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ORIGINAL ARTICLE

# Eco-hydrologic stability zonation of dams and power plants using the combined models of SMCE and CEQUALW2

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**Abstract**

Construction of dams has a significant impact on hydrological conditions of rivers. Eco-hydrology, as a sub-discipline of hydrology, focusses on ecological processes occurring within the hydrological cycle and strives to utilize them for enhancing the environmental sustainability. The aim of this study was to determine the stable and instable eco-hydrologic regions in the study area. First, the factors affecting the eco-hydrologic stability were selected according to field surveys. Afterwards, the layers related to each factor were prepared in geographic information system (GIS) and ArcGIS 10 software. These factors were also weighted using the analytic hierarchy process and pairwise comparisons. Ultimately, the final map was prepared by integrating and determining the homogenous units. The CEQUALW2 software, as a water quality and hydrodynamic model, was used to confirm the accuracy of the quality data and to perform the water quality simulation in the studied dam. According to the results, pollutant source and water quality were found to be the most important factors. The final map indicated that most of the areas had not a suitable condition in terms of stability at the downstream reaches.

**Keywords** CEQUALW2 Software · Eco-Hydrology (EH) · Dam · Geographic Information System (GIS) · Power Plant · Spatial Multi-Criteria Evaluation (SMCE)

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## Abbreviations

| | |
|---|---|
| AHP | Analytic Hierarchy Process |
| EH | Eco-Hydrology |
| GIS | Geographic Information System |
| SMCE | Spatial Nulti-Criteria Evaluation |

## Introduction

Sedimentation, water contamination, habitat destruction and overexploitation are known to be responsible for major environmental problems. Most of these problems are triggered through the interaction between lakes and adjacent catchment areas. Eco-hydrology (EH) encourages the efforts to solve the problems integratively by increasing the understanding of key processes in the inland water carrying capacity and the resilience to the environmental stresses (Chrismadha and Haryani 2011). The eco-hydrological approach can be potentially applied to overcome various problems in lakes and reservoirs. This approach can be considered efficient as it is mostly focused on better understanding of key processes that largely determine the sustainability of lakes, both in terms of hydrology and ecological aspect, particularly the habitat functions, to support biodiversity and bio-productivity (Chrismadha and Haryani 2011). River network structures and their embedded hydrologic dynamics play an important role in eco-hydrological stability (Derakhshannia et al. 2020). In fact, they provide supporting landscapes for ecological processes, many of which are essential to human life and societies (Rinaldo et al. 2018). Within riverine systems, flow plays an essential role in ecosystem structure and function, as it controls many important abiotic conditions. The characteristics of flow represent the environmental conditions such as current velocity, substratum stability, channel geomorphology, water temperature and chemistry and habitat area (Ostad-Ali-Askari et al. 2018). Additionally, extreme flood events play a principal role in influencing the structure and function of lotic ecosystem. Although dams provide the society with many benefits, their construction for regulating the river flow rates changes the quantity and quality of water (do Vasco et al. 2019). By altering flow of water nutrients, sediments, energy and biota in a river, dams induce various negative effects and threaten the health of riverine ecosystems (Bevelhimer et al. 2015). In many cases, these ecological effects put pressure on the societies that interact with and depend on the natural resources provided by these ecosystems. Dam construction can affect the upstream and downstream river reaches in different ways. As the most obvious impacts of dam construction on upstream, the created reservoir floods the riparian and adjacent lands and transforms lotic environments to lentic or semi-lentic systems. The impacts of dam on downstream are less acute and include the continuous impacts as a result of permanent change in flow regime. Typically, dams affect the flow by reducing the magnitude of flood, increasing the base flow and increasing the number and rate of changes of reversals in discharge. The stunted flood pulses and the increased base flow reduce the downstream floodplain habitats and encourage the encroachment of upland vegetation, resulting in degradation of floodplain forests and loss of biodiversity. Therefore, eco-hydrology has been proposed as the best environmental management method to achieve sustainable development. Eco-hydrology is based on the fact that environmental degradation can only be remedied by restoring some of the functions of an ecosystem and helping a partially restored system to improve itself naturally (Jørgensen 2016). Furthermore, in freshwater, eco-hydrology has been successfully applied to the constructed wetlands, rivers and floodplains, for the issues concerning aquaculture and management of shorelines and river beds to maximize fish yield and improve water quality in reservoirs (Wolanski 2007).

Hoenke et al. (2014) applied a GIS-based approach to prioritize the dams for removal based on the presented eco-hydrologic and social metrics. They found that the dams with the highest ranking in ecological prioritization were located on reaches of high habitat quality and longer connected river miles (Ostad-Ali-Askari and Shayannejad 2021). Hayati et al. (2013) used an organized three-step road network developed by DELPHI, AHP and spatial multi-criteria evaluation (SMCE) in ArcGIS in order to manage the forest resources sustainability (Chakroun et al. 2015). They reported that these models were useful for detecting the roads. Ahmadpour (2013) used five hydrological methods ([1) FDC, (2) Tenant, (3) RVA, (4) FDC shifting and (5) DRM) for ecological assessment of Nazlu River and concluded that protection of the river required a continuous flow supply of 0.8–8.0 $m^3$/s. Zeng et al. (2012) developed a web-based decision support system for integrated water resources management based on genetic algorithm as a dss. They demonstrated that the dss was very helpful to deal with complex problems in water resources management and could be used in similar cities. Mahmoudian and Talebbeydokhti (2013) utilized the IHA/RVA method to assess the hydrological changes of Neka River and concluded that the factors negatively affecting the eco-hydrological conditions of the river were responsible for destruction of the ecosystem (Kothari and Mishra 2015). Zalewski (2011) investigated the eco-hydrology theory as a comprehensive approach and proved that obtaining such multi-science knowledge required specific consideration of the hierarchy of adjuster factors involved in interactions of water vegetation and animal species of the ecosystem. Negussie et al. (2011) used Gomera River basin, as one of the eco-hydrologic exhibition sites, for balancing the eco-hydrologic principles and resolving the environmental problems and finally established a regional center for eco-hydrology. Madadi (2011) employed the hydrologic variation indices and different methods to evaluate the effect of Karkheh Dam on eco-hydrologic conditions of downstream. He showed that Karkheh Dam extremely changed the natural flow, range of conditions and spatial variations. Hipsey et al. (2011) used a systemic model for restoring the natural biodiversity in Bryde Lake in south west of Australia to develop an eco-hydrologic model for evaluating the response of flood plain pond to altered flow discharges (Zalewski 2015). He indicated that the model could predict flow discharge and inundation of the flood plain. Zalewski (2010) believed that eco-hydrology, as a framework presented in the international hydrological program of UNESCO, can be used (1) to slow down water exchange between atmosphere and sea in order to reduce flood and drought effects; (2) to regulate and reduce pollutants discharged into the aquatic systems; and (3) to harmonize the ecosystem potential and society requirements. Debele et al. (2006) applied two strong models of soil and water assessment tool (SWAT) and CEQUALW2 for better management of water resources in a complex river basin. They concluded that these models were compatible and could be used for evaluation of water resources in complex basins. Latyan dam was constructed to store and adjust the flow of Jajrood River and supply a part of water needed for Tehran's residents and Varamin Plain's agriculture (Fuladipanah and Jorabloo 2015). Considering sustainable development and conservation of natural ecological factors, water releasing would be necessary for stability, regeneration and improvement of water ecosystem in lowland areas, self-purification of rivers and maintenance of water quality (Ostad-Ali-Askari et al. 2019; Hera et al. 2016; Golian et al. 2020). The aims of this study are to map eco-hydrologic stability of Latyan dam basin and determine the eco-hydrologically stable and instable places in the study area using the combined models of CEQUALW2 water quality Simulation and SMCE. Moreover, DELPHI method and Analytical Hierarchy Process (AHP) were used in the statistical approach adopted in this study. Geographic Information System (GIS) was also applied for zonation. This study has been performed in Latyan Dam of Tehran in 2015.

## Materials and methods

### Study area

The study area is located between longitudes of 51° 23′ to 51° 55′ E and latitudes of 35° 45′ to 36° 50′ N. The average annual rainfall in Roodak, Latyan and Mamloo stations, which are close to the watershed, are 580, 413 and 249 mm, respectively. The study area, with an area of 69,800 $km^2$, includes two classes of antisols and inceptisols with different types of land use such as bare lands, rangeland, forest, shrub lands and residential areas. The average annual flow of the river in the studied watershed is 350000000000 $m^3$. Latyan Dam, with a height of 107 m, has been constructed on the river in outlet of the study area.

### Data preparation

The topography, lithology, soil, land use, location of the areas under conservation maps of the Department of Environment were used. To simulate different conditions including temperature lamination and eutrophication and to simulate quality parameters including oxygen, nitrate, phosphate, biochemical oxygen demand (BOD) and algae in Latyan Dam, the CEQUALW2 model was used. According to the experts' opinions collected by a questionnaire, the mentioned parameters were classified into five groups of physical, biologic, economic and social, contaminant and water quality factors. In the next step, the questionnaires were filled in by several qualified experts and analyzed by DELPHI model. Each question covered five importance degrees of 1, 3, 5, 7 and 9 to be selected by the experts. After validation of the questionnaires by geometric average, 19 out of 30 questionnaires were selected for analytic hierarchy process (AHP). Using Cronbach's alpha, the validity and reliability of the questionnaires were tested by SPSS 20 software. Subsequently, CEQUALW2 was used for simulation of the water quality. Furthermore, ArcGIS and SMCE models were used for zoning and representing eco-hydrologically stable and instable zones.

### Analytical hierarchy process (AHP)

AHP is based on some principles including decomposition and comparative judgment of priorities (Saaty 1980). This approach relies on a pairwise comparison as an input implementing a point scale to show individual judgments when comparing each pair of factors (Saaty 1980; Jamali et al. 2014). AHP produces relative weights as output and thus builds a ratio matrix which is checked for consistency based on the standard AHP methodology (Saaty 1980). However, as a weakness, the uncertainty related to mapping of the decision maker's judgment about priority number is not considered by AHP, and preference of the decision maker has a high influence on the result of AHP (Kordi 2008). SMCE can be used to reduce the weak points of AHP.

### Spatial multi-criteria evaluation (SMCE)

SMCE, as a combination of multi-criteria evaluation and GIS, was introduced in 1980 (Looijen 2009). SMCE is used to solve the spatial problems, where goals, factors and other elements in programing are related to the space. ITC Center has developed SMCE in ILWIS software. Outputs of SMCE are maps of a specific region (i.e., factors or elements) and a tree of factors including method of classification, standardization and weighting of factors (Jamali et al. 2014).

### CEQUALW2 model

CEQUALW2 model was developed for water quality and hydrodynamic modeling based on the experiment database of American Rivers. CEQUALW2 is a two-dimensioned numerical, hydrodynamic, water quality model. This model contains both water quality and hydrodynamic modules. Its calculations are affected by variable density obtained from temperature, saltiness, solutes and suspended material. CEQUALW2 is capable of predicting the changes in water table, velocity and temperature of water. Since temperature affects the water density, temperature calculation has been included in the hydrodynamic sub-system and should not be deleted.

**Table 1** Weights of the physical factor assigned by AHP

| Factor | Climate | Topography | Hydrology | Lithology | Soil | Weights |
|---|---|---|---|---|---|---|
| Climate | | 1.5 | 1.8 | 2 | 2.3 | 0.36 |
| Topography | | | 1.3 | 1.6 | 1.9 | 0.26 |
| Hydrology | | | | 1.2 | 1.5 | 0.18 |
| Lithology | | | | | 1 | 0.1 |
| Soil | | | | | | 0.1 |

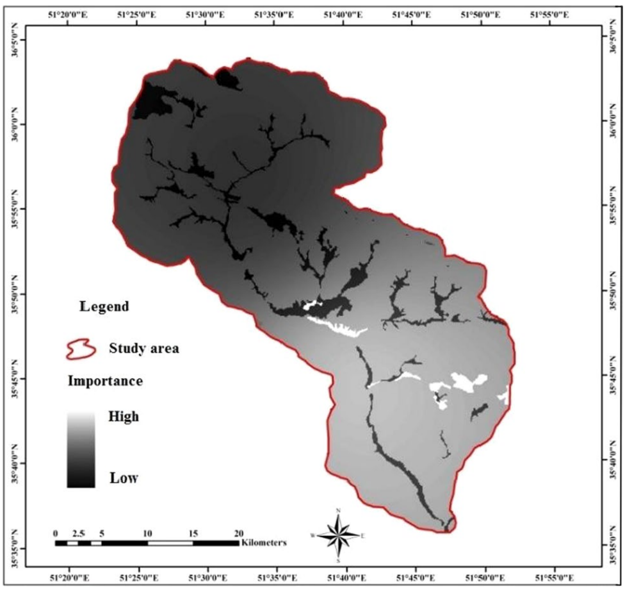


**Fig. 1** Eco-hydrologic stability map of the biological factor

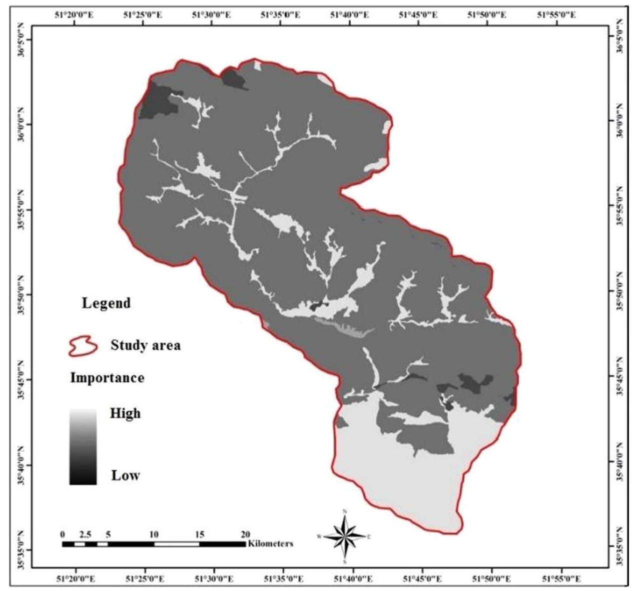


**Fig. 2** Eco-hydrologic stability map of the social-economic-cultural factor

**Table 2** Weights of the water quality factor assigned by AHP

| Factor | Physical | Chemical | Biologic | Weights |
|---|---|---|---|---|
| Physical | | 1.5 | 1.7 | 0.45 |
| Chemical | | | 1.1 | 0.3 |
| Biologic | | | | 0.25 |

**Table 3** Weights of the pollutant resources factor assigned by AHP

| Factor | Industrial | Civic | Mine | Agricultural | Weights |
|---|---|---|---|---|---|
| Industrial | | 2 | 3 | 4 | 0.45 |
| Civic | | | 2 | 3 | 0.25 |
| Mine | | | | 1 | 0.15 |
| Agricultural | | | | | 0.15 |

## Results and discussion

In the first step, five dominant factors related to eco-hydrologic stability were calculated using different sub-factors. For example, the physical factor was determined using five sub-factors of climate, topography, hydrology and water resources, geology and soil and land capability (Table 1). The biological factor included vegetation cover, aquatic system and distance of rivers from susceptible and important ecologic locations (Fig. 1). In the water quality factor, physical and chemical quality, biologic water quality and bacteriologic water quality were considered to produce the final map (Table 2). Occupation types and population were considered in the economic, social and cultural factor (Fig. 2). Finally, to investigate the pollutant sources factor, the industrial, civic, mine and agricultural pollutants in the study were considered (Table 3).

Using AHP, the specific weights were assigned to different factors and the eco-hydrological stability map was produced. Table 4 shows the results of AHP for different factors in the present study. It can be seen that the pollutant sources have the highest weight of 0.43. Moreover, the water quality

**Table 4** Weights of different factors obtained based on the goal

| Factor | Pollutant resources | Water quality | Social, economic and cultural | Physical | Biological | Weights |
|---|---|---|---|---|---|---|
| Pollutant resources | | 1.5 | 2 | 2.5 | 3 | 0.43 |
| Water quality | | | 1.5 | 2 | 2.5 | 0.28 |
| Social, economic and cultural | | | | 1.5 | 2 | 0.15 |
| Physical | | | | | 1 | 0.07 |
| Biological | | | | | | 0.07 |

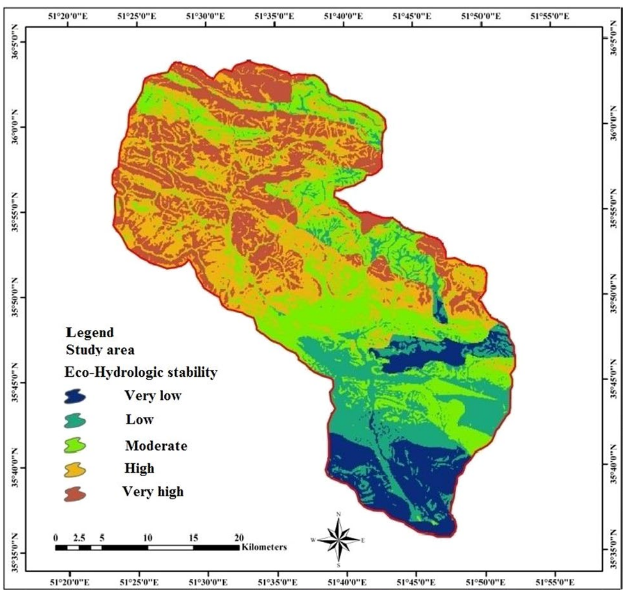


**Fig. 3** Classified eco-hydrologic stability map

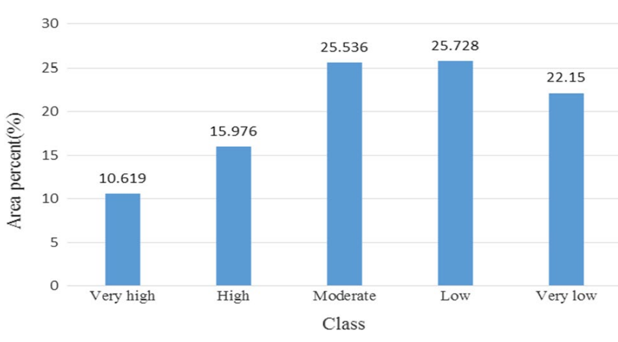


**Fig. 4** The area related to each class of the eco-hydrologic stability map

factor and the social, economic and cultural factor have the weights of 0.28 and 0.15, respectively. However, both physical and biological factors have the lowest weight of 0.07.

The final eco-hydrologic stability map was presented using Eq. (1).

$$\begin{aligned} \text{Map} =& 0.43 * \text{Pollutant resources} + 0.28 \\ & * \text{Water quality} + 0.15 \\ & * \text{Social, economic and cultural} \\ & + 0.07 * \text{Physical} + 0.07 * \text{Biological} \end{aligned} \tag{1}$$

Based on the experts' opinions, the final eco-hydrological stability map was then classified into five classes of very high, high, moderate, low and very low (Fig. 3). According to Fig. 3, the northern parts of the study area have high and very high eco-hydrologic stabilities, while the southern parts have low and very low eco-hydrologic stabilities.

The area related to each class of the eco-hydrologic stability map is represented in Fig. 4. According to Fig. 4, low, moderate, very low, high and very high classes occupy 25.73%, 25.54%, 22.1%, 15.976% and 10.619% of the study area, respectively.

## Conclusion

Among the various models, CEQUALW2 model was used to simulate the quality of inlet and outlet water of Latyan dam reservoir and to investigate the thermal layering of the reservoir and the biological conditions of the downstream ecosystem. A combination of AHP method and ArcGIS software was used to weigh and integrate the main components in order to obtain the eco-hydrologic zones in terms of sustainability. Results of the AHP method indicated that among the five components studied, pollutant resources and water quality had higher weights, and both physical and biological factors had the lowest weight (0.07). The final map of eco-hydrologic stability zoning was obtained by calculating the total weights of the target criterion. Considering the complexity of making decision based on the obtained map, it was classified into five classes using the experts' opinions and statistical methods. The defined classes included the zones with very high (10.6%), high (15.9%), moderate (25.5%), low (25.7%) and very low

(22.1%) eco-hydrologic stabilities. According to the final classification map, most of the areas at the northern parts had very high and high eco-hydrologic stabilities, and the southern parts had very low and low eco-hydrologic stabilities. The results also showed that the areas with very low and low ecologically stable conditions could be regarded as sensitive ecological areas and should be placed at the top priority in allocating the minimum environmental water requirement.

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**Author's Contributions** All authors designed the study, collected data, wrote the manuscript and revised it.

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**Availability of data and materials** Some or all data, models or code generated or used during the study are available from the corresponding author by request.

## Declarations

**Conflict of interest** The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission and redundancies have been completely observed by the authors.

**Ethical approval** The present Study and ethical aspect was approved by Water Engineering Department, College of Agriculture, Shahrekord University, Shahrekord, Postal Code: 8818634141, Iran.

**Consent to participate** All authors designed the study, collected data, wrote the manuscript and revised it.

**Consent to publish** All authors agree to publish this manuscript. There is no conflict of interest.



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