation of the proposed Bekhma Reservoir and the four upstream alternative reservoirs: (a) Bekhma, (b) Deraluk (D4), (c) Derana (D2), (d) Dore (D5), and (e)

Sheladiz (D3).

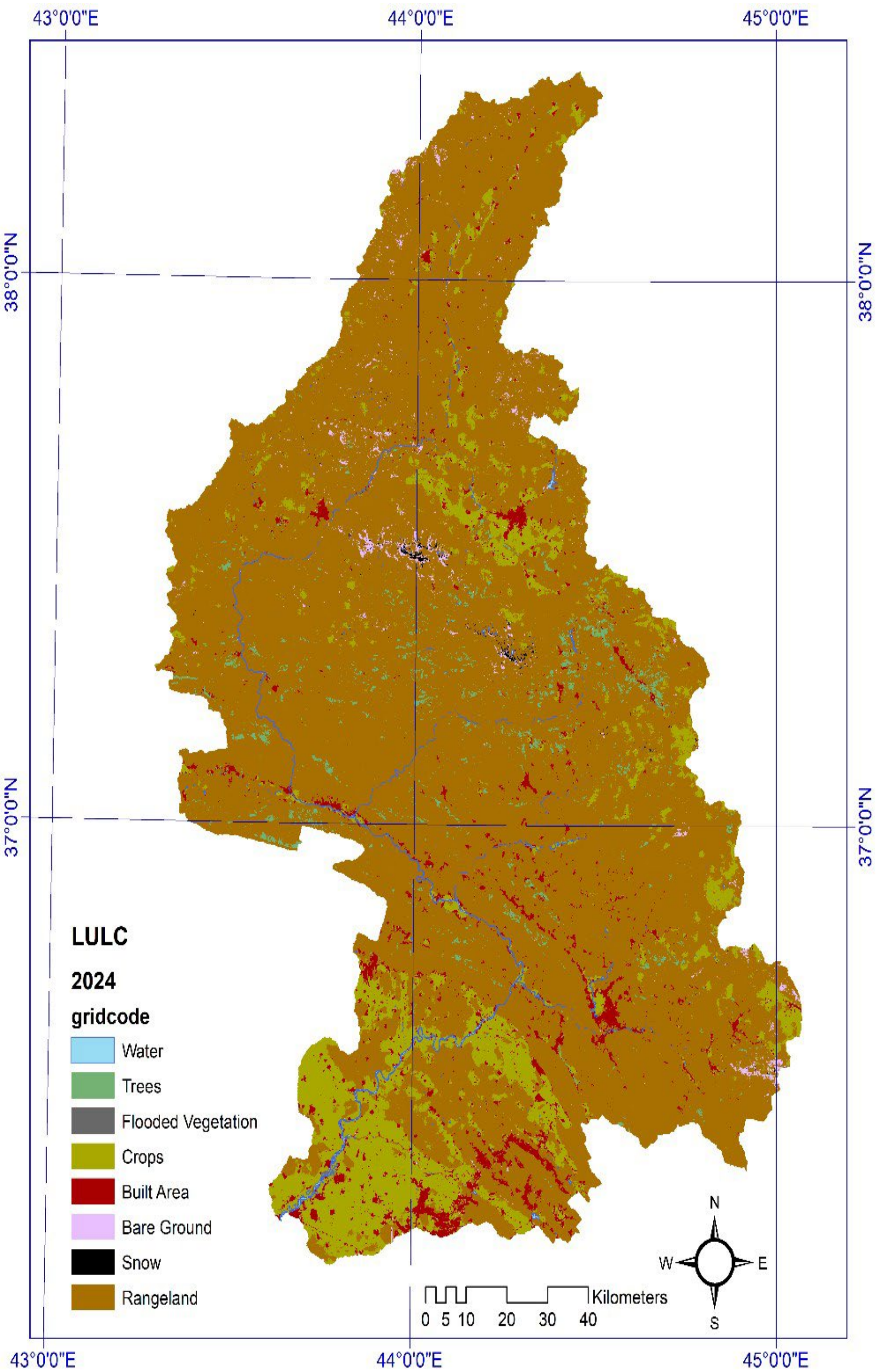

Figure 3. Land use and land cover distribution within the Eski Kalak watershed

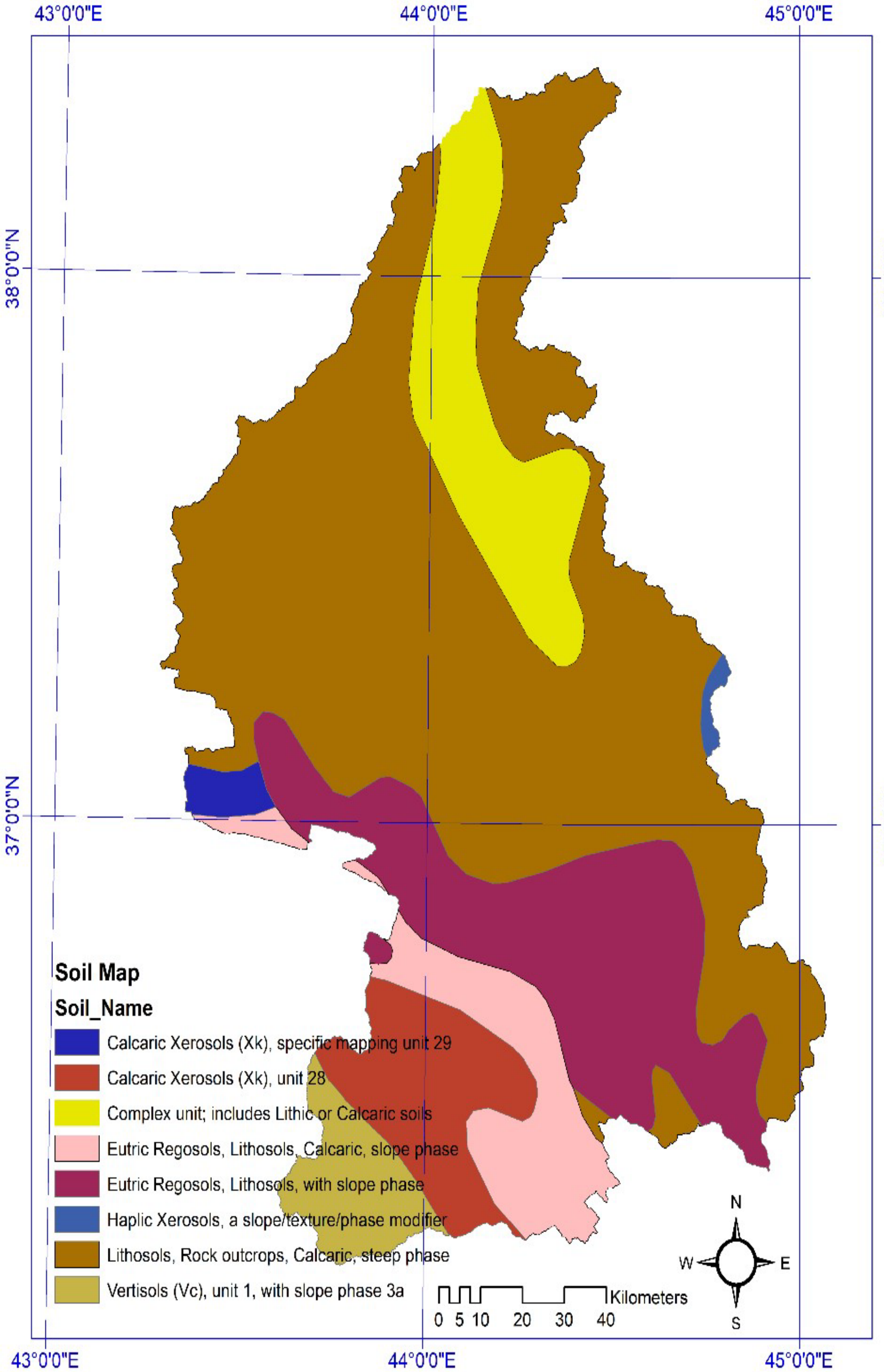

Figure 4. Soil classification map indicating spatial variability in erosion susceptibility.

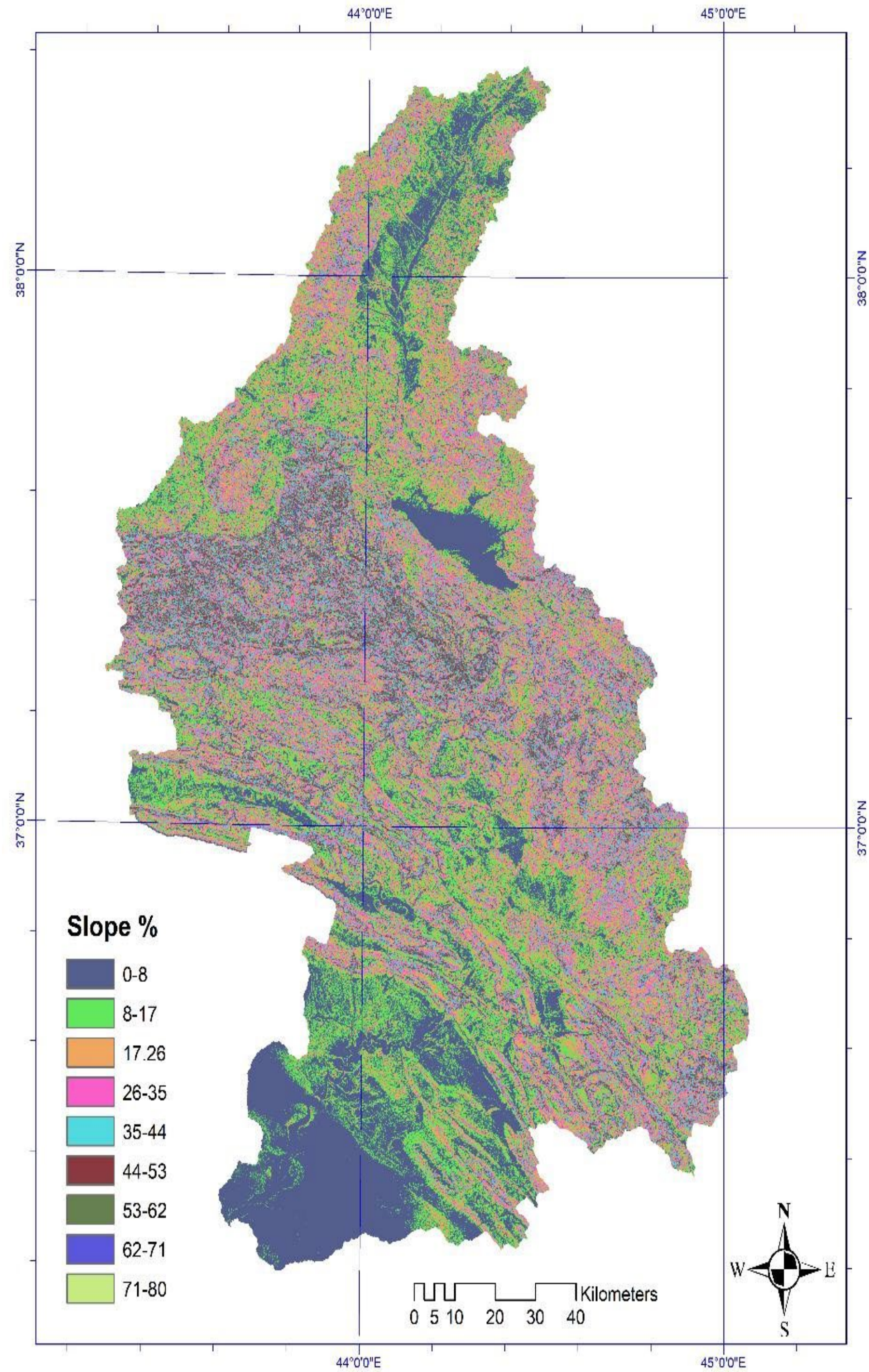

Figure 5. Slope distribution derived from DEM analysis within the study area.

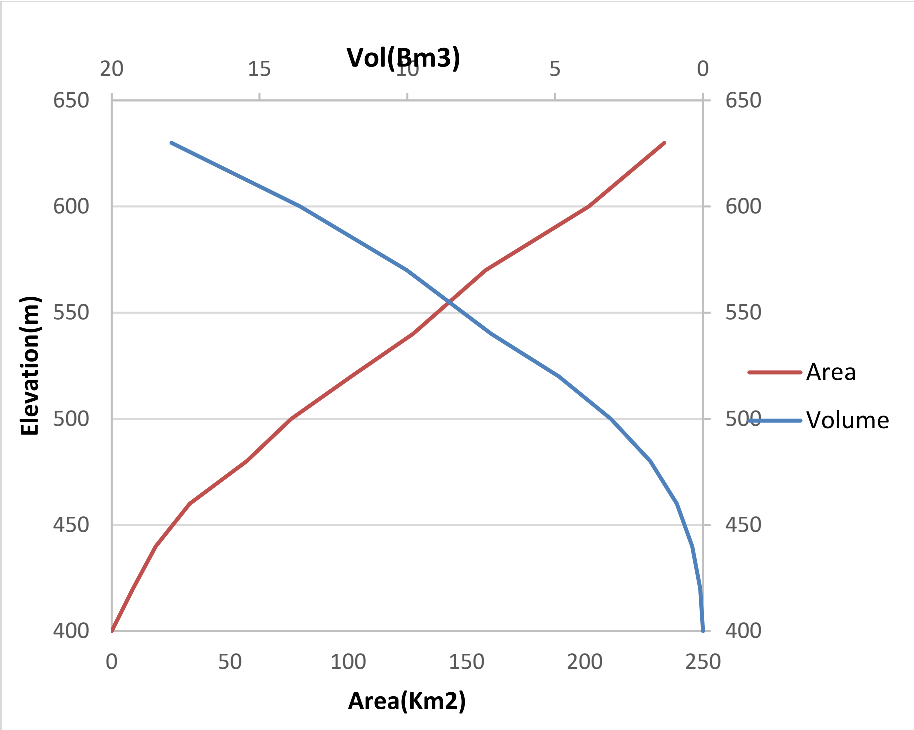

Figure 6. Elevation–volume relationship of the Proposed Bekhma Reservoir derived from DEM analysis.

Table 1. Design parameters of the Bekhma Dam (Ahmed & Khoshnaw).

Parameter	Value
Proposed Height (m)	230
Crest Length (m)	530
Storage Capacity (BCM)	17.0
Dead Storage Volume (BCM)	4.0
Power Generation (MW)	1,500

Table 2. Comparison of storage capacities for Proposed Bekhma Dam and upstream alternatives.

Site	Elevation (m)	Height (approx. m)	Storage Volume (BCM)
Bekhma (Original) (D1)	630	230	17.99
Bekhma (Reduced)	540	140	7.2
Derana (D2)	880	200	3.93
Sheladiz (D3)	770	200	2.26
Deraluk (D4)	860	200	2.25
Dore (D5)	640	120	0.96
Total (Alt. 2–5)	—	—	9.40

Table 3. Common sediment transport models and their applications

Model	Type	Application
Shields Diagram	Threshold analysis	Initiation of sediment motion
Ackers–White	Transport rate	Alluvial channels
Meyer-Peter & Müller	Bed load	Coarse sediment transport
Engelund-Hansen	Total load	Uniform flow conditions

Table 4. Parameters used in the Shields and Ackers–White calculations

Parameter	Symbol	Value	Unit
Median sediment size	D50	0.20×10^{-3}	m
Specific gravity of sediment	Sg	2.65	–
Water depth	d	4.0	m
Channel slope	S	0.00186	m/m
Kinematic viscosity	ν	1.308×10^{-6}	m^2/s
Hydraulic radius	R	4.0	m
River width	B	200	m

Table 5. Sediment inflow and dead storage characteristics of upstream alternative reservoirs.

Dam Site	Sediment (m^3/year)	Load Dead Storage Elevation Relative Sediment (m) Impact	
Derana (D2)	215,469	685	Low
Sheladiz (D3)	888,455	580	Moderate
Deraluk (D4)	1,719,000	670	High
Dore (D5)	549,693	525	Moderate

Table 6. Comparison of sediment inflow to the Proposed Bekhma Reservoir before and after implementation of upstream alternative dams, highlighting the reduction achieved under the decentralized system and System-level evaluation of sediment inflow and percentage sediment reduction

Scenario	Sediment (m^3/year)	Dead Load Elevation (m)	Reduction (%)	Sediment Behavior	Storage System Behavior
Bekhma only	4,067,829	410	—	Centralized accumulation	Rapid sediment accumulation
With upstream dams	696,000	405	>80%	Distributed interception	Controlled sediment distribution

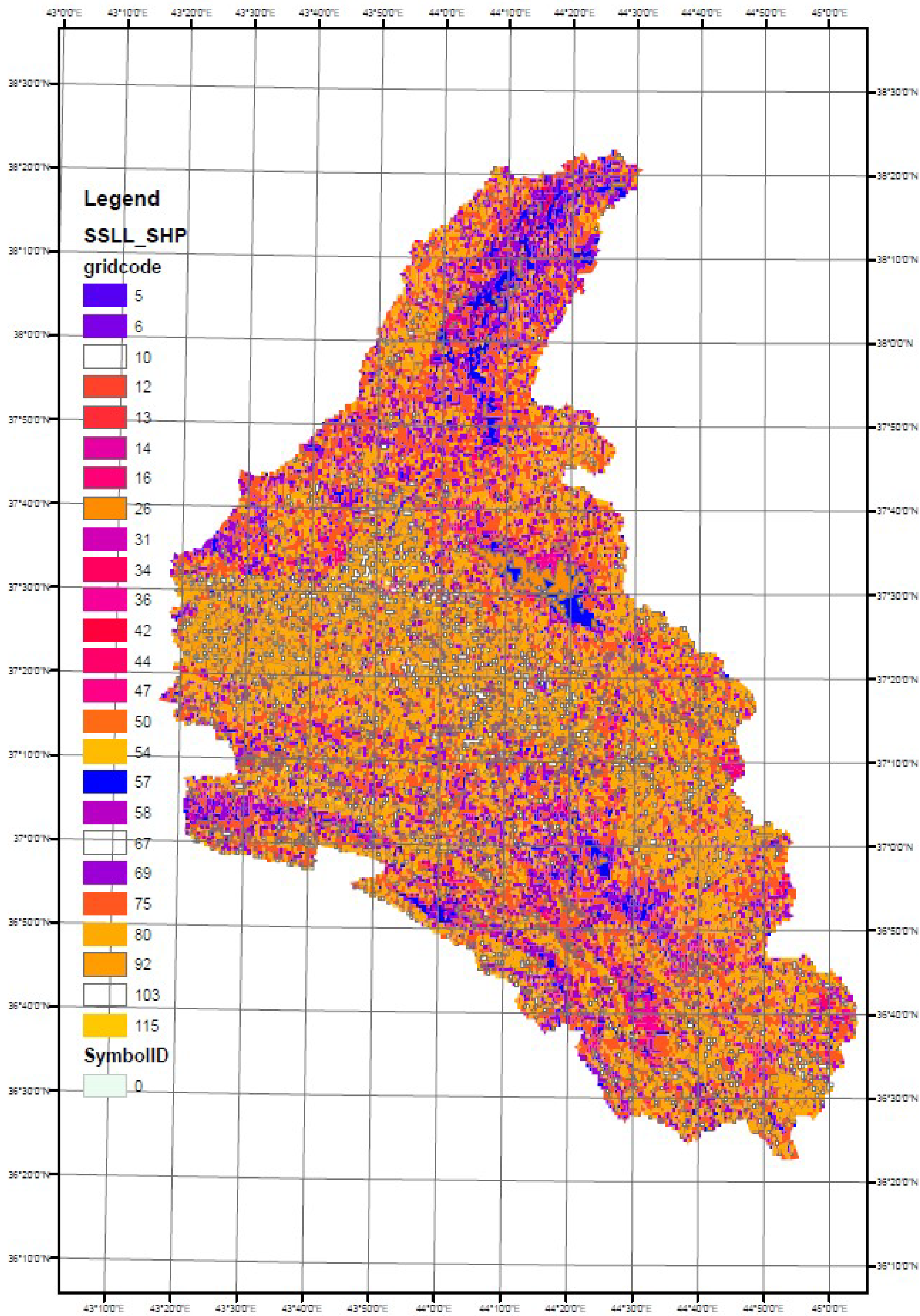

Figure 7. Initial spatial distribution pattern of sediment transport in the Greater Zab Basin with the centralized reservoir scenario (Proposed Bekhma Reservoir only), showing downstream accumulation of sediment.

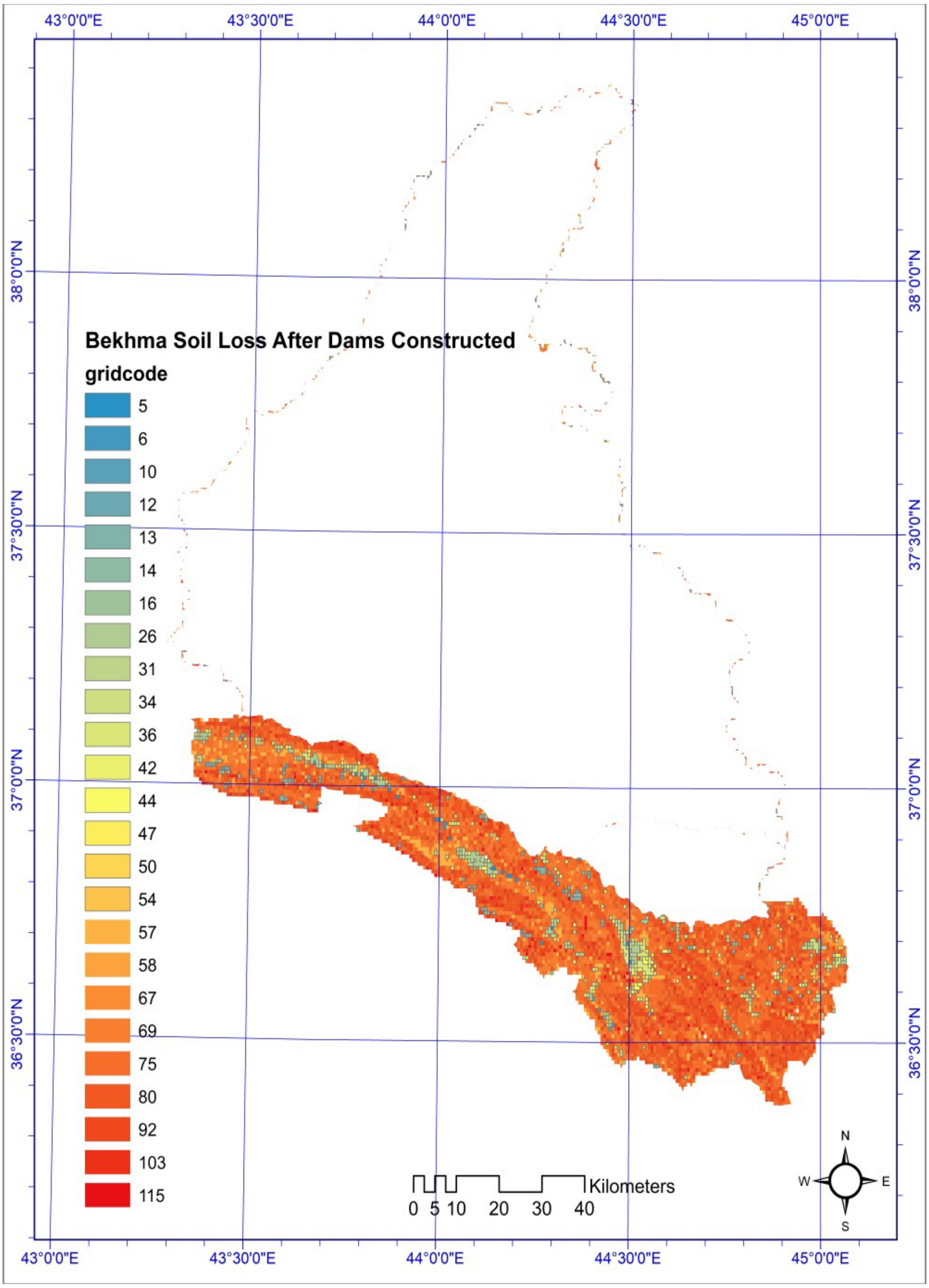

Figure 8. Sediment redistribution pattern with the introduction of upstream alternative reservoirs (D2-D5), with distributed trapping of sediment in upstream sub-catchments.