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Adaptation of Dams and Reservoirs to Climate Change and Environmental Flows

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Abstract

Dams and Reservoirs (D&R) are vulnerable to climate hazards; thus, they need to be adapted to climate change. In this adaptation procedure D&R systems are broken into components, the impacts of the climate hazards on each component are determined, the vulnerable components whose risks are high are identified, and adaptation measures are proposed to reduce these risks. One of the most important components of D&R systems is the environmental flow (E-FLOW). In the literature, there exist more than 200 methods for assessing E-FLOW that can be categorized as hydrological, hydrodynamic habitat modelling (HHM), and holistic methods combining the first two methods. In this work the HHM method is presented using indicative examples and the effects of climate change on E-FLOW are briefly discussed.

1. INTRODUCTION

Dams and Reservoirs (D&R) are essential water infrastructure systems that serve multiple purposes, such as water storage, flood control, hydroelectric power generation, irrigation, and recreation. During their long history D&R systems suffered from hundreds of failures that caused severe and often catastrophic consequences, such as loss of life, injuries, and damage to infrastructure. The mechanisms of these failures can be accelerated by climate change and climate hazards, the most important of which can be categorized into three groups that are: (1) mean air temperature increase and extreme heat; (2) mean precipitation decrease, aridity and droughts; and (3) extreme precipitation and flooding (Stamou et al. 2025). The effects of climate change on D&R systems are usually assessed via a Climate Risk and Vulnerability Assessment. According to one of these methodologies (Stamou et al. 2024), which is based on literature and the EC guidelines technical guidelines on climate-proofing infrastructure, D&R systems are broken into components, the impacts of the climate hazards on each component are determined, the vulnerable components whose risks are high are identified, and adaptation measures are proposed to reduce these risks. The main components of D&R systems can be categorized into five groups: (1) inflows, (2) functions (storage, flood control, hydropower, and recreation), (3) assets (embankment, spillway, auxiliaries, and buildings), (4) outflows (water supply, hydropower production, and environmental flow), and (5) supporting infrastructure (power supply, communications, transportation, and personnel). One of the most important components of D&R systems is the environmental flow (E-FLOW) that is the flow regime necessary to maintain river ecosystems. In the literature, there exist more than 200 methods for assessing E-FLOW that can be categorized as: (1) hydrological, (2) hydrodynamic habitat modelling (HHM), and (3) holistic methods combining the first two methods; HHM involves a hydrodynamic model and a habitat model for the species of interest. In the last ten years research has been performed in the NTUA on the determination of E-FLOW using HHM; this research, which was initiated in the Technical University of Munich (Prof. Peter Rutschman) and continued within a TUM-NTUA cooperation, resulted in a significant number of publications that described various versions and applications of the HMM method for assessing E-FLOW. In this work the main steps of the HHM method are presented using indicative examples and the effects of climate change on E-FLOW are briefly discussed.

2. METHODOLOGY

The main steps of the HMM method to assess E-FLOW the following:

1. Determination of the river reach and the species of interest, and the environmental parameters (or conditions) that affect E-FLOW. Usually, the river reach is located downstream of the technical work that interrupts river continuity, i.e. the D&R system, while the environmental parameters include hydraulic characteristics, such as flow velocity (V) and water depth (D); however, they may also include water temperature (T), conductivity (C), pH, substrate type (S), and concentrations of water quality parameters, such as dissolved oxygen (DO).
2. Construction of the 3D geometry of the river reach (usually via a topographic survey) that is used as input in the hydrodynamic model.
3. Performance of field measurements for water depths and flow velocities, at various sections of the river reach, which are used for: (i) the development of the stage – discharge (rating) curves, and (ii) the calibration and validation of the hydrodynamic model.
4. Selection, formulation, calibration, and verification of the hydrodynamic model. Typically, a 2D hydrodynamic model is selected, such as TELEMAC-2D or RIVER2D, that determines V and D; then the model is formulated using the 3D geometry of the reach (see 2), calibrated to determine the values of roughness coefficient and verified using the hydrodynamic data (see 3).
5. Development of the habitat model that is virtually the Habitat Suitability Curves (HSCs); these are constructed based on collected microhabitat data in the river reach. HSCs quantify the suitability of the hydraulic conditions (i.e. V and D), which is typically expressed as Suitability Index (SI_D for D and SI_V for V) and measured on a scale from 0 (unsuitable) to 1 (optimal). In Fig. 1 the HSCs for small and large chub are shown for D and V, respectively (Stamou et al. 2018).
6. Application of the HMM that involves the application of the hydrodynamic and the habitat model to calculate the 2D distributions of V, D, SI_D and SI_V, and the Weighted Useable Area (WUA) for various values of discharges (Q); WUA is an indicator of habitat quality and quantity equal to the sum of the areas weighed by the inferred suitability within the entire domain of the hydrodynamic model. In Fig. 2 indicative WUA-Q curves are shown for the small and the large chub, expressed in m^2 (left) and m^2/1000 m length of river (right).

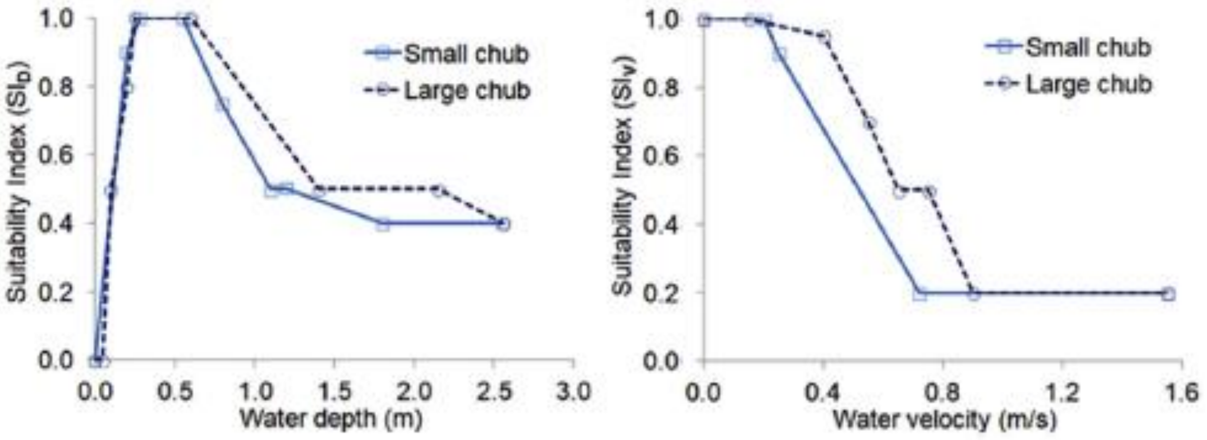

Fig. 1. Indicative HSCs for D and V (Stamou et al. 2018).

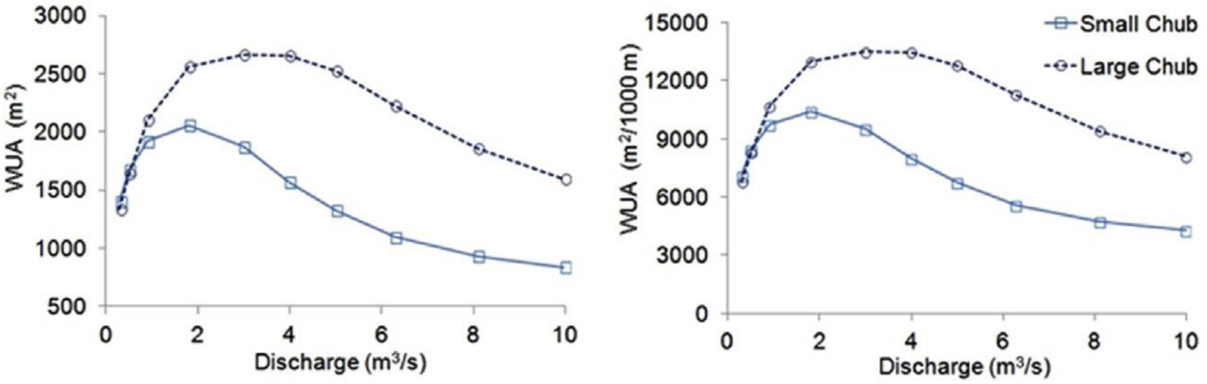

Fig. 2. Indicative WUA-Q curve (Stamou et al. 2018).

3. DISCUSSION AND CONCLUSIONS

Figure 2 indicates that the optimum range of E-FLOW is 2–4 m^3/s for large chub and 1–3 m^3/s for small chub, i.e. E-FLOW is ideally in the range 2–3 m^3/s; higher or lower discharges are expected to have a negative impact on suitable habitat availability. Climate hazards may affect E-FLOW. For example, mean air temperature increase and extreme heat increase T, decrease DO, and increase the pollution of the reservoir, while mean precipitation decrease, aridity, and droughts increase the concentrations of pollutants and sediments in the reservoir; thus, both groups of hazards reduce the water quality of the reservoir and thus of the downstream flow, increase the demand for higher E-FLOW that creates management conflicts for multi-purpose reservoirs. Extreme precipitation and flooding increase the downstream flow, create flooding and pollution, and deterioration of S. These effects on the E-FLOW can be taken into account via including in the HHM the relevant environmental parameters, such as T, DO, and S.

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