Optimal reservoir operation strategy for balancing ecosystem and human needs

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Abstract The frequency of extreme hydrological events varies highly in Taiwan, and increasing attention has been paid to the optimal reservoir operations. This study establishes an optimization model for watershed management through reservoir operations subject to human and ecosystem needs. The Shihmen Reservoir in Taiwan is used as a case study. This study adopts the Taiwan Eco-hydrological Indicator System (TEIS) to classify river flow patterns. We combine the non-dominated sorting genetic algorithm II (NSGA-II) with the self-organizing radial basis network (SORBN) to develop the optimal model of reservoir operation. The results indicate that it is possible to simultaneously satisfy human and ecosystem needs, where ecosystem diversity can be retained in high SI values (1.7–1.9) while human demands can also be highly satisfied (α higher than 0.85). The proposed approach allows decision makers to easily determine the best compromise in water allocation through the trade-off between human and ecosystem needs.

Key words Taiwan Eco-hydrological Indicator System (TEIS); non-dominated sorting genetic algorithm II (NSGA-II); reservoir operation; water resources management; self-organizing radial basis network (SORBN)

INTRODUCTION

Modern water resources management continues to develop new management tools to assure the protection and maintenance of the environment, while sustaining the ecological integrity in watersheds subject to human influences. A great challenge to water resources management in this century is that both ecosystem and human needs should be considered with regime-based approaches in the development of management strategies for reservoir operations and stream management. The flow regime assessment in Taiwan has been facilitated by the Taiwan Eco-hydrologic Indicator System (TEIS), which was developed to identify the hydrologic statistics most appropriate to Taiwan fisheries (Chang *et al.*, 2008, 2013; Suen & Herricks, 2009).

In this study, we propose a novel optimizing technique for reservoir operation to deal with multiple water users, in particular, the downstream ecological flow demands. To handle multiple objectives, trade-off methodologies have shown promise as an effective means for considering non-commensurate objectives that are subjectively compared in operation determinations (Cohon & Marks, 1975; Kollat & Reed, 2007; Chang, 2008; Reed, *et al.*, 2013). Artificial neural networks (ANNs) are effective in extracting significant features from complex databases and are recognized for their outstanding abilities in modelling complex nonlinear systems. The self-organizing feature map (SOM) and radial basis function (RBF) neural networks are combined to produce a self-organizing radial basis network (SORBN) that takes the advantages of both methods for strengthening the power of presentation and the reliability of estimation (Chang *et al.*, 2013). We combined the non-dominated sorting genetic algorithm II (NSGA-II) (Deb *et al.*, 2002) with the self-organizing radial basis network (SORBN) to optimize reservoir operations in consideration of fish biodiversity. The Shihmen Reservoir is used as the case study. The objective function for human demands is expected to provide the satisfaction degree of human needs; while the objective function for ecological demands is expected to satisfy human needs as well as riverine biodiversity based on flow regime management.

STUDY AREA AND DATA DESCRIPTION

Study area

The Shihmen Reservoir is the most important hydraulic facility in the Danshui River basin of northern Taiwan. The watershed coverage of the Shihmen Reservoir is of 763.4 km^2, with an effective storage capacity of 2.35 × 10^8 m^3. The reservoir was built primarily to serve multi-objectives: water supply to irrigation; industrial and public sectors over the whole of Taipei and Taoyuan areas; hydropower generation; and flood control. We chose flow gauging stations that can provide discharge data to correspond with the fish data in the Danshui River basin (Fig. 1).

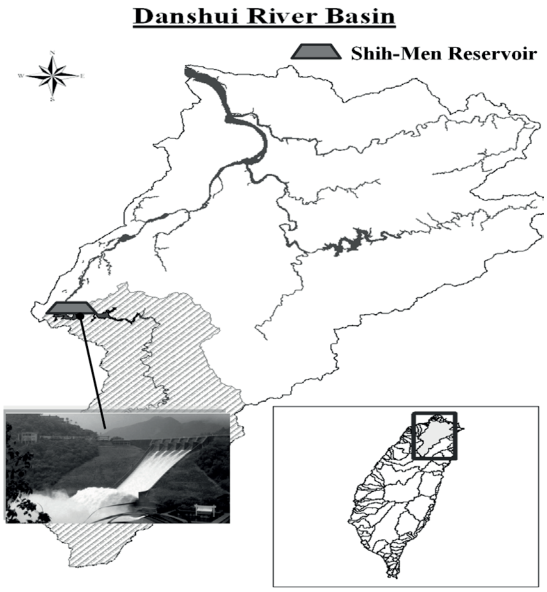

Fig. 1 Study area – Danshui River basin in Taiwan.

Taiwan Eco-hydrologic Indicator System (TEIS)

The TEIS is explored based on autecological information for water resources management (Suen & Herricks, 2006). It is developed to integrate habitat and ecological information for a known fish community with hydrologic statistics selected based on fish community relationships. It has proven useful in water resources management when considering the integrity of ecosystems (Suen & Herricks, 2009). The TEIS includes 30 statistics coded as TEIS 1 – TEIS 30 for differentiating consecutive values, high/low flow event magnitudes, frequency of high/low flow events and reversals, and high/low flow event duration for flows (Group 1–4), and 36 statistics of mean 10-day flows for reservoir operation (Group 5) (Chang *et al.*, 2013).

Fish diversity

The Shannon Index (*SI*) is used to estimate the diversity of an ecosystem. This index was proposed for quantifying the entropy in the theory of communication (Shannon, 1948). The idea applied to a river ecosystem is: based on the equal proportional abundances of species present, it is more difficult to estimate the diversity accurately if more different fish species are present (Chang *et al.*, 2013). The *SI* for estimating the fish diversity is calculated as follows:

$$SI = -\sum_{i=1}^{N} Pi * \ln Pi \text{ , } \quad Pi = \frac{n_i}{N} \tag{1}$$

where n_i is the number of individuals in the *i*th species; the abundance of the *i*th species; N is the total number of all individuals; and *Pi* is the relative abundance of each species, calculated as the proportion of individuals of a given species to the total number of individuals in the community.

METHODS

The water release associated with the human and ecosystem needs in the downstream region is the decision variable in this study. First, this study uses observational data to construct a hybrid neural network, SORBN, for estimating the fish biodiversity by the TEIS statistics. Subject to the limited understanding about the river ecosystem, this estimated biodiversity which considers the relationship between flow regime and fish communities (Chang *et al.*, 2013) is utilized as the ecosystem objective function in the multi-objective optimization. Then we follow the study procedure combining the NSGA-II with the SORBN to search the optimal reservoir operation that meets both ecosystem and human needs (Fig. 2).

This study uses the SORBN for estimating fish community diversity based on the TEIS statistics. The centroids of the topological layer in the SOM (unsupervised) are selected as the centroids of the hidden nodes in the RBF (supervised). The SORBN not only can estimate the fish biodiversity but also can relate flow regime to fish community. This study chooses the correlation coefficient (CC) to evaluate the performance of the SORBN.

The NSGA-II has been successfully applied in reservoir operation (Kim *et al.*, 2006; Malekmohammadi, 2011). The NSGA-II uses an elite-preservation strategy that can provide a fast non-dominated sorting. The non-dominated solution set is also called the Pareto front set. For any objective function, no solutions better than the solutions in the Pareto front set can be found within the solution set. The solutions in the non-dominated front are all equally good and can provide decision makers with an opportunity to evaluate trade-offs.

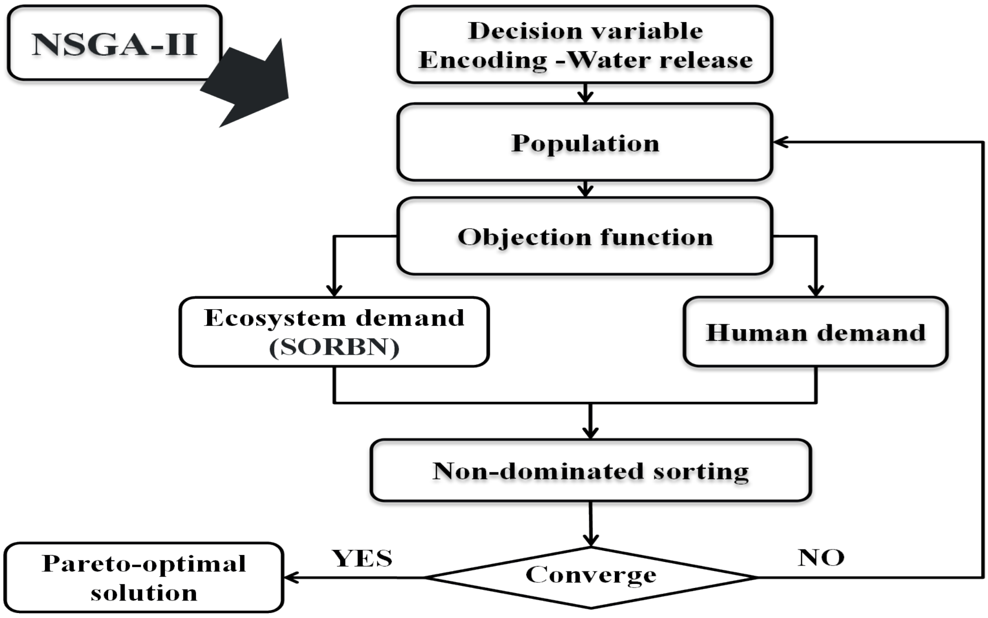

Fig. 2 Flowchart of this study.

Objective function

The objectives of human needs include domestic, agricultural, industrial and power generation needs. The objective of ecosystem needs is the fish biodiversity, which is estimated by the SORBN based on the TEIS statistics. The Pareto set of the target effective storage can be determined by the trade-offs between water shortages associated with human needs and the maintenance of the ecological flow regime. The objective function of human needs (Chang *et al.*, 2010) is designed as follows:

$$Min\left\{\sum_{i=1}^{36}\left[\left(\max(0,\frac{D_i - Rd_i}{D_i})\right)^2 \times n_i\right]\right\} \tag{2}$$

where D_i is the human water needs in the ith 10-day period; Rd_i is the downstream water release in the ith 10-day period; and n_i is a positive constant to enlarge the effect of continuous deficiency and to avoid an occurrence of a continuous deficiency. For matching real world situations, this study adopts the fuzzy programming (Bellman & Zadeh, 1970) to transform the objective function of human needs into a satisfactory value, α, which ranges between 0 and 1, to denote the satisfaction degree of human needs. The objective function of ecosystem needs is designed as follows: *Max Shannon index, estimates by the SORBN.* Figure 3 displays the procedure to obtain the Shannon index by the SORBN.

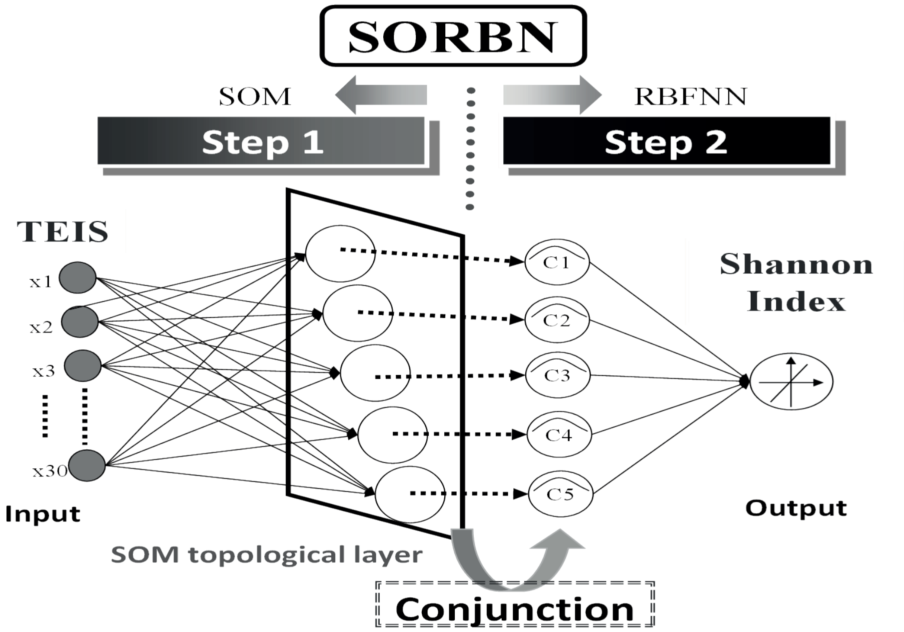

Fig. 3 Shannon index estimated by the SORBN.

RESULTS

SORBN results

In this study, the SORBN is developed to relate flow regime to fish communities. The number of neurons in the SORBN is set as five, and each neuron contains 30 input variables. Figure 4 shows the results of the SOM. It can be easily identified that the trend of Group 1 is separated by season types (dry and wet), where TEIS 2 and TEIS 4 are the statistics of dry seasons and have similar trends. In Group 2, the trend is separated significantly by the event magnitudes. The statistics about the minimum values, TEIS 5-8 and TEIS 12-14, in Group 2 have the highest weights in node 3 and the lowest weights in node 5. However, the statistics about the maximum values, TEIS 9-11 and TEIS 15-18, in Group 2 have the highest weights in node 5. In Group 3, all the statistics have the highest weights in node 3. In Group 4, no significant trend can be identified. There is also one interesting finding from the biodiversity aspect: node 5 has the highest SI with relatively high variance, while node 3 has the lowest SI with low variance. The results represent that the first 18 TEIS statistics dominate the classification of datasets.

Eleven datasets including sampled fishery data associated with TEIS data were used. Due to data scarcity when constructing the SORBN, we implemented the cross-validation technique, where a random process is used for data selection. Of the data, 80% are used for training, and the remaining 20% are used for testing (repeated 50 times). In the SORBN, the Gaussian function is used as a radial basis function to build up a mapping between flow regime and fish diversity. The CC values of the SI are 0.91 in the training set and 0.65 in the testing set, respectively. The results in this analysis demonstrate that the SORBN can estimate the fish diversity based on TEIS in practice.

NSGA-II results

In this study, the NSGA-II with a population size of 1000 is used to solve this multi-objective reservoir operation. Figure 5 shows the Pareto front solutions, where ecosystem needs and human needs are well distributed along the Pareto front. The solutions close to A indicate that the effective reservoir storage of each 10-day period can produce more suitable flow regimes to achieve the maximum fish biodiversity. The solutions close to B indicate that the effective reservoir storage of each 10-day period can reduce the number of 10-day periods experiencing water shortage. We notice that there are compromise solutions between human and ecosystem needs, where the diversity of an ecosystem can be retained in high SI values (1.7–1.9) while the human demand can also be highly satisfied (α higher than 0.85) The tradeoff information can be useful in making a sound decision for alternative options.

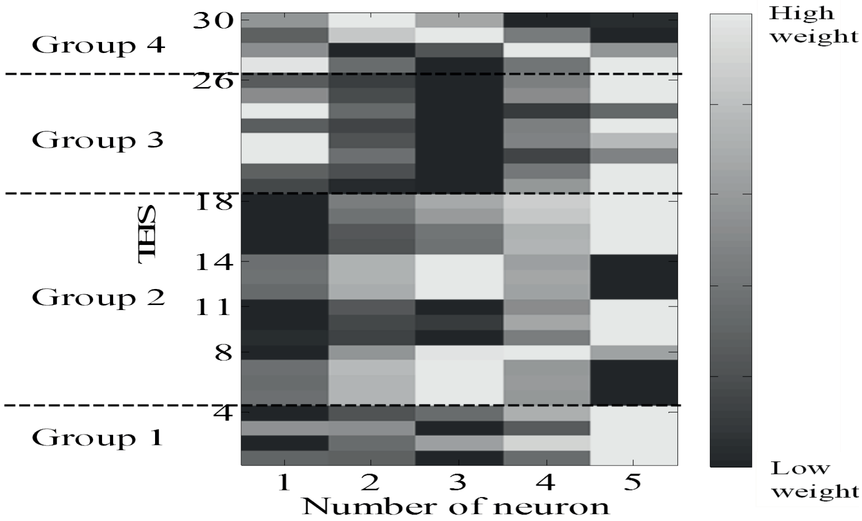

Fig. 4 Topological structure of the SOM.

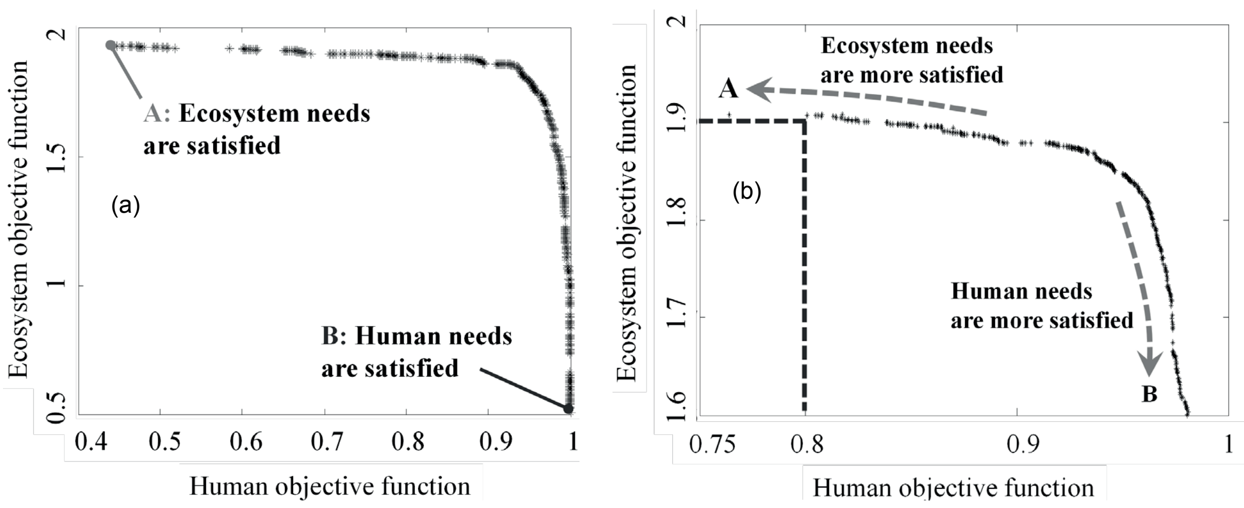

Fig. 5 Pareto front for ecosystem and human objective functions obtained from the NSGA-II (a) Overall, (b) Enlarged compromise part.

CONCLUSION

This study presents a flow regime management method that considers ecosystem and human needs for multi-objective water resources management. The objective of ecosystem needs is to maximize the biodiversity estimated based on flow regimes. In the topological map of the SOM, the first 18

TEIS statistics can directly distinguish their characteristics according to the dry/wet seasons or event magnitudes. In the estimation process, the SORBN suitably estimates the fish biodiversity based on the flow regime in a complex river ecosystem. The results indicate that the SORBN not only can effectively classify flow data but also reasonably identify the relationship between flow regime and fish communities.

The NSGA-II has great capability in handling multi-purpose water resources management problems. By using this optimization technique, the proposed model assists decision makers in searching the Pareto optimal frontier between ecosystem and human needs. The proposed model enables water managers to identify suitable reservoir operation rules that make an acceptable water balance between human and ecosystem needs. According to the results of the NGSA-II, it is possible to satisfy human and ecosystem needs at the same time, where the diversity of an ecosystem can be retained in high SI values (1.7–1.9) while the human demand can also be highly satisfied (α higher than 0.85). This analysis provides practical alternatives on flow regime management for promoting fish diversity and insignificantly reducing human satisfaction. In summary, the proposed method combined with the NSGA-II and the SORBN can provide a meaningful tool to suggest the optimal reservoir operation in balancing ecosystem and human needs for water resources management and river restoration.

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