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MASTER THESIS

Ecohydraulic field-based measurements and simulations in two unexplored North African rivers

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«ΕΠΙΣΤΗΜΗ &
ΤΕΧΝΟΛΟΓΙΑ
ΥΔΑΤΙΚΩΝ
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ΕΘΝΙΚΟ ΜΕΤΣΟΒΙΟ ΠΟΛΥΤΕΧΝΕΙΟ

ΔΙΕΠΙΣΤΗΜΟΝΙΚΟ – ΔΙΑΤΜΗΜΑΤΙΚΟ
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«ΕΠΙΣΤΗΜΗ & ΤΕΧΝΟΛΟΓΙΑ ΥΔΑΤΙΚΩΝ ΠΟΡΩΝ»

ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

Οικοϋδραυλική μελέτη πεδίου και προσομοίωση δύο ανεξερεύνητων ποταμών της Βορείου Αφρικής

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جامعة أثينا التقنية الوطنية

برنامج الدراسات العليا المتعدد التخصصات والأقسام

"علوم وتكنولوجيا موارد المياه"

رسالة الماجستير

قياسات ومحاكاة ميدانية إيكوهيدروليكية في نهرين غير مستكشفين في شمال إفريقيا

جورجيوس فاجيناس (Georgios Vagenas)
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Foreword

The present study was implemented in the framework of my Master Research thesis under the academic and research collaboration-supervision of the National Technical University of Athens (Greece), the Hellenic Centre for Marine Research (Greece), the Cadi Ayyad University and the Museum of Natural History of Marrakech (Morocco). My Master studies were financially supported by the academic scholarship (no. 1788) of the Bodossaki Foundation, which I was grateful to accept and receive.

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Abstract (English)

Freshwater ecosystems are considered as one of the most vulnerable types of aquatic systems facing several natural and anthropogenic threats such as pollution, irrigation pressures and flow modification (e.g., dam constructions). These threats are more impactful in semi-arid and arid regions that are heavily impacted by climate change, with phenomena such as drought and desertification, there is a demanding need for research, in order to facilitate advanced biological and hydraulic simulation models to effectively estimate the potential impact of severe stressors. In the present work, we carried out ecohydraulic field measurements and simulations in two unexplored rivers (Oum Er Rbia; Ziz) located in central and east Morocco (North Africa). Initially, we collected field-based data through hydraulic and biological river sampling (benthic macroinvertebrates; BMs) upstream of a major dam in each river. As a result, region-specific Habitat Suitability Curves (HSCs) were produced through dedicated fitting algorithms based on the aquatic preferences of organisms. Afterwards, several ecohydraulic simulations were performed using real-time topographic/hydraulic field data in order to identify the optimal ecological and environmental flow for the examined aquatic biota in both regions. Finally, we proceeded with a comparative analysis between the produced HSCs and the ecohydraulic patterns of both sites, along with comparisons with research works applied in other Mediterranean regions.

Keywords: Ecohydraulics, North Africa, habitat suitability, Drought, environmental flow, RIVER2D

Abstract (Ελληνικά)

Τα οικοσυστήματα εσωτερικών υδάτων χαρακτηρίζονται ως ένας από του πιο ευάλωτους τύπους υδατικών συστημάτων, τα οποία αντιμετωπίζουν ένα πλήθος φυσικών και ανθρωπογενών πιέσεων όπως φαινόμενα ρύπανσης, πιέσεις άντλησης καθώς και τροποίηση της ροής από κατασκευαστικές επεμβάσεις (π.χ. φράγματα). Ειδικότερα σε υδατικά σώματα που βρίσκονται σε ζώνες με ημι-ξηρό και ξηρό κλιματικό χαρακτήρα, οι οποίες επηρεάζονται αρνητικά από κλιματικές πιέσεις, καθιστούν τις ζώνες αυτές ως κρίσιμες περιοχές μελέτης. Ένας από τους κύριους στόχους έρευνας είναι η εφαρμογή εξειδικευμένων οικολογικών και υδραυλικών προσομοιώσεων ώστε να εκτιμήθουν αποτελεσματικά οι δυνητικές επιπτώσεις των περιβαλλοντικών πιέσεων. Η παρούσα εργασία έχει ως στόχο την συλλογή και εφαρμογή οικοϋδραυλικών δεδομένων και προσομοιώσεων, αντίστοιχα, σε δυο ανεξερεύνητους ποταμούς (Oum Er Rbia; Ziz) στο κεντρικό και ανατολικό Μαρόκο (Βόρεια Αφρική). Αρχικά, συλλέγχθηκαν πρωτογενή δεδομένα βιολογικού (βενθικά μακροασπόνδυλα) και υδραυλικού τύπου, ανάντη από δύο κύρια φράγματα κάθε ποταμού. Έπειτα, δημιουργήθηκαν καμπύλες καταλληλότητας ενδιαιτημάτων (HSCs) με τη χρήση ειδικών αλγορίθμων προσαρμογής σχετικά με τα δεδομένα περιβαλλοντικής προσαρμογής των οργανισμών. Στη συνέχεια, εφαρμόστηκαν πολλαπλές οικοϋδραυλικές προσομοιώσεις, αξιοποιώντας δεδομένα τοπογραφίας και υδραυλικών μετρήσεων πραγματικού χρόνου με στόχο τον υπολογισμό της βέλτισης οικολογικής και περιβαλλοντικής παροχής των υπό μελέτη οργανισμών. Τέλος, έλαβε χώρα η συγκριτική ανάλυση των παραγόμενων καμπυλών καταλληλότητας και των οικοϋδραυλικών προτύπων για τις δύο περιοχές καθώς και συγκρίσεις με άλλες αντίστοιχες έρευνες σε διαφορετικές κλιματικές ζώνες (π.χ. Μεσόγειος).

Λέξεις κλειδιά: Οικοϋδραυλική, Βόρεια Αφρική, καταλληλότητα ενδιαιτήματος, ξηρασία, περιβαλλοντική παροχή, RIVER2D

Abstract (العربية)

تعتبر النظم الإيكولوجية للمياه العذبة واحدة من أكثر أنواع النظم الإيكولوجية المائية ضعفًا حيث تواجه العديد من التهديدات الطبيعية والبشرية الأصل مثل أحداث التلوث وضغوط الري وتعديل التدفق (إنشاء السدود على سبيل المثال). ولهذه التهديدات تأثير أكبر في المناطق شبه القاحلة والقاحلة التي تتأثر بشدة بالتغيرات المناخية ويتمثل ذلك في ظواهر مثل التصحر. لذلك، هناك حاجة ماسة إلى إجراء بحوث، من أجل تيسير وضع نماذج محاكاة بيولوجية وهيدروليكية متقدمة لتقدير الأثر المحتمل للضغوط البيئية بشكل فعال. في العمل الحالي، أجرينا قياسات ومحاكاة ميدانية إيكوهيدروليكية في نهرين غير مستكشفين (أم الربيع، زيز) الذين يقعان في وسط وشرق المغرب (شمال إفريقيا). في البداية، جمعنا بيانات ميدانية من خلال أخذ عينات نهرية هيدروليكية في أعلى مجرى السد الرائد في كل نهر. ونتيجة لذلك، تم إنتاج منحنيات ملاءمة (BMs اللافقاريات القاعية الكبيرة) وبيولوجية الخاصة بالمنطقة من خلال خوارزميات ملائمة مخصصة بناءً على التفضيلات المائية للكائنات الحية. بعد (HSCs) الموائل / ذلك، تم إجراء العديد من عمليات المحاكاة الإيكولوجية الهيدروليكية من خلال استخدام البيانات الميدانية الطبوغرافية .الهيدروليكية في الوقت الحقيقي من أجل تحديد التفريغ البيئي الأمثل للكائنات الحية المائية التي تم فحصها في كلا المنطقتين المنتجة والأنماط اليكوهيدروليكية، إلى جانب مقارنات مع الأعمال البحثية المطبقة HSCs أخيرًا، شرعنا في تحليل مقارن بين .في مناطق أخرى من حوض البحر الأبيض المتوسط

Extended abstract

The ecological concepts of "*habitat*" and "*niche*" have been thoroughly investigated by biologists and environmental scientists for the determination of the organisms' environmental preferences. In the case of aquatic ecosystems, the integration of both biotic (e.g., inter/intraspecific competition, food availability) and abiotic (e.g., flow, depth, temperature) parameters resulted in a holistic, multidimensional approach defined as the "*ecotope hypervolume*". In conjunction with novel engineering tools, such as the application of hydrodynamic habitat models (HHMs), the scientific field of ecohydraulics emerged and has been constantly developed since the middle of the previous century. Through the implementation of ecohydraulic models, the scientific and engineering community has been able to examine alternations and distributional shifts into aquatic ecosystems due to nature or human-related pressures, either for research or operational purposes. The essential input data for the so called HHMs is related to habitat preference of certain aquatic taxa (e.g., plants, insects, fish). Among the variety of all the taxa, freshwater benthic macroinvertebrates (BMs) function as one of the most efficient alternatives due to the fact that BMs are relatively stationary, environmental sensitive organisms characterized with immense biodiversity. As it was mentioned, multiple factors can affect the distribution of BMs due to their ecohydraulic response. To this end, we used BMs of two unexplored, in terms of their ecohydraulic properties, North African rivers as the case studies of our research by enabling both natural and anthropogenic stressors (i.e., dams & regions sensitive to desertification-drought events).

Initially, we sampled in-situ biological material and collected hydraulic data upstream (reference region) of the Al Hassan Addakhil (Ziz river; arid climate region) and the Al Massira (Oum Er Rbia river; semi-arid climate region) in central and east Morocco, respectively. Moreover, we collected hydraulic and topographic information downstream of the two case studies. Subsequently, we applied the GAMLSS algorithm to construct, to the best of our knowledge, the first habitat suitability curves (HSCs) for aquatic organisms in North Africa. More specifically, we applied two alternative formulas (standardized; normalized) of the generic habitat suitability index (HSI). Through the utilization of the GAMLSS algorithm we examined the relationship between the HSI and flow velocity, depth, substrate type, pH and conductivity. Additionally, we compared the produced HSCs between the semi-arid and the arid aquatic rivers, along with HSCs derived from BMs in Mediterranean systems. Afterwards, we compiled the HSCs and the downstream hydraulic/topographic data into a two-dimensional ecohydraulic simulation, operated in the

computational environment of RIVER2D. As a final step, we calibrated (i.e., overlap between observed and predicted outputs) the ecohydraulic model in order to assess the optimal ecological and the environmental flow.

The results exhibited that the standardized suitability index was the statistically dominant formula during the GAMLSS modelling. The relationships showed that there was a statistically and significant relationship between the habitat suitability index and depth-velocity, a common finding with relevant studies. The HSCs patterns revealed that BMs from the arid region demonstrated a more tolerant profile regarding the environmental adaption, compared to the semi-arid region. The comparison between the Mediterranean and the semi-arid HSCs resulted in a rather different pattern, thus highlighting the need for regional-specific field-based habitat curves. According to the analyses, riverine sites with relatively fast-flow sites facilitate environmental conditions that favor the presence of BMs due to the adequate energy supply and increased water purification rates. The ecohydraulic simulations showed that the optimal ecological flow downstream of the two case studies was estimated at 2 m^3s^{-1}. Even though the optimal flow estimation was equivalent in the Ziz and Oum Er Rbia river, the relationship of the overall suitability index (OSI) and the discharge simulation was rather different. In specific, the ecohydraulic simulation of the Oum Er Rbia (semi-arid region) exhibited a rapid decline of suitability after a certain threshold of discharge values while in the case of Ziz (arid region) there was a relatively stable and gradual reduction of suitability towards higher discharge simulation scenarios. This anticipated dissimilarity can be attributed to the different environmental tolerance of the BMs expressed by the aforementioned HSCs, a fact which enforces the hypothesis that more tolerant and resistant biota, with larger range of adaptivity are dominant in stressed systems (i.e., arid systems: low depth and flow-dependent BMs). Finally, the environmental flow has been suggested as 1 m^3s^{-1} as a minimum outflow that would favor both human activities, freshwater BM communities and ultimately, the conservation and management of life downstream of both dams.

In conclusion, the selected case studies located in the North African region are among the most water stressed aquatic systems globally due to the severe anthropogenic and climatic pressures that are facing. As it was previously mentioned, the results of the present work represent the first ecohydraulic output in the region and thus, can be used as reference baseline data for the implementation of operational-based simulations targeted to mitigate environmental pressures through the establishment of management strategies.

1. Introduction

1.1. Ecological baseline

Since the beginning of the 20th century, ecologists have been thoroughly investigating the role of organisms and their subsequent biological communities in terrestrial and aquatic ecosystems. The term "*niche*" has been initially proposed by Johnson (1910) as a concept where several species are located in a common spatial unit. In addition, Clarke (1954) refined the term by highlighting the significance of the functional role (i.e., "*functional niche*") of species rather than their actual presence in space (i.e., "*place niche*"). Eventually, Hutchinson (1957) supported that the "*niche*", as an environmental space, integrates different individuals/species which utilize the available resources in order to survive, reproduce and sustain their populations. Given the fact that the "*niche*" describes the role of a species in an ecosystem, the term "*habitat*" has been attributed to the fundamental distributional unit in which species are dominated by structural and functional limitations (Grinnell, 1924). In conjunction, the combination between the previously mentioned "*niche*", "*habitat*" and the commonly used "*population measurement*" comprise a three-dimensional "*ecotope hypervolume"* in a manner to describe the response of the species against the environmental conditions and constraints (Fig. 1; Whittaker et al. 1973). In a sense, this "*ecotope*" is structured by the interaction of abiotic variables onto the biotic elements of an ecosystem, and vice-versa.

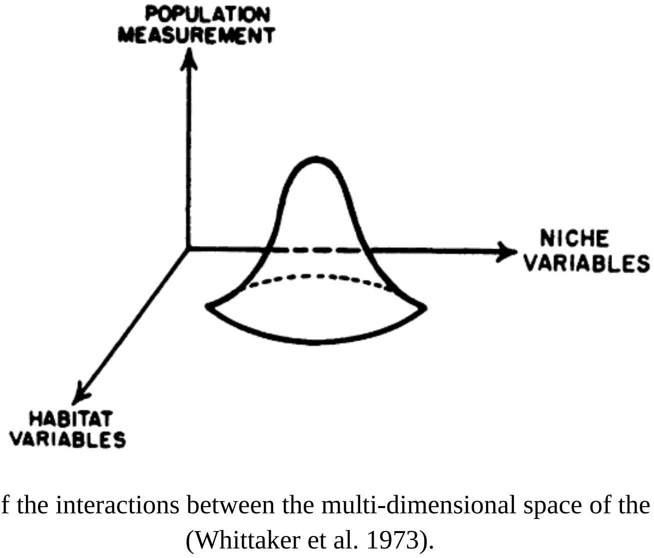

Figure 1. Representation of the interactions between the multi-dimensional space of the "*ecotope hypervolume*" (Whittaker et al. 1973).

Freshwater ecosystems have been described as one the most vulnerable types of aquatic habitats, as they are open systems that can be heavily affected by the transfer of energy, matter and solutes (i.e., pollutants) from adjacent regions (Angeler et al. 2014; Reid et al. 2020). At the same time, freshwater fishes are characterized by immense diversity (Tedesco et al. 2017), while their global distribution is a response to riverine alternations (Leveque et al. 2007). Correspondingly, benthic macroinvertebrates (BMs), as relatively stationary organisms, are considered as an excellent biological indicator since their diversity and distribution is, at a great extent, related to environmental changes (Kemp et al. 2000, Shearer et al. 2015, Theodoropoulos et al. 2018a). Both aquatic taxa are highly significant for the needs of a holistic ecological representation of a riverine system since ecological flow dynamics (i.e., energy and matter flow transferred through streams) can be explained by the abiotic gradients (Fig. 2; *river continuum concept*, Vannote et al. 1980) and the predator-prey biotic interactions between the species, which can synergistically affect the ecological state of an aquatic ecosystem (e.g., Jeppesen et al. 1997, 2000; Gibert 2019). Hence, trophic dynamics can affect vegetation cover, disease, erosion, biochemical and hydrological cycles (Estes et al. 2011).

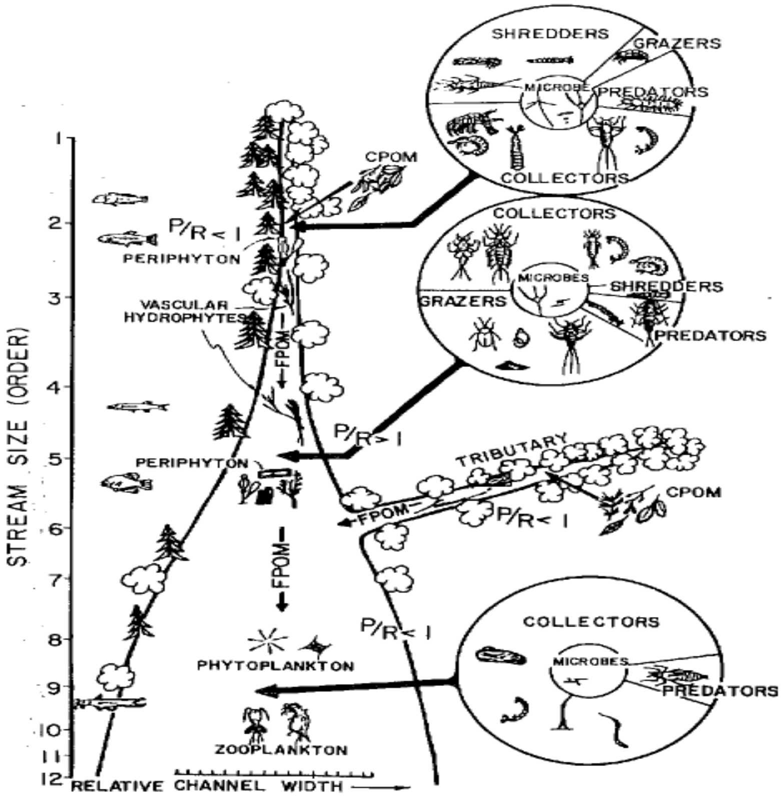

Figure 2. The *river continuum concept* (RCC) on the relationship between environmental gradients, the structure and functionality of ecological interactions within a riverine system (Vannote et al. 1980).

1.2. Hydrodynamic Habitat Models (HHMs)

Among the various environmental parameters, flow variability is a crucial determinant for the distribution, abundance and diversity of the aquatic communities in riverine ecosystems (Allan, 1995). In case of a significant alternation or discrepancy of the flow regime, the disordered aquatic equilibrium can affect aquatic ecosystems by causing negative morphological and functional changes (Suen & Eheart, 2006). Thus, the concept of the estimation of environmental flow has been proposed, which is defined as the required water discharge (m^3s^{-1}) that can maintain suitable conditions for aquatic species in a river basin (Wang & Lu, 2009). Based on the literature, taxa and/or species-specific environmental flow estimations are applied through hydrodynamic habitat models (HHMs), which are able to determine the ecohydraulic responses of the aquatic biota in a riverine system (see Theodoropoulos et al. 2018a).

The so called HHMs are based on the fundamental technological branch of computational fluid mechanics (CFD), the scientific field of numerical solving fluid motion equations. These three equations are solved either in a one- (1D) or two-dimensional (2D) space through transect or geometric mesh-based discretization methods, respectively (Fig. 3).

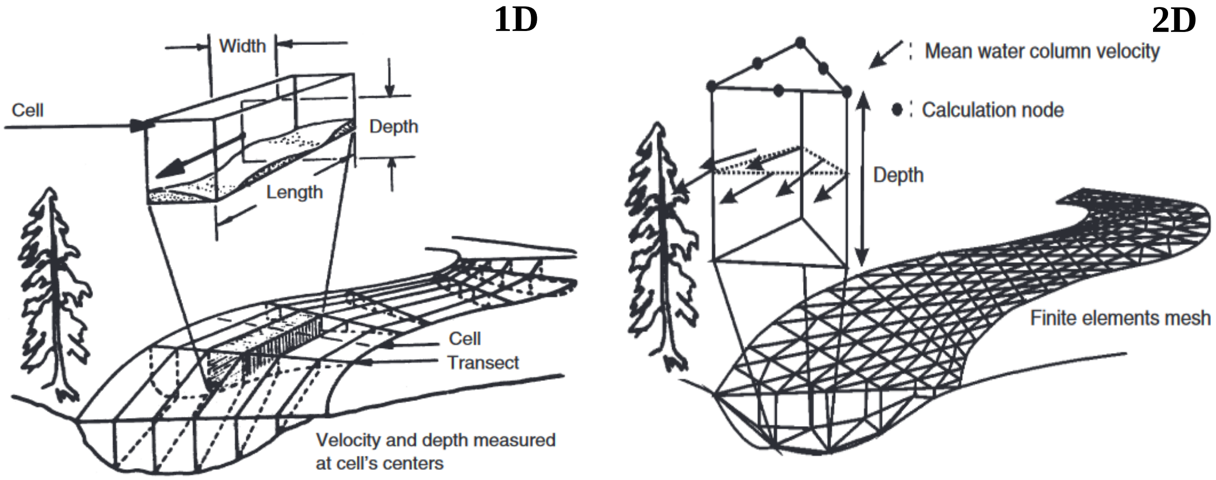

Figure 3. One-dimensional (left) and two-dimensional (right) discretization approaches of a riverine stream (Leclerc, 2005).

The first approach (1D) was first implemented with the launch of the PHABSIM (Physical Habitat Simulation System; Bovee & Milhous, 1978), whereas the hydraulic simulation is applied on rectangular transect cells along the river channel. With the rapid increase of computational power, and thus the advanced capabilities in solving CFD complex systems, 2D hydraulic simulation models emerged with the first being the TELEMAC-MASCARET system (Galland et al. 1991). Afterwards, the River2D was launched as a two-dimensional hydrodynamic model for habitat simulations (Steffler & Blackburn, 2002). Due to the expanded computational capacities, complex physical processes were integrated in the simulations such as:

- Saint-Venant shallow water equations for the determination of the two-dimensional (x,y) depth and flow velocities across a riverine system
- Conservation of mass (or continuity conservation)

As a consequence, spatial and temporal evolution of flow motions in terms of depth and flow velocity could be performed. The mathematical solution of the aforementioned processes is taking place with the conversion of the partial differential equations into sequential algebraic formulas through a computational mesh of nodes (Fig. 4). This step-wise discretization method can be executed through the finite differential, finite element, finite volume and the spectral approach (Hu et al. 2012).

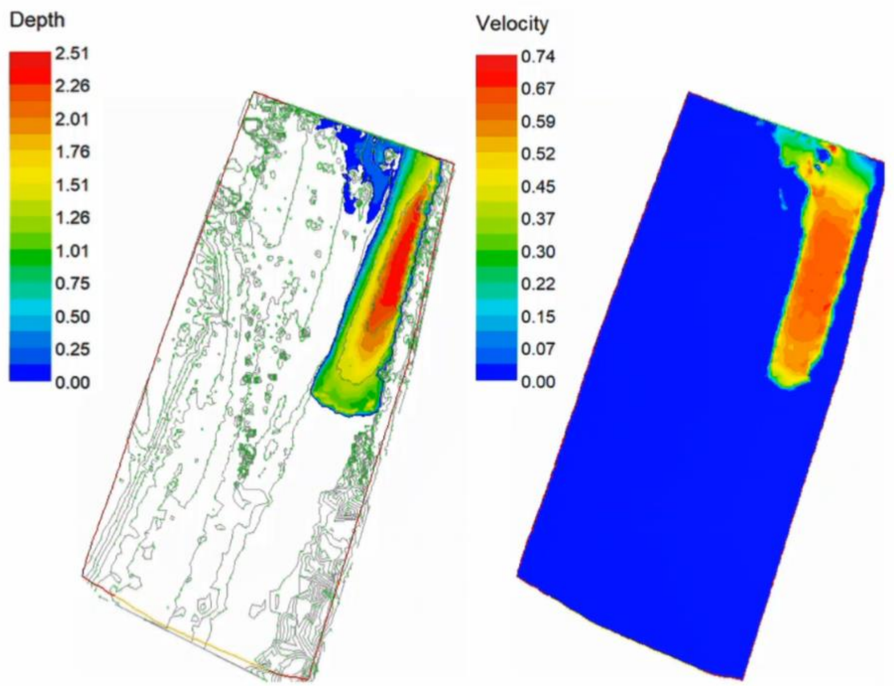

Figure 4. A two-dimensional hydraulic simulation (River2D) of a riverine system providing spatial (x,y) and temporal information on the evolution of the average depth and flow velocity of the river bed.

The major biological component in HHMs are the univariate habitat suitability curves (HSCs) which demonstrate the relationship between the environmental variables and the preference range of each examined taxon/species (Nestler et al. 2019). The HSC scheme was first proposed in the work of Bovee and Cohnauer (1977), where they based their approach on the fact that individuals of species are described with three phases of habitat preferences (Fig. 5):

- Phase I: Decreased probability for the individuals of the taxon/species to be favored
- Phase II: Increased probability for the individuals of the taxon/species to be favored
- Phase III: Maximum (optimal) probability for the individuals of the taxon/species to be favored

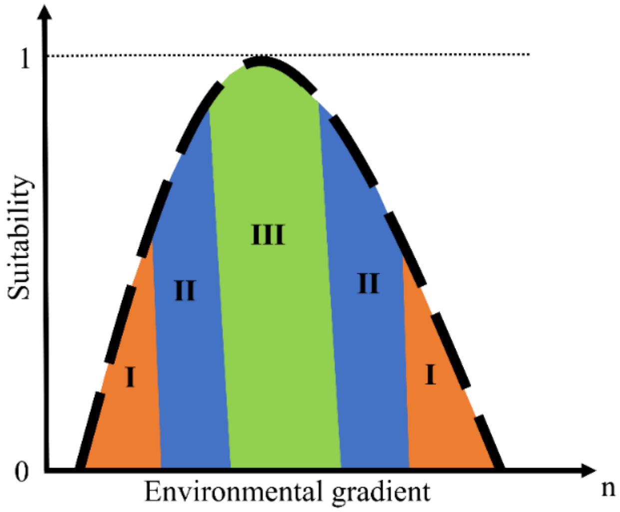

Figure 5. Schematic representation of the three phases (I-II-III) of the habitat suitability curve (HSC) between the observed suitability and the environmental gradient. The dotted line represents the maximum suitability.

The suitability index in the HSCs ranges from 0 (unsuitable) to 1 (highly suitable). In addition, the HSCs are classified into three main categories (Bovee et al. 1998):

- Expert-based curves, derived from the accumulated knowledge through an expert consensus on the habitat use by species
- Habitat utilization curves, derived by field observations on habitat use on each target species life stage
- Habitat preference/suitability curves, derived by actual field-based information on habitat use of a certain aquatic habitat

Even though the latter category represents the most transferable, and scientific defensible type of information, in the comprehensive review of Nestler et al. 2019, it was characterized as the most cost and time-consuming alternative.

1.3. North African arid systems

Desertification is described as the long-term land degradation process towards arid, semi-arid and dry sub-humid areas (i.e., drylands) caused by climatic variability and anthropogenic pressures (Fig. 6; Mizarbaev et al. 2019). A recent report showed that 8% of the size of the European Union has been found to be sensitive or very sensitive to the phenomenon of desertification (ECA, 2018), while north Mediterranean countries have been estimated with a percentage of 33.8% drylands (Safriel, 2009). A more severe pattern is observed in the south Mediterranean region (North Africa), whereas relevant works have demonstrated that in several countries (i.e., Morocco, Tunisia, Egypt) 90% of inhabited regions are considered as sensitive or critical regions to desertification (Rasmy et al. 2010; INES, 2017; Bedoui, 2020). Additionally, drought is another major climatic issue that negatively affects local communities and the vulnerable aquatic systems at a national scale. Specifically, in July 2022 the Moroccan Ministry of Water and Logistics announced that the country is at a "state of water emergency" due to a severe drought that is taking place for the last 30 years.

Figure 6. An example of a typical arid landscape in the region of the Ziz river basin in the Errachidia Province (eastern Morocco) during an ecohydraulic sampling. Field expedition team: Hassan Benaissa, Soumia Mouataouakil, Yassine Fendane, Georgios Vagenas.

North Africa represents a region where experimental studies can obtain significant results regarding extreme hydrobiological adaptions of organisms. Morocco is located on the western side of the Maghreb region and is characterized by a wide range of climatic types and biodiversity. In view of the fact that Morocco is among the countries which are highly affected by environmental fluctuations, specific actions should take place to establish mitigation strategies. A relevant promising note is that the committee of the Climate Change Performance Index 2021, an independent organization that monitors climate mitigation efforts, ranked the country with the fourth-highest national performance at a global scale (CCPI, 2021). Henceforth, Morocco demonstrates one of the most suitable national case-studies, whereas basic and operational hydrobiological field research should be established that can be used for environmental conversation practices.

Climatic fluctuations and land degradation intensify the phenomenon of desertification and pose a constant stress to aquatic ecosystems. Furthermore, freshwater organisms possess several biological adaptions, to overcome extreme habitat conditions, such as temperature/chemical resiliency, migratory behavior and opportunistic strategies (Milton & Dean, 2004). Thus, the combination of biotic and abiotic (e.g., species abundance; HHMs) field-based and simulation data, are considered as essential for the investigation of potential biological responses under habitat degradation conditions in extreme aquatic (i.e., highly arid) ecosystems, and can provide a tool for ecosystem management.

1.4. Aim of the study

We focused on the construction of, to the best of our knowledge, the first HSCs for aquatic biota (i.e., benthic macroinvertebrates) and ecohydraulic simulations based on microhabitats in North Africa, respectively. The regional cases studies were the upstream and downstream sites of the Oum Er Rbia (Al Massira, Settat region) and the Ziz river (Al Hassan Addakhil dam, Errachidia region). As a result, we estimated the required optimal ecological and environmental flow for benthic macroinvertebrates in a semi-arid and arid aquatic ecosystem, respectively. Finally, we proceeded in the comparison of Mediterranean and North African HSCs to evaluate whether the biological output can be extrapolated in different climate zones for ecohydraulic simulations and we discussed the outputs of our work in comparison with relevant studies in the field.

2. Materials and Methods

2.1. Sampling procedure

2.1.1. Study area

The selected case studies were carried out in central and eastern Morocco (Fig. 7A). Two sites of no or very minor anthropogenic pressures, above the Al Massira dam (A1; Oum Er Rbia river; Fig. 7B) and the Al Hassan Addakhil dam (B1; Ziz river; Fig. 7C), were selected as reference (control) sites. The A1 and B1 sites are located 4 km and 6 km upstream of the Al Massira and Al Hassan Addakhil dam, respectively. Two sampling sites, downstream of each dam (A2, 4 km below the Al Massira dam; B2, 10 km below the Al Hassan Addakhil dam), were used for topographic and hydraulic measurements.

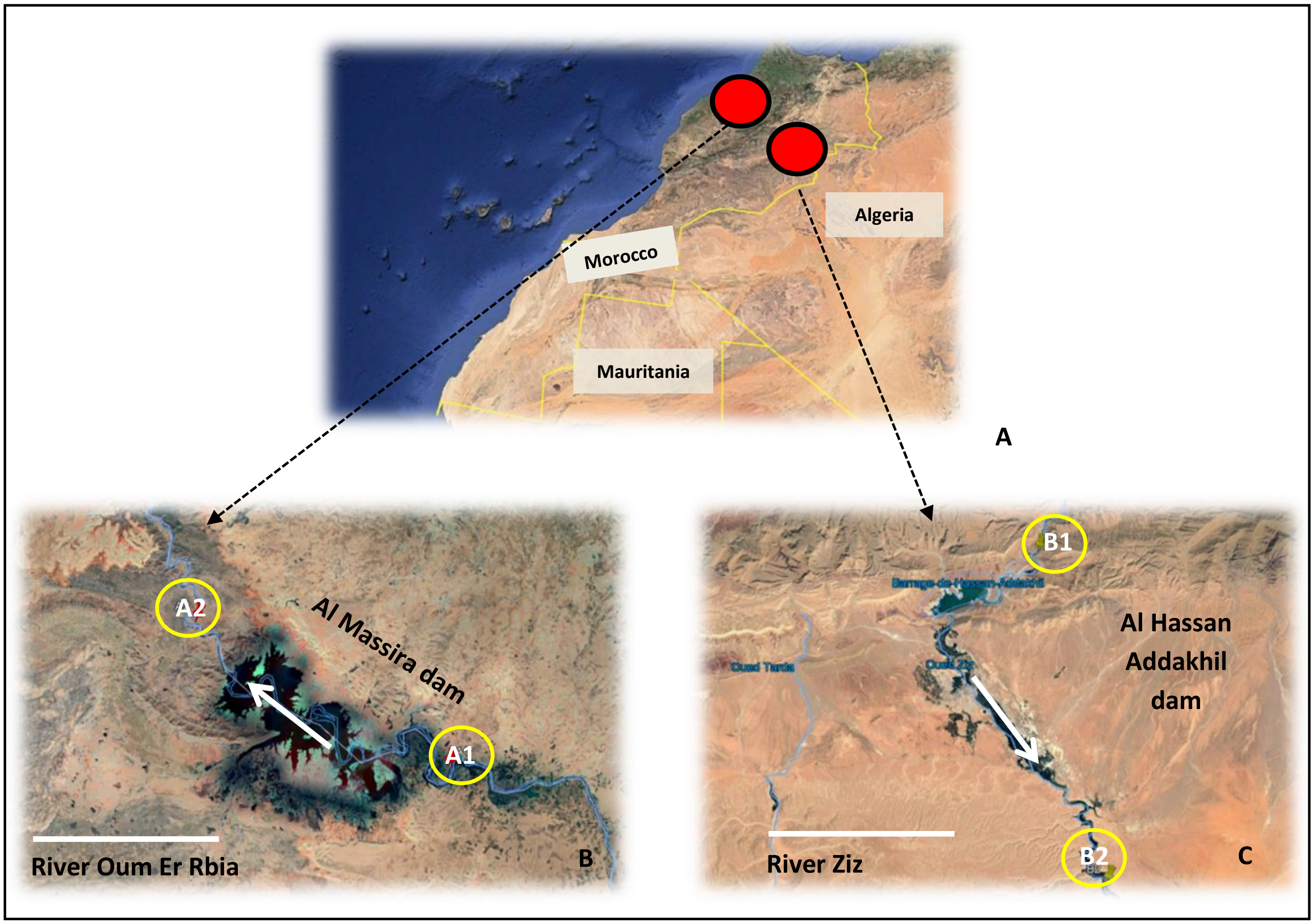

Figure 7. The Moroccan sampling regions in the Al Massira (bottom left; A) and in Al Hassan Addakhil (bottom right; C) dams located in the Moroccan mainland.

2.1.1.A. Ziz River, Al Hassan Addakhil Dam

The Al Hassan Addakhil dam was built in 1971 in the main course of the Ziz river, north of the city of Errachidia (Fig. 8; Appendix III). It has a total capacity of 347 million cubic meters and is one of the oldest dams in Morocco (Salem et al. 2011; Clavero et al. 2017). Ziz river directs its water flow 282 km from the High Atlas southwards to the Sahara Desert into Algeria, thus the regional climate is described as continental and arid (Salem et al. 2011). During the dry period, several patches of the river have reduced connectivity and aquatic life is supported mainly by regional pools. The annual rainfall ranges from 290 mm in the north (Imilchil; High Atlas) to 70 mm in the extreme south at Erfoud (i.e., Sahara Desert). There is a large fluctuation in daily temperature, recorded from 5°C to 40°C, with an annual average daytime high of 20°C (Salem et al. 2011).

Figure 8. Al-Hassan Addakhil dam (A; Drâa-Tafilalet region) located in the middle area of Ziz River (B). Photo derived by A: Vagenas G. (2022); B: [Link].

2.1.1.B. Oum Er Rbia River, Al Massira Dam

Al Massira dam is located in central-west Morocco, is operating since 1979 and has a capacity of 2.5 billion cubic meters (Fig. 9; Appendix III). It is described as the second national largest artificial reservoir, established in the middle part of the Oum Er Rbia, the nation's longest perennial river (Darwall et al. 2014; Bousseba et al. 2020). The river sources originate from the Middle Atlas Mountains area at 1800 m altitude and flow until the coasts of the Atlantic Ocean at the proximity of the Azemmour city (Souilmi et al. 2021). The region where the dam is located, at 275m altitude, is described with a semi-arid to arid climatic profile. The dam is used for energy production, land irrigation, domestic/industrial water supply and fisheries, along with ecological purposes for the organisms inhabiting the region (Darwall et al. 2014; Bousseba et al. 2020). The Oum Er Rbia river basin is characterized by an ongoing gradual drying, since the average annual precipitation demonstrates approximately 2 to 7.9 mm decrease per year, while historical observations (1950-1970 vs 1980-2000) showed a mean annual precipitation decline of 180 mm (Zerouali, 2009).

Figure 9. Al Massira dam (A; Settat region), the 2nd largest Moroccan reservoir part of the national longest permanent Oum Er Rbia river (B). Photo derived by A: [Link] & B: Vagenas G. (2022).

2.1.2. Biota sampling – Microhabitat approach (upstream)

Benthic macroinvertebrates (BMs) sampling was performed using a 0.25 m x 0.25 m sampler with a mesh size of 500 μm during November-December 2021 (i.e., late dry period) in Ziz and Oum Er Rbia river (see Chapter 2.1.1.). Concurrently, we collected information regarding hydraulic and physicochemical data from 123 microhabitats regarding: velocity (V; m/s), depth (H; m), temperature (T; ^{o}C), conductivity (C; mS/s), pH and substrate type (S). BMs samples were preserved in bottles containing 70% ethanol and were transferred to the laboratory for further analysis. Macroinvertebrates were counted, sorted and identified to the family level for each site in the Natural History Museum of Marrakech, using a stereo-microscope and macroinvertebrate identification guides for the North African region (Tachet et al. 2010).

2.1.3. Topographic data (downstream)

For the needs of the georeferenced data sampling, channel topography was carried out in a ~300-500m long reach transect in the downstream stream (A2 & B2; Fig. 7) of each station for the collection of longitude (X), latitude (Y) and altitude (Z). All the abiotic measurements were used for the calibration procedure of the hydraulic model (Chapter 2.2.2.). The number of points acquired for the topographic display of each case study were more than 10.000 points (0.25 x 0.25m resolution), a number which is adequate for relevant simulations (Stiffler & Blackburn, 2000) by using the following drone unit:

Topographic coverage (Longitude, Latitude, Altitude)

- *GPS integrated drone* [DJI Mavic Pro (SN: 08QUE9M02100VK)]

2.1.4. Hydraulic measurements (upstream & downstream)

In each of the 123 microhabitats the required hydraulic data consisted of flow velocity (V), depth (D), temperature (T), conductivity, pH and the substrate type (S). Temperature, velocity and length measurements took place with the use of the according:

Temperature measurements (^{o}C)

- *A Temperature tester* [Hanna HI98130]

Velocity (m/s) and depth (m) measurements

- *A Small - Mini Current meter for discharge measurements* [OTTC2-1 (SN: 440529)]

- *A calibrated stick*

According to Nolan and Shields (2000), sampling depth (D_s) was estimated as:

$$D_s = \begin{cases} 0.6 \times \mathrm{D}, \mathrm{D} \leq 0.75 \\ or \\ \frac{0.2 \times \mathrm{D} + 0.8 \times \mathrm{D}}{2}, \mathrm{D} > 0.75 \text{ m} \end{cases}$$

At the downstream region, there were four required types of measurements:

1) Collection of topographical information (Chapter 2.1.2.; water surface elevation -H- at the downstream boundary)
2) Measurement of velocity and the respective length of the upper and lower stream boundary cross-section in order to compute the flow discharge (Q; m^3/s) along with some scattered selected cross-sections in the aquatic region as well.
3) Visual-based record of the substrate level types across the studied river section according to the classification proposed by Schneider et al. 2010 (Table 1).
4) Selection of a number of randomly positioned sampling points and measurement of flow velocity (V) and water depth (D) which were used for the calibration of the hydrodynamic model (Theodoropoulos et al. 2018a).

Table 1. Substrate types classification scheme applied during sampling and their subsequent identification code (ID) (Schneider et al. 2010).

Substrate type (Descriptor)	Grain size (mm)	ID
Silt	0.001-0.0625	1
Sand	0.0625-2	2
Small gravel	2-6	3
Medium gravel	6-20	4
Large gravel	20-60	5
Small stones	60-120	6
Large stones	120-200	7
Boulders	>200	8

2.2. Data Analyses

2.2.1. Suitability index

Initially we analyzed our dataset to estimate the habitat suitability index (HSI). The index varies dynamically with the estimated patterns of the imported environmental variables (Yao et al. 2014). In the study of Theodoropoulos et al. 2018a, there was an expansion of the aforementioned approach since they used a multi-metric compilation of biological indices to simulate the presence of macroinvertebrates, downstream of dam construction. For the needs of our work, we applied both the standardized [K_s; Eq. 1-3] and the normalized [K_n; Eq. 2-3] versions of the dimensionless suitability index (SI) as:

$$Ks_i = 0.4n_i + 0.3H_i + 0.2EPT_i + 0.1a_i \text{ [1]}$$

$$Kn_i = 0.4\frac{n_i}{n_{i[max]}} + 0.3\frac{H_i}{H_{i[max]}} + 0.2\frac{EPT_i}{EPT_{i[max]}} + 0.1\frac{a_i}{a_{i[max]}} \text{ [2]}$$

$$K_i = \frac{\sum_{i=1}^{N} K_i}{K_{i[max]}} \text{ [3]}$$

where K_i denotes the habitat suitability of the i^{th} habitat ranging from 0 (unsuitable) to 1 (optimal habitat); n_i is the number of the BMs taxa (families); H_i denotes the Shannon's diversity index; EPT_i is the number of Ephemeroptera-Plecoptera-Trichoptera (EPT) taxa; a_i is the abundance of BMs taxa; N is the total number of the i^{th} habitats. In order to search for statistically significant relationships between the dependent variable (K_i) and the abiotic dataset we used the generalized additive models for location scale and shape algorithm (GAMLSS) by simultaneously excluding random effects induced by abiotic variables.

The indices that were used in order to define the level of significance between the relationships were p-value and the Cox-Snell pseudo-R^2 of each produced model. All analyses were implemented in the non-parametric R package 'Generalized Additive Models for Location, Scale and Shape' (GAMLSS; Rigby & Stasinopoulos, 2005). The GAMLSS-based HSI were displayed into a two-dimensional scale along with a smoother function (i.e., GAM) to detect minor local variations of the data. In cases where GAM smoothing splines were too sensitive in maxima or minima thresholds, we applied the conventional method of 3rd level polynomial function. All the aforementioned analyses and visualizations were performed using the R 4.2.1 free software environment for statistical computing and graphics.

Afterwards, we produced the upstream habitat suitability curves (HSCs) for all the benthic macroinvertebrate families and we calculated the overall Habitat Suitability Index (HSI_o; Eq. 4), the weighted usable area (WUA; Eq. 5) and the overall suitability index (OSI; Eq. 6) with the use of downstream hydraulic and topographic data. Finally, calculated the proportional change (Δ%; Eq. 7) of WUA per each discharge simulation step (WUA_x, WUA_{x+1}; Eq. 8). The equations are described as follows:

$$HSI_o = \sqrt[2]{SI_V * SI_D} \quad [4]$$

$$\text{WUA} = \sum_{i=1}^{M} A_i * HSI_{o\_i} \quad [5]$$

$$\text{OSI} = \frac{\sum_{i=1}^{M} A_i * HSI_{o\_i}}{\sum_{i=1}^{M} A_i} \quad [6]$$

$$\Delta\% = \frac{WUA_{x+1} - WUA_x}{WUA_{x+1}} \quad [7]$$

where A denotes the size area (m^2) at the i^{th} site of region M (total), the SI_V, SI_D represent the suitability index of flow velocity and depth, respectively (Yao et al. 2014).

2.2.2. <u>Ecohydraulic model</u>

The spatial and temporal simulations were operated via the RIVER2D (R2D) model. It represents a two-dimensional model for the hydrodynamic and habitat simulation of a river system. As it is mentioned previously (Chapter 1.2., HHMs), 2D hydraulic models are based on the conservation of mass [Eq. 8] and the two-dimensional conservation of momentum [Eq. 9 & 10; Navier-Stokes] equations:

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = 0 \qquad [8]$$

$$\frac{\partial uh}{\partial t} + \frac{\partial}{\partial x}\left(u^2 h + \frac{1}{2} g h^2\right) + \frac{\partial uvh}{\partial y} - gh(S_{0x} - S_{fx}) = 0 \qquad [9]$$

$$\frac{\partial vh}{\partial t} + \frac{\partial}{\partial y}(v^2 h + \frac{1}{2} g h^2) + \frac{\partial uvh}{\partial x} - gh(S_{0y} - S_{fy}) = 0 \qquad [10]$$

whereas h (m) denotes the depth of water, u-v are the velocity components in the x-y axis, g (ms^{-2}) is the acceleration of gravity, x-y-z (m) are the space coordinates, t (s) is the time, $S_{o(x,y)}$ is the channel bottom slope in the x-y directions, $S_{f(x,y)}$ is the friction slope in the x-y directions based on the Manning's equation, n is the Manning's bed roughness coefficient and C_o is the correction factor.

Initially, we retrieved the georeferenced digital surface model (DSM) from the DJI Mavic drone unit, through the Pix4Dcapture© and Pix4Dmapper© software, which was used for the topographic measurements in both downstream sites. Afterwards, we imported the DSM raster file into the free and open-source Quantum Geographic Information System (QGIS) software and convert it to a longitude-latitude-altitude array (.xyz). This three-dimensional file was converted to a text (.bed) format and was successively imported in the R2D_Bed, R2D_Mesh and River2D routines. Finally, the HSCs were imported in the .prf files in order to be included in the habitat simulation. The proposed methodological framework and the standardization process are described in detail in the River2D manual **(**Steffler & Blackburn, 2002). The ecohydraulic model of Ziz river required a larger number of hydraulic simulations (i.e., step-wise low discharge values) since is located in an arid-to-desert climate zone with historical low discharge runoffs (see Chapter 2.1.1.A. & Chapter 4). As a result, we applied 19 simulations regarding a variety of discharge scenarios (0-1, step=0.1 m^3s^{-1}; 1-10; step=1 m^3s^{-1}) for Ziz and 10 simulations in Oum Er Rbia river (1-10; step=1 m^3s^{-1}), respectively.

For the needs of the time-consuming ecohydraulic simulations, we utilized an Intel® Core™ i7-12650H processor, a memory of 16GB DDR5 and a PCIe® NVMe™ M.2 SSD 512GB storage disk. Finally, during the calibration we adjusted the Manning's roughness coefficient (n; determined in R2D as a proxy of the roughness coefficient k_s) values at different sections of the river reaches based on the calibration measurements until the predicted velocity and depth values reach a significant high Pearson correlation coefficient (R^2) and a low Root Mean Square Error (RMSE) when compared to the observed topographic values downstream the river site (Boskidis et al. 2018; Theodoropoulos et al. 2018a).

3. Results

The present chapter is divided in two main parts. The first sub-chapter is related to the sampling expedition in the upper reference zones of both upstream river regions and, to the best of our knowledge, in the construction of the first published HSCs for BMs in northwest Africa (Chapter 3.1.). The second part focuses on the computational ecohydraulic simulations and their produced outcomes based on the integration of both the HSCs and the topographic/hydraulic background information of each river body (Chapter 3.2.).

3.1. Habitat Suitability Curves (HSCs)

3.1.1. Ziz river

For the needs of the exploration of the ecological and hydraulic properties of the Ziz river, we proceeded in the collection of environmental data in 64 sampling stations. The data statistics (Table 2) showed that the river channel demonstrated a diverse hydraulic profile based on the wide range of depth and flow measurements, as in its physicochemical properties (i.e., Temperature, pH).

Table 2. Descriptive statistics of the environmental data collected of all the microhabitats sampled (N=64) in Ziz river.

Variables	Mean	Standard Deviation	Minimum	Maximum
Depth (m)	0.217	0.154	0.3	0.85
Flow (m/s)	0.33	0.47	0.033	1.23
Temperature (°C)	13.5	3.48	8.5	19.63
pH	8.25	0.34	7.57	8.75
Conductivity (mS/s)	617.19	604.45	461	2340

Based on the GAMLSS regressions the standardized index appeared to have a better statistical fitting in the abiotic data compared to the normalized suitability index, by taking account the adequate statistical significance ($p<0.1$) and the relatively moderate statistical relationships ($0.25< R^2<0.47$) between the majority of the environmental variables (Table 3). As a result, the standardized index was selected for the construction of the HSCs within the application of 3rd polynomial degree fitting for depth, flow, temperature and the substrate type. The HSCs of the BMs in the Ziz river (Fig. 10) displayed that there is a general preference towards habitats with low to moderate depth (0.2-0.3m) and flow (0.3-0.7 m/s) regimes. The aforementioned fitting was operated through while there is a discrete allocation of increased suitability (HSI>0.8) in lower temperatures (<14°C) and in large substrate elements (i.e., small & large stones).

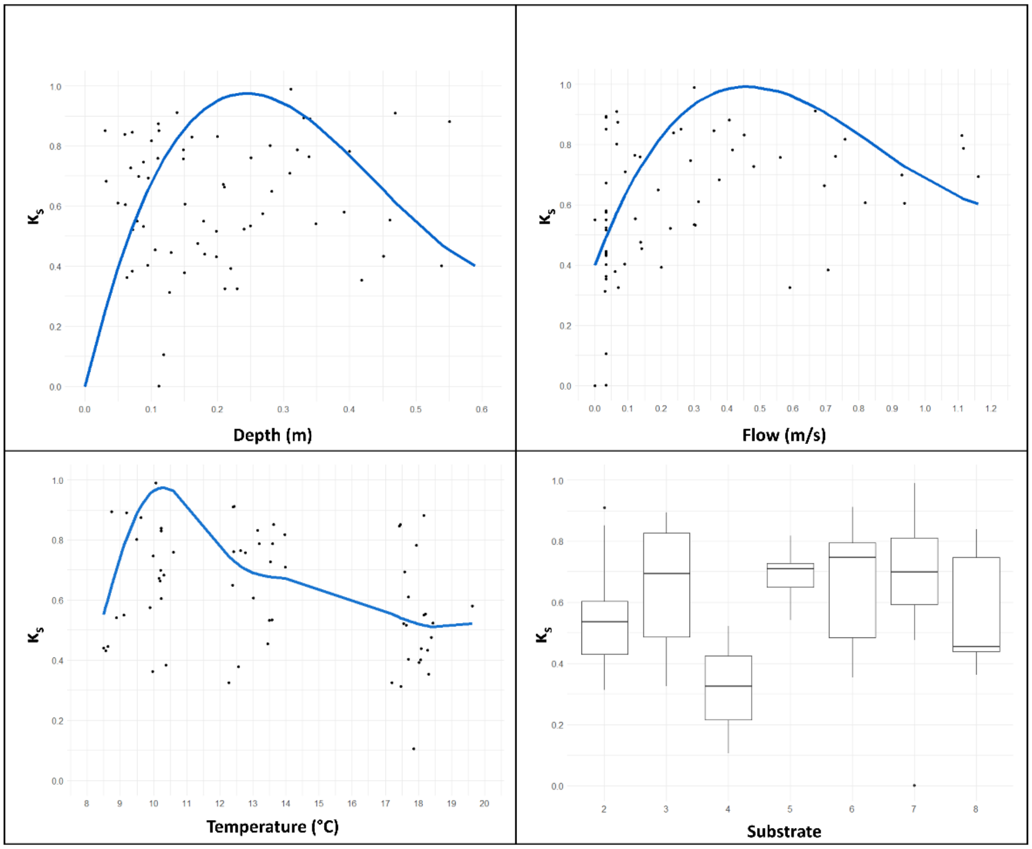

Figure 10. Habitat suitability curves (HSCs; 0-1) for benthic macroinvertebrates in the Ziz river (Morocco; North Africa) based on the standardized suitability index (K_s) for water depth (m), flow velocity (m/s), water temperature (ºC) and substrate type (S).

Table 3. Statistical parameters (p-value and pseudo-R^2) of the GAMLSS-based models, for the multivariate response of the standardized suitability index (K_s) and the explanatory abiotic parameters in the Ziz river. The asterisk (*) indicates the level of statistical significance ($p^{**}<0.05$; $p^{*}<0.1$).

Abiotic parameters	**K_n** (normalized SI)		**K_s** (standardized SI)	
	p-value	**pseudo-R^2**	**p-value**	**pseudo-R^2**
Flow* (V; m/s)	0.0123**	0.26	0.0065**	0.43
Depth* (D; m)	0.178	0.62	0.11*	0.47
Temperature* (ºC)	0.015**	0.46	0.0085**	0.47
Substrate (S)	0.22	0.23	0.55	0.25
pH*	0.027	0.45	0.0053**	0.52
Conductivity* (C)	0.139	0.33	0.022**	0.31

3.1.2. Oum Er Rbia river

Overall, 59 microhabitats have been investigated in the middle reaches of Oum Er Rbia river. The data collection showed that the river channel showed relatively homogenous hydraulic characteristics without significant divergences being observed in the sampling stations (Table 4). In specific, depth and flow showed a normal-like distribution around 0.3 m and 0.36 m/s while temperature, pH and conductivity demonstrated a narrow range profile regarding the field measurements.

Table 4. Descriptive statistics of the environmental data collected of all the microhabitats sampled (N=59) in Oum Er Rbia river.

Variables	Mean	Standard Deviation	Minimum	Maximum
Depth (m)	0.29	0.13	0.04	0.68
Flow (m/s)	0.36	0.27	0.033	0.99
Temperature (ºC)	13.37	0.58	11.31	14.53
pH	8.65	0.041	8.57	8.81
Conductivity (mS/s)	3394.31	36.45	3328	3479

As in the case of Ziz river, the standardized suitability index resulted in robust suitability since statistically significant and strong relationships were observed ($p<0.1$ and pseudo-$R^2>0.6$) for the examined abiotic variables (Table 5). As a result, the K_s was universally applied for both regions for the development of the HSCs.

Table 5. Statistical parameters (p-value and pseudo-R^2) of the GAMLSS-based models, for the multivariate response of the standardized suitability index (K_s) and the explanatory abiotic parameters in the Oum Er Rbia river. The asterisk (*) indicates the level of statistical significance (p**<0.05; p*<0.1).

Abiotic parameters	K_n (normalized SI)		K_s (standardized SI)	
	p-value	**pseudo-R^2**	**p-value**	**pseudo-R^2**
Flow* (V; m/s)	0.123	0.26	0.07*	0.72
Depth* (D; m)	0.036**	0.51	0.00005**	0.61
Temperature* (ºC)	0.434	0.56	0.0545*	0.6
Substrate* (S)	0.0004**	0.63	0.000765**	0.78
pH	0.409	0.53	0.401	0.59
Conductivity (C)	0.0006**	0.18	0.283	0.73

BMs in the Oum Er-Rbia River exhibited increased suitability (K_s) in depths ranging from 0 to 0.2 m, while there was constant decrease of HSI values in larger depths (Fig. 11). Regarding flow velocity, low values of HSI were recorded for velocities from 0 to 0.5 m/s while there was a peak in optimal values from 0.5 ms^{-1} to 0.75 ms^{-1}. Temperature suitability peaked at 13.6°C, with higher/lower temperatures leading to lower HSI, respectively. Large stones were characterized as the optimal suitable substrate type.

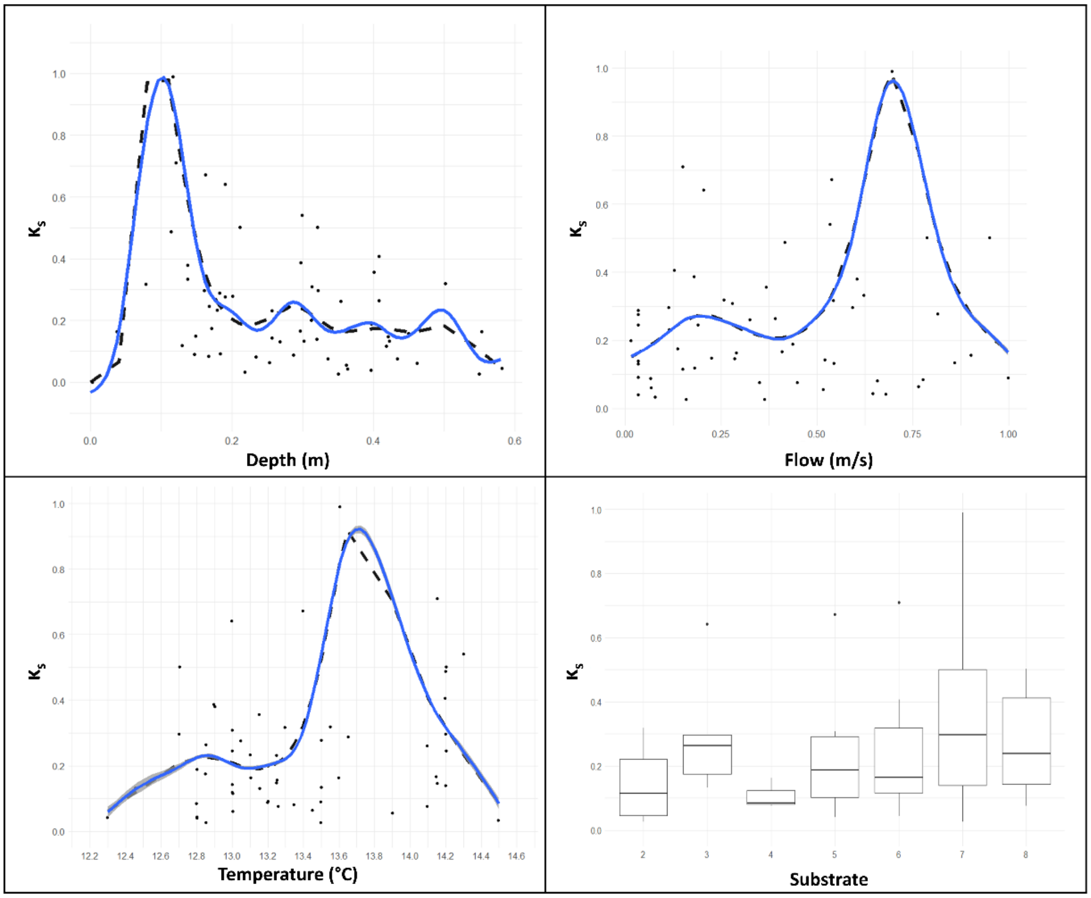

Figure 11. Habitat suitability curves (HSCs; 0-1) for benthic macroinvertebrates in the Oum Er-Rbia River (Morocco; North Africa) based on the standardized suitability index (K_s) for water depth (m), flow velocity (m/s), water temperature (°C) and substrate type (S).

3.1.3. Comparative analysis Mediterranean (Greek) – Semi arid (Moroccan) HSCs

In order to examine potential differences in the habitat preferences of freshwater BMs from different climatic zones, we developed and compared HSCs from 380 Mediterranean (Greek; Theodoropoulos et al. 2018a) and 59 semi-arid (Moroccan) microhabitat sampling stations (Fig. 12). We attempted to explore whether is possible to extrapolate HSCs between reaches of different climate zones, which has often led to inaccurate or unrealistic ecohydraulic results (Hudson et al. 2003).

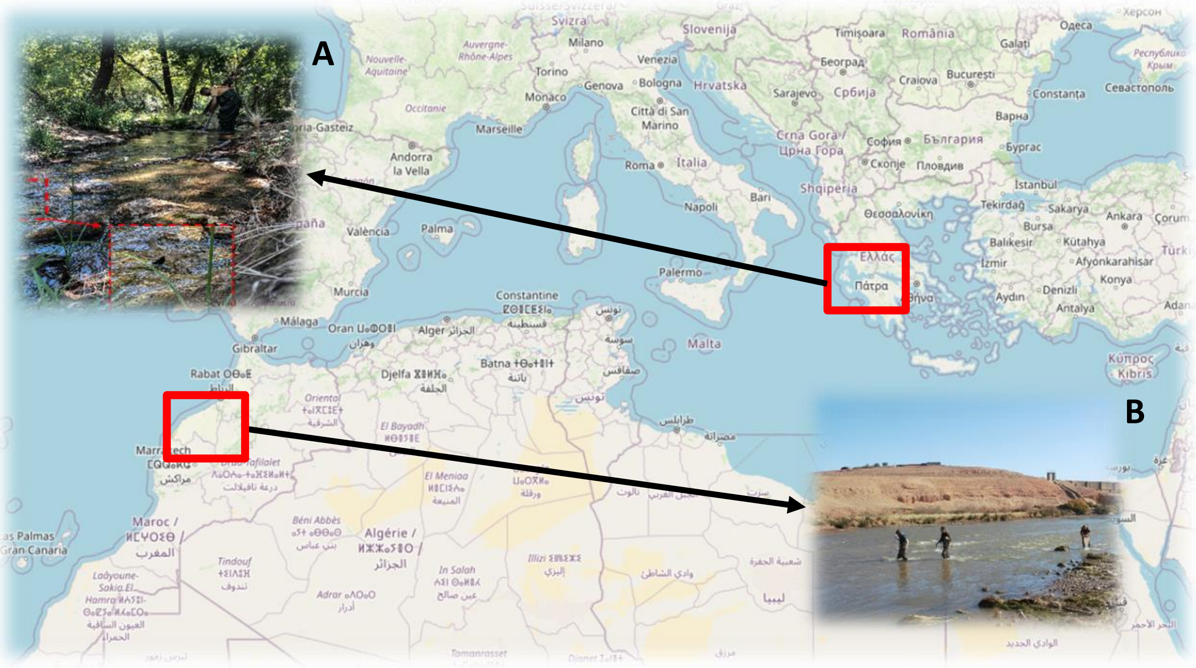

Figure 12. Map demonstrating the two different climatic zones that were used for the comparative analysis of the habitat suitability curves (HSCs; A: Mediterranean climate, Greece; B: Semi-arid climate; Morocco).

The methodological protocol used for this comparative approach is similar with the analyses applied in the previous chapters. It is noteworthy to mention that in this case, we have normalized the suitability index (0-1) by diving the maximum K_n in each regional dataset of each climate zone. Hence, we've attempted to avoid biases relevant to spatial and/or temporal autocorrelation. The results derived through the GAMLSS regressions demonstrated that K_n was statistically significant related ($R^2 > 0.5$) with water depth and the substrate type in the Moroccan river reaches (semi-arid climate), while in the Greek river reaches (Mediterranean climate) water depth and flow velocity were the major hydraulic drivers ($0.32 \geq R^2 \geq 0.14$; Table 6).

Table 6. Statistical significance (p) and strength of correlation (pseudo-R^2) between hydraulic variables and macroinvertebrate habitat suitability (**<0.01; *<0.05).

Hydraulic variables	**Habitat suitability | Greece**		**Habitat suitability | Morocco**	
	p	**R^2**	**p**	**R^2**
Flow velocity (m/s)	**0.046***	0.14	0.248	0.64
Water depth (m)	**3.41e-16****	0.32	**0.01****	0.51
Substrate type	0.15	0.13	**0.001****	0.81

Based on the results (Fig. 13), BMs in the semi-arid zone preferred mostly shallow, rocky habitats (large gravel, small, large stones and boulders; optimal D values between 0.1 m and 0.2 m). On the other hand, BMs in the Mediterranean zone preferred slow to moderately flowing waters (with wider optimal V range, from 0.4 ms^{-1} to 0.9 ms^{-1}), compared to semi-arid communities where they mostly preferred moderately flowing waters (with narrower optimal V range, from 0.65 to 0.85 ms^{-1}). The Mediterranean HSCs exhibited increased tolerance for suboptimal flow velocities with larger suitability range from ($0.4 > V > 1$ ms^{-1}; $K_n > 0.5$). In contrast, the suitability index in the Moroccan reaches resulted in a narrower range of preference since both flow velocity and water depth exhibited a peak in conditions of $0.6 < V < 0.8$ ms^{-1} and $0.05 < D < 0.15$ m.

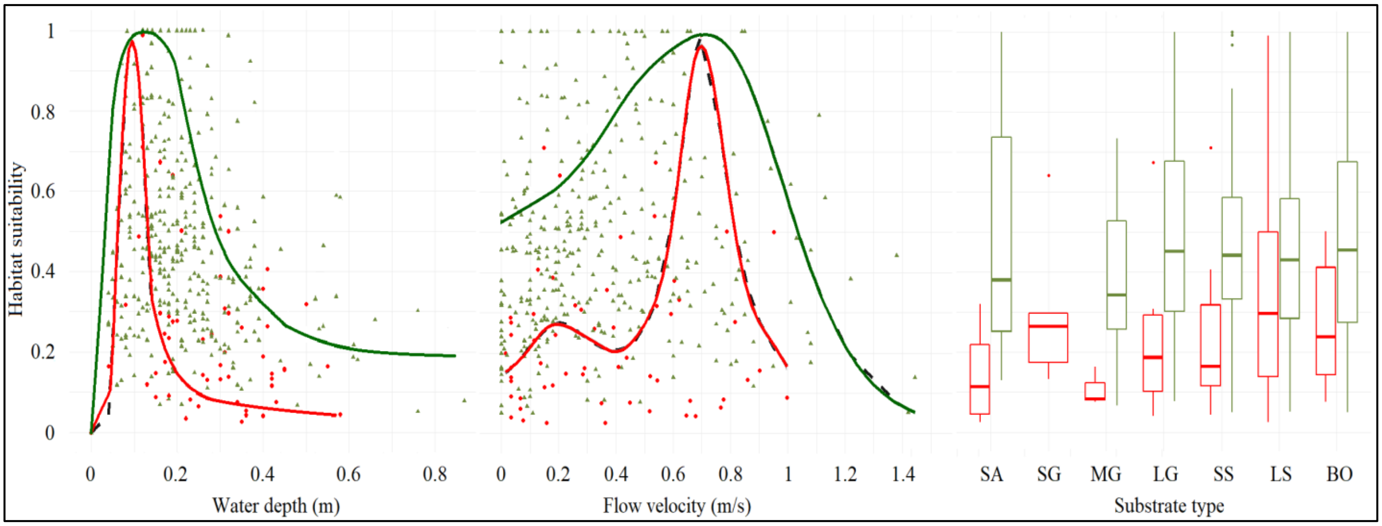

Figure 13. HSCs for BMs from the Greek (green; n=380) and Moroccan (red, n=59) river reaches. The figures display the relationship between the suitability index (K_n) and water depth (m), flow velocity (ms^{-1}) and the substrate type. SA: Sand; SG, MG, LG: Small, medium, large gravel; SS, LS: Small, large stones; BO: Boulders.

3.2. Ecohydraulic simulations (R2D)

3.2.1. Ziz river

As it was mentioned above, the HSCs (Chapter 3.1.) have been imported into R2D, a two-dimensional ecohydraulic simulation software that enables the integration of both biological and abiotic data of the examined rivers. In the case of the Ziz river, the R2D ecohydraulic routine resulted that discharge inflow of 3 m^3s^{-1} had the highest weighted usable are (WUA=1802.47 m^2) through 19 consecutive discharge simulations (Table 7). Additionally, the lowest value was recorded for the minimum discharge volume of 0.1 m^3s^{-1}. In terms of the overall suitability area, the highest value resulted at 11.86% and 4.87% for the highest and the lowest WUA, respectively. The total simulated area for all the simulated scenarios was equal to 1786m^2.

Table 7. Relationship between discharge volumes (Q) during R2D ecohydraulic simulations and the resulted weight usable area (WUA; m^2), the overall suitability index (OSI; %) and the proportional change of the overall suitability index for benthic macroinvertebrates downstream of the Al Hassan Addakhil dam in the Ziz river, east Morocco. The highest value (Q=3 m^3s^{-1}) and the optimal value (Q= 2 m^3s^{-1}) is indicated with blue and green color, respectively.

Q (m^3s^{-1})	WUA (m^2)	OSI (% of area)	Δ%
0.1	739.89	4.87%	+28.9%
0.2	1040.77	6.85%	+14.0%
0.3	1209.95	7.96%	+7.7%
0.4	1310.99	8.63%	+4.8%
0.5	1376.77	9.06%	+4.2%
0.6	1437.44	9.46%	+3.9%
0.7	1495.10	9.84%	+2.7%
0.8	1536.67	10.11%	+2.8%
0.9	1580.39	10.40%	+2.2%
1	1615.56	10.63%	**+9.6%**
2	**1786.76**	**11.76%**	+0.9%
3	**1802.47**	**11.86%**	-0.1%
4	1801.37	11.85%	-5.4%
5	1709.69	11.25%	-9.1%
6	1567.22	10.31%	-12.3%
7	1395.90	9.18%	-12.8%
8	1237.53	8.14%	-7.7%
9	1148.56	7.56%	-3.1%
10	1114.55	7.33%	

Based on the relationship between the OSI and Q, it appears that there is a gradual increase in the OSI values from 0.1 to 2 m^3s^{-1}. At discharge volume of 2 m^3s^{-1} there is a relatively discrete threshold, known as plateau, until discharge volume of 4 m^3s^{-1} whereas afterwards, there is a decrease of the suitable proportional area (Fig. 14).

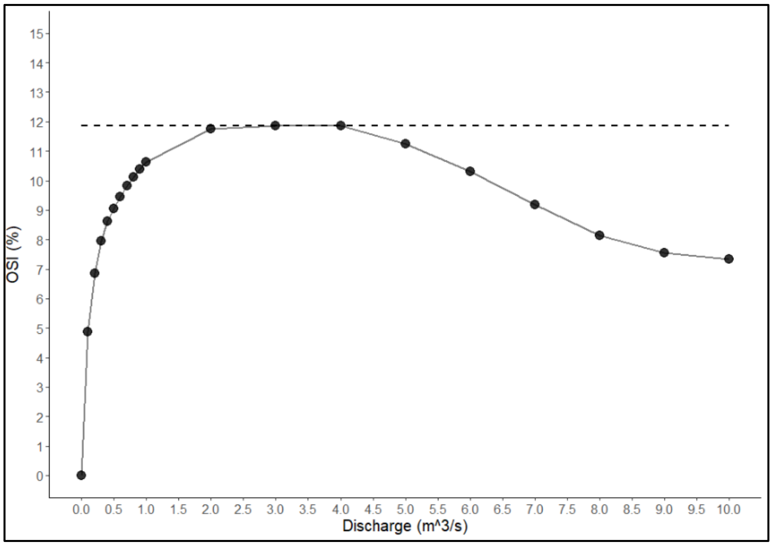

Figure 14. Relationship of the overall suitability index (OSI; %) and the discharge volumes of the simulations (N=19) operated in the R2D environment, in the Al Hassan Addakhil dam (Ziz river, east Morocco). The dashed line indicates the threshold of the maximum discharge level (OSI= 11.86%; Q=3 m^3s^{-1}).

Nevertheless, the maximum OSI value is not an adequate proxy to clarify the optimal discharge downstream of the dam. Hence, the application of the proportional change of the OSI value (Δ%; Fig. 15) demonstrated that discharge volume of 3 m^3s^{-1} may result in the maximum WUA. The aforementioned plateau arises at discharge volume of 2 m^3s^{-1}, with an insignificant increase following later on (Table 7; Q: 1-2 m^3s^{-1}; Δ%= +9.6% | Q: 2-3 m^3s^{-1}; Δ%= +0.9%). **As a result, discharge of 2 m^3s^{-1} is determined as the optimal ecological flow for BMs in the Ziz river.**

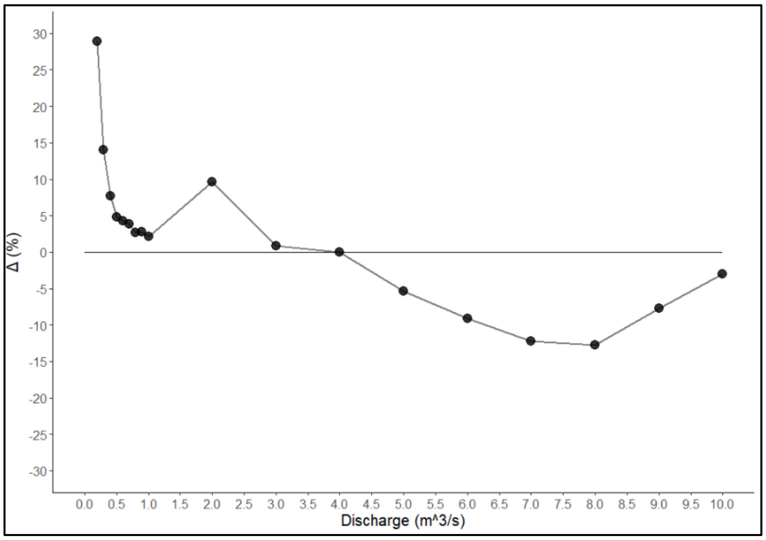

Figure 15. Relationship of the delta (Δ%) proportional difference of the overall suitability index and the discharge volumes of the simulations (N=19) operated in the R2D environment, in the Al Hassan Addakhil dam (Ziz river, east Morocco).

The spatial and temporal distribution of the weighted usable area (WUA; Fig. 16) resulted that the regions with increased suitability (WUA> 2.5), based on the preferences of the BMs, were located in the downstream side of the Ziz river while the major sectors appeared in the main river bank and not in the floodplain. The simulation was completed when inflow was relatively equal to outflow discharge in a complete timeframe of 34502 seconds (~9.5 hours of simulation). During this time step, R2D simulation environment have reached steady flow and the temporal changes in the outputs of the resolving shallow water and continuity equations were negligible.

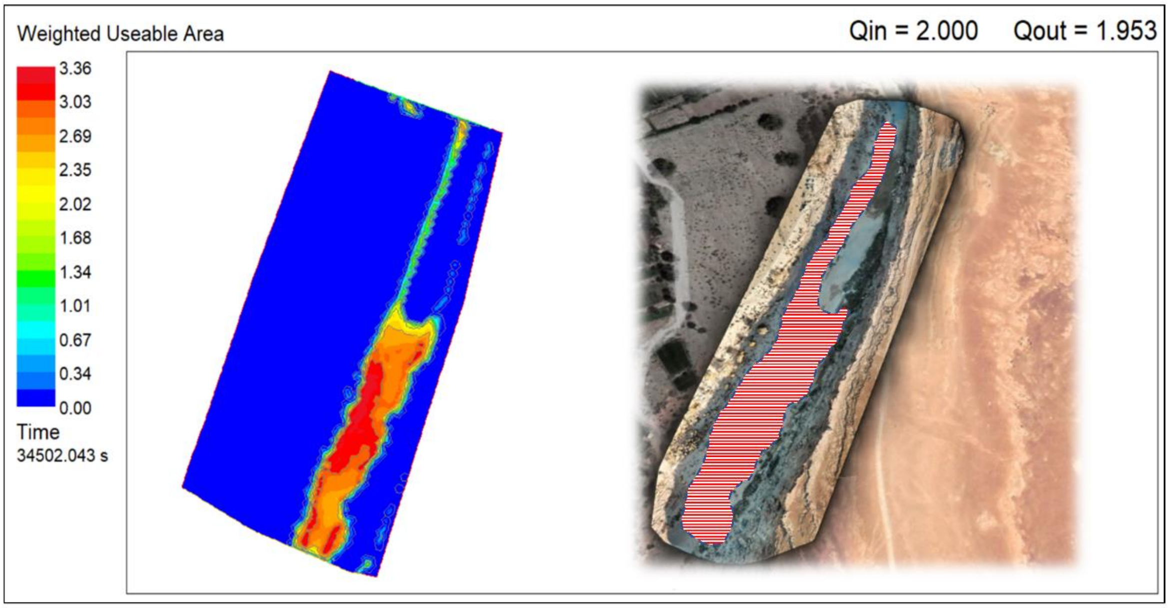

Figure 16. Weighted Usable Area (WUA; left) spatial distribution for BMs downstream of the Al Hassan Addakhil dam in Ziz river (Errachidia province, east Morocco; right).

3.2.2. Oum Er Rbia river

The methodological framework applied to Oum Er Rbia was similar to the previous chapter, the ecological and hydraulic data were imported into the R2D environment. The calibration process resulted in a statistically strong and sufficient fitting between simulated and observed values both for depth (RMSE=0.018; R^2=0.87) and for flow velocity (RMSE=0.025; R^2=0.74). According to the resulted indices, discharge value of 2 m^3s^{-1} was selected as the optimal ecological discharge inflow value with the highest suitable area (WUA=2192 m^2; Table 8). The lowest value was resulted for discharge volume of 10 m^3s^{-1} (WUA=1872 m^2).

Table 8. Relationship between discharge volumes (Q) during R2D calibrated ecohydraulic simulations and the resulted weight usable area (WUA; m2), the overall suitability index (OSI; %) and the proportional change of the overall suitability index for benthic macroinvertebrates downstream of the Al Massira dam in the Oum Er Rbia river, central Morocco. The highest value (Q=3 m3s-1) and the optimal value (Q= 1 m3s-1) is indicated with blue and green color, respectively.

Q (m^3s^{-1})	WUA (m^2)	OSI (% of area)	Δ%
1	2050.03	11.7%	**+6.48%**
2	**2192.08**	**12.53%**	**-0.32%**
3	2185.20	12.5%	-1.73%
4	2148.14	12.28%	-1.16%
5	2123.42	12.14%	-3.39%
6	2053.77	11.74%	-1.63%
7	2020.77	11.55%	-1.65%
8	1988.05	11.37%	-2.98%
9	1930.55	11.04%	-3.10%
10	1872.56	10.71%	

The output figure displaying the relationship between OSI and Q showed that there is an increase for 1 m^3s^{-1} to 2 m^3s^{-1} inflow discharge volume, while afterwards there is a clear a decrease of the suitable proportional area (Fig. 17). The estimated values for OSI ranged from 10.7-12.5%. An interesting result is that the non-calibrated scenario with the application of the standard roughness coefficient (k_s=0.45) compared to the calibrated scenario (i.e., k_s=0.1-1.8) exhibited a negligible divergence of 8-199m^2 of WUA.

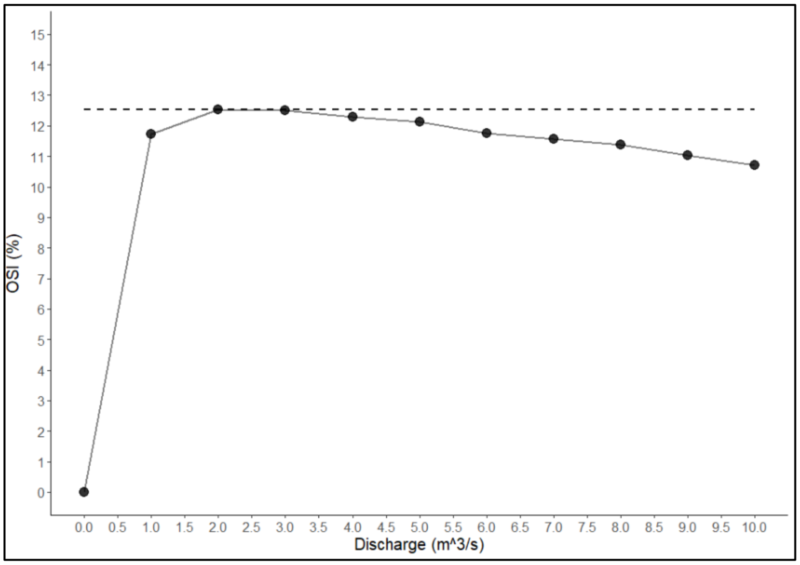

Figure 17. Relationship of the overall suitability index (OSI; %) and the discharge volumes of the simulations (N=10) operated in the R2D environment, in the Al Massira dam (Oum Er Rbia, central Morocco). The dashed line indicates the threshold of the maximum discharge level (OSI= 12.53%; Q=2 m^3s^{-1}).

The application of the proportional change of the OSI value (Table 8; Q: 1-2 m^3s^{-1}; Δ%= +6.48% | Q: 2-3 m^3s^{-1}; Δ%= -0.32%; Fig. 18) enforced the hypothesis that since there is not any observed plateau, the peak results in the target value regarding the optimal flow. **Hence, correspondingly to Ziz river, discharge volume of 2 m^3s^{-1} is determined as the optimal ecological flow for BMs in the Oum Er Rbia river.**

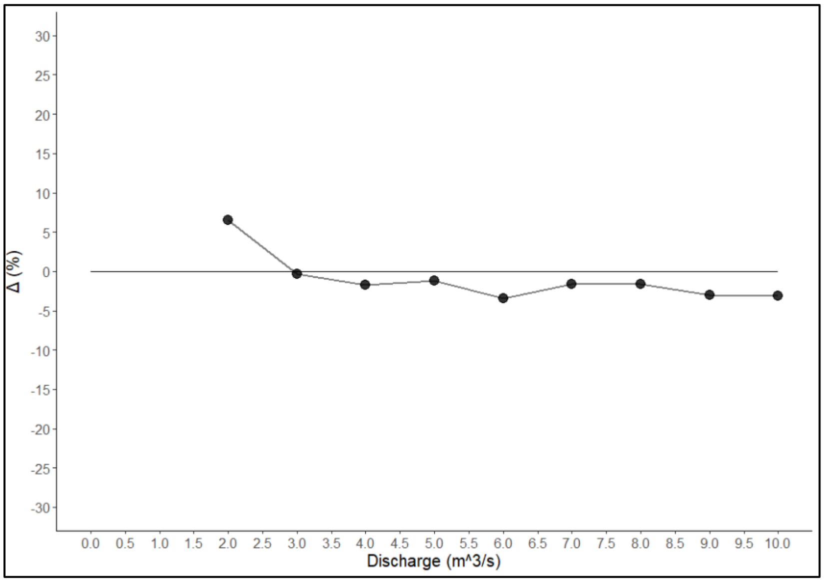

Figure 18. Relationship of the delta (Δ%) proportional difference of the overall suitability index and the discharge volumes of the simulations (N=10) operated in the R2D environment, in the Al Massira dam (Oum Er Rbia river, central Morocco).

Habitat preferences during the R2D simulation have been displayed by visualizing the spatial distribution of WUA in the river channel downstream of the Al Massira dam. It was evident that when steady flow was reached (37561 seconds: ~10.4 hours of simulation), the whole river channel had moderate to high habitat suitability preference (1< WUA< 3; Fig. 19). As a result, the examined river site downstream of the dam can effectively function as a biological layer for the establishment of BMs.

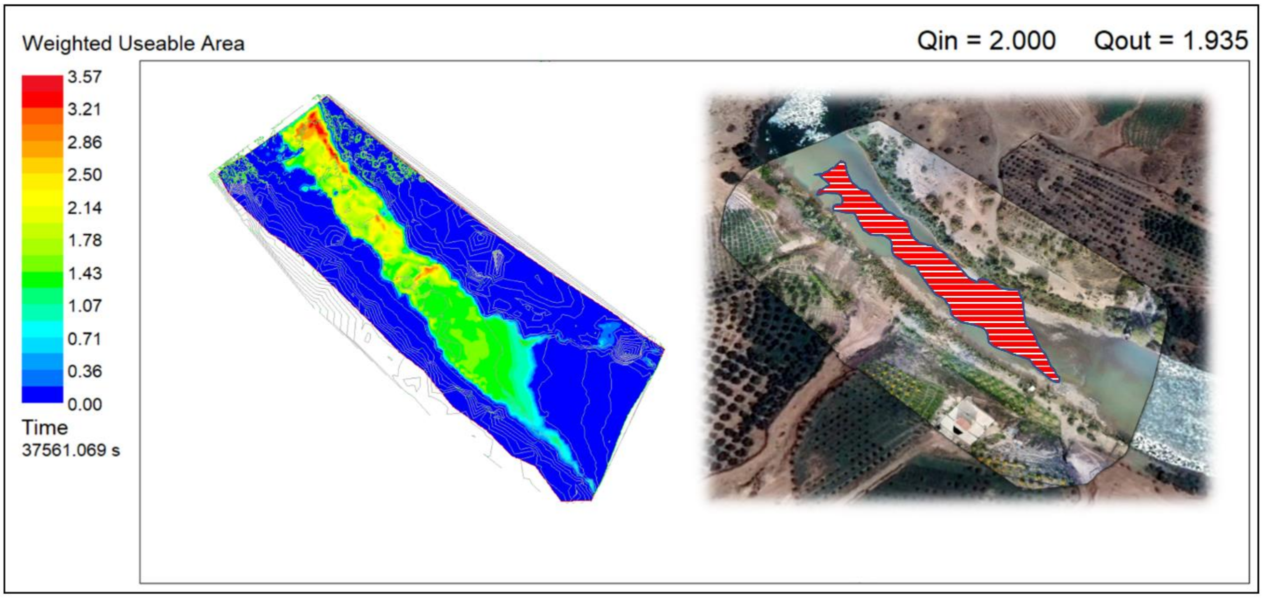

Figure 19. Weighted Usable Area (WUA; left) for BMs downstream of the Al Massira dam in Oum Er Rbia river (Settat province, central Morocco; right).

4. Discussion

The ecohydraulic simulations of the present study included information from two unexplored, in terms of their ecohydraulic properties, aquatic systems (Oum Er Rbia & Ziz river) located in a semi-arid and an arid climate zone, respectively. The simulations were based on real-time topographic data, while the biological input resulted from an extensive field-based microhabitat sampling dataset of BMs. The produced HSCs are, to the best of our knowledge, the first habitat suitability curves constructed for the region of North Africa in semi-arid/arid aquatic systems. In conjunction with the ecohydraulic simulations and the estimated optimal ecological flows, we attempted to set the biological and hydraulic baseline information for the essential element of water and subsequently, for the vulnerable aquatic biota.

As it was mentioned in the introduction (Chapter 1.2.), the third category of HSCs (i.e., HSCs-III) is considered as the most time-consuming and expensive type of ecohydraulic information. During the early years of ecohydraulic research, scientists have suggested the use of generalized HSCs in order to overcome this operational obstacle (Bovee, 1982; Jowett et al. 1991). However, it has been proved that river-specific HSCs (i.e., category-III) provide more accurate baseline information regarding the observed habitat preference of the BMs (Kelly et al. 2015; Theodoropoulos et al. 2018a; 2018b). To this end, we constructed HSCs-III for the two selected case studies. A reasonable hypothesis would be that since the two rivers are located in two different climate zones, the regional-specific adaptions of BMs will lead to different HSCs as a response of the environmental conditions. The descriptive statistics of the obtained dataset were not adequately indicative to highlight the hydraulic divergence of the semi-arid and the arid aquatic systems (Tables 3 & 4). This is due to the methodological sampling framework of microhabitat sampling, since during the field expedition the sampling stations were supposed to cover a wide range of the river basin's hydraulic features (Theodoropoulos et al. 2018a). The anticipated antithesis, and thus the validation of the initial hypothesis, was evident in the produced HSCs since the output of the Ziz river basin resulted in wider range of preference compared to the narrow range of Oum Er Rbia, thus characterizing the arid BM community as "generalists" (Fig. 10 & 11). This can be attributed to the fact that BMs communities of intermittent riverine systems with reduced connectivity and limited water availability, such as several sites of Ziz river during dry periods, can be dominated by mainly tolerant and resistant organisms (Bertoncin et al. 2019).

During the examination of the two alternative suitability indices (K_n; K_s), we showed that the standardized suitability index (K_s; Eq. 1 & 3) fitted better the ecohydraulic dataset of both case studies. During the GAMLSS modelling, there was a statistically significant relationship between K_s, depth and flow velocity, a common finding with previous works in Mediterranean basins (Theodoropoulos et al. 2018a). The results of the Oum Er Rbia river were in agreement with previous works that validated the positive relationship between increased suitability in shallow and fast-flowing habitats. In specific, riverine sites characterized with relatively fast-flow conditions (i.e., perennial streams) facilitate hydraulic conditions that favor and support ecological niches through adequate energy supply and increased water purification rates (Khudhair et al. 2019). Our results exhibited that robust suitability can be observed even in pools ($D > 0.4$ m) with low-flow regimes ($V < 0.4\ ms^{-1}$) as a potential response of organisms in stressed regions (Fig. 10; Ziz river).

The comparative analysis between the HSCs of the BMs in the Mediterranean and the semi-arid river reaches of Greece and Morocco (Oum Er Rbia), respectively, revealed that there was a common robust effect of the suitability index between the different hydraulic drivers (D and S in the Moroccan river reaches; D and V in the Greek river reaches). Additionally, as it was mentioned previously, the optimal habitat preferences conditions between the two areas were different. As a result, the application of generalized predetermined HSCs in river reaches of different climate zones will potentially produce unrealistic ecohydraulic outputs, inadequate environmental flow recommendations and freshwater management strategies.

According to the ecohydraulic-based estimations of both riverine systems, the optimal ecological discharge flow downstream of the examined dams was estimated at 2 m^3s^{-1} (Tables 8 & 9). Although the optimal flow estimation was equivalent in both rivers, the OSI-discharge profile in the simulated scenarios of Oum Er Rbia was maximized in simulations from 2 to 3 m^3s^{-1} ("plateau"), while afterwards the trend showed a rapid decline (Fig. 14). On the contrary, the response of OSI-discharge observed in Ziz river was less variant with a relatively steady reduction from the optimal ecological flow towards lower/larger discharge simulations. This observation functions as an additional statement to enforce the hypothesis that more tolerant and resistant biota, with larger range of adaptivity are dominant in stressed systems (i.e., less depth and flow-dependent BMs).

There is a critical momentum for the application of ecohydraulic research since the Kingdom of Morocco has declared an emergency status regarding water consumption and management (WDO, 2022). The Al Massira dam, the second largest national dam and the second case study of this work, demonstrates the most indicative example of this alarming phenomenon since its water storage has been dramatically reduced over the last 5 years (Fig. 20).

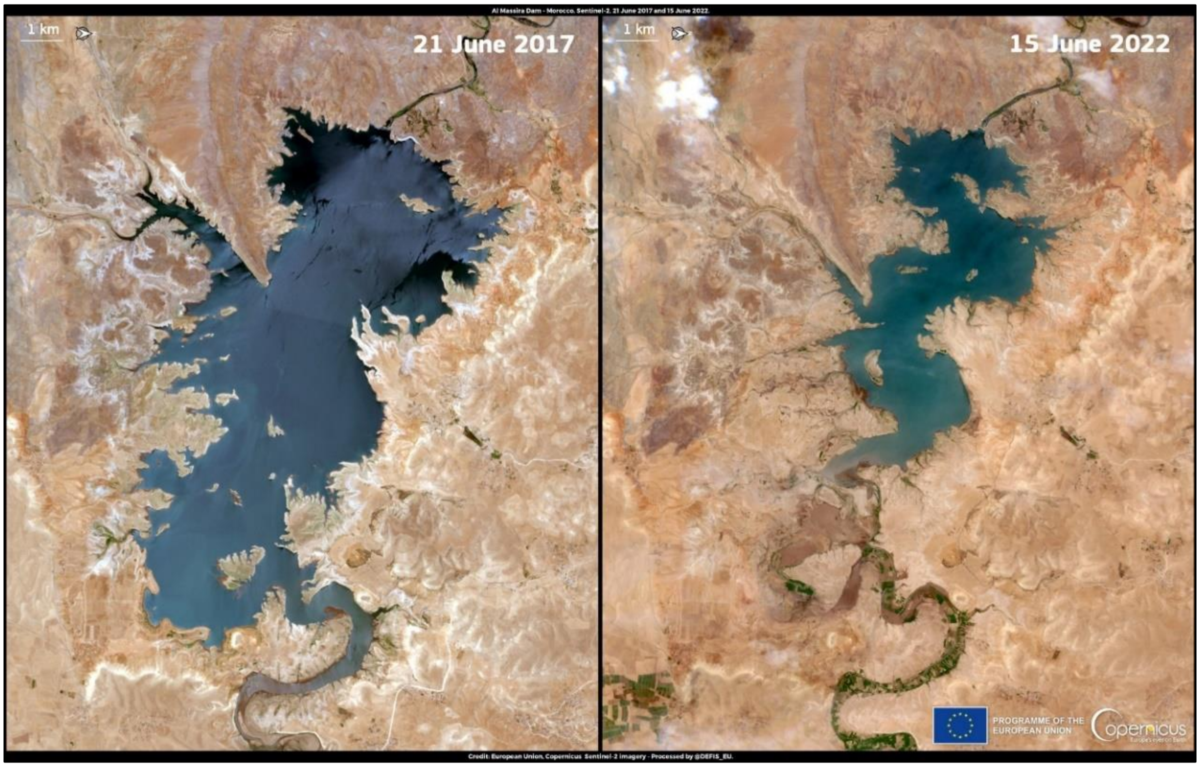

Figure 20. The reduction of water storage in the Al Massira dam (Oum Er Rbia river), the second largest dam of Morocco, displayed by two Sentinel2 satellite images from 2017 to 2022. [Link]

It is clear that the synergistic effect of the intense human activities related to water usage (i.e., agriculture) and the decrease of precipitation at an annual scale in both sites (Elhassnaoui et al. 2021; Tahiri et al. 2022), have resulted in the reduction of the water storage volume in the Al Massira dam of the Oum Er Rbia river. The same pattern is observed in the Al Hassan Addakhil dam of the Ziz river, respectively. In specific, daily-scale time series retrieved for the Directorate of Hydraulics from the Kingdom of Morocco (GDH, 2022) validate this ongoing reduction trend, whereas in October 2022 the Al Massira and Al Hassan Addakhil dam have been recorded with 4.9% and 22.6% storage capacity, respectively (Fig. 21). Hence, the phenomenon of reduced water availability is observable across the Atlas Mountains through several hydro-climatic zones.

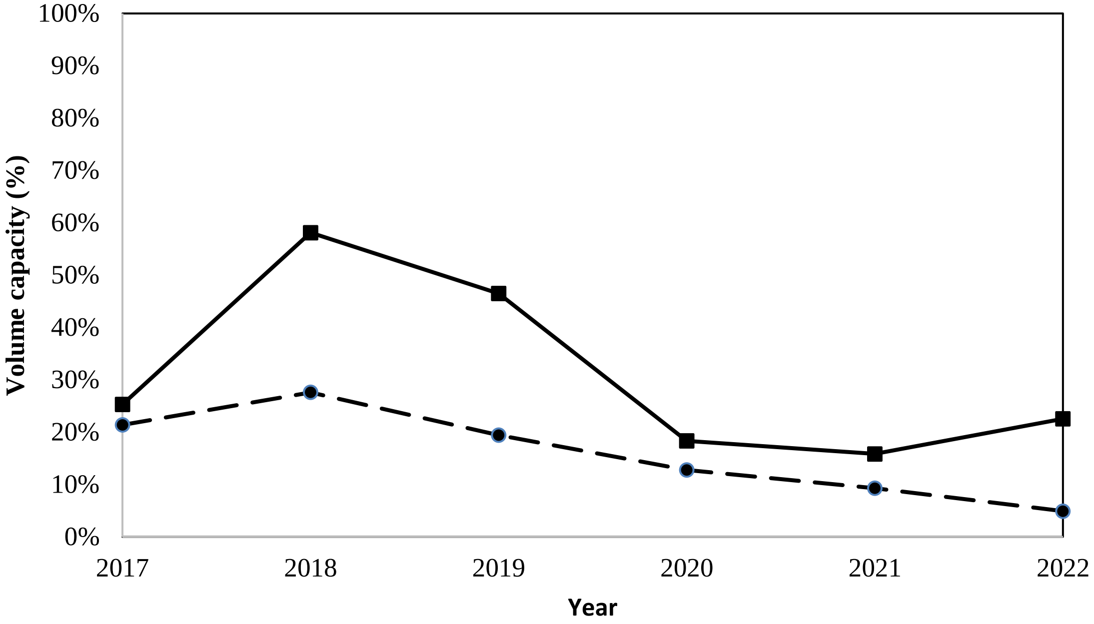

Figure 21. Time series of water volume capacity (%) for the Al Massira (dashed line) and the Al Hassan Addakhil (solid line) dam of Morocco. Data retrieved for the National Directorate of Hydraulics of Morocco (DGH, 2022). Data are derived for the 21st of October of each respective year. [Link]

Throughout our analyses we have concluded that the optimal ecological flow for BMs has been estimated at 2 m^3s^{-1}, a value that ensures the optimal suitability for organisms in the examined regions. However, the environmental flow should to be in agreement with national (public and/or private) administrative organizations along with the local communities. Additionally, natural conditions must be met such as that the value should fall into the historical surface data, otherwise the proposed recommendations are unrealistic. Available historical data from the Global Runoff Data Centre (GRDC, 2022) from stations upstream of the examined dams indicate that the mean monthly discharge was approximately 2.5 and 20 m^3s^{-1} for the Ziz (Foum tillich; Time series: 1974-1989) and Oum Er Rbia river (Dechra el oued: 1953-1989), respectively. More recent gauging stations (1994-2010) in the Oum Er Rbia validated the previous estimation (Strohmeimer et al. 2019), while in the case of Ziz discharge data are rather limited. Considering the hydrological background of the Ziz and Oum Er Rbia river basins and the continuing decline of water resources, a reasonable recommendation is that environmental flow (e.g., balance between ecosystem and human demand; Theodoropoulos et al. 2018b) of 1 m^3s^{-1} would sustain the aquatic habitats of BM communities downstream of both dams.

Even though the methodological framework of the present study was based on previous state-of-the-art published works (Chapter 2), several limitations can be identified for future improvement towards more advanced results and recommendations. Principally, the lack of a seasonal ecohydraulic dataset is a significant disadvantage of this work since the produced outcomes can be utilized only for the accounted sampling period. Moreover, the number of sampling stations (~60 sites) can be considered as a limiting factor which inhibits the generalization of the observed patterns in various hydro-climatic zones. As regard the biological components of this study, the integration of additional aquatic taxa (i.e., macrophytes, fish) under a common ecohydraulic protocol would have crucially expanded the scientific and operational applications of relevant research. Nevertheless, considering the available time and resources for the needs of the present master thesis, we attempted to provide a valuable reference dataset combined with novel analysis in order to elucidate the ecohydraulic properties of the two unexplored Moroccan riverine systems.

In summary, Middle East and North African (MENA) aquatic systems are the most water stressed regions globally that undergo climatic and anthropogenic pressures, such as desertification and drought (Kacem et al. 2019; Bedoui, 2020; Fragaszy et al. 2020), conditions that facilitate a dystopian future for local human communities (e.g., increase poverty rates) and biodiversity as well (Reynolds et al. 2007). The produced outcomes of this study can be used as the biological reference for the implementation of ecohydraulic simulations targeted to mitigate climatic pressures through the establishment of management strategies. Several applied taxa have been used as bioindicators towards the exploration of the status and the structural-functional characteristics of aquatic ecosystems. Our results exhibited that BMs served as excellent bioindicators, since their immense biodiversity and their relevant environmental response was adequate to provide valuable information which can be utilized in applications especially in the field of ecohydraulics (Karaouzas et al. 2019; Theodoropoulos & Karaouzas, 2021).

5. Conclusions

The present master thesis was focused on the ecological and hydraulic response of freshwater BMs in two unexplored rivers of North Africa (Morocco). The major conclusions derived from the study are the following:

- Middle East and North Africa (MENA) aquatic systems are the most water stressed aquatic systems globally, however rather limited ecohydraulic research and/or baseline information is available on the published literature.
- Morocco represents one of the most beneficial case-studies on the field of ecohydraulics, considering the fact that the nation is currently under a severe water emergency state in several river basins located at a variety of climate zones.
- The HSCs-III for freshwater BMs of the northwestern Africa in the Ziz (arid) and Oum Er Rbia (semi-arid) river demonstrated that the major hydraulic drivers were depth, flow-velocity and temperature. The GAMLSS routine showed that the standardized habitat suitability index (K_s) was the most suitable formula in our dataset.
- Regarding habitat suitability, BMs mostly preferred shallow ($0.1 < D < 0.4$ m), fast-flowing ($0.4 < V < 0.8$ m/s) and waters with relatively moderate temperature (10^o C< T < 14^o C). However, the HSCs between the arid and semi-arid region resulted in a distinct divergence: The arid BMs communities showed a more generalized profile in terms of environmental preference compared to the semi-arid community of our study, which showed a larger range of preference at the majority of the abiotic factors. This can be attributed to the fact that organisms at excessively stressed conditions (e.g., lack of connectivity, reduced inflow) tend to adapt as generalists in a wide set of environmental pressures.
- Even though the HSCs differed, the ecohydraulic simulations resulted that the optimal ecological flow was estimated at 2 m^3s^{-1} for both case studies. This value was determined according to the proportional change of the OSI value, via the River2D ecohydraulic software. The obtained optimal ecological flows fell into the expected range of historical discharge data in both regions. Finally, we concluded that environmental flow of 1m^3s^{-1} could be a reasonable recommendation as a minimum outflow for the sustainable interaction between human activities, freshwater BM communities and ultimately, the conservation and management of life downstream of both dams.

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External links

WDO (2022): Water Diplomat Organization | 7th October 2022
https://www.waterdiplomat.org/story/2022/10/moroccan-dams-25-country-struggles-drought

GDH (2022): General Directive of Hydraulics, Kingdom of Morocco | 21st October 2022

http://81.192.10.228/?lang=ar

GRDC (2022): Global Runoff Data Centre | 21st October 2022

https://portal.grdc.bafg.de/applications/public.html?publicuser=PublicUser#dataDownload/Stations

Appendix I: Peer-review Conference publications

Proceedings of the 7th Europe Congress of the International Association for Hydro-Environment Engineering and Research (pp. 32-34)

7th IAHR Europe Congress, September 7th – 9th, 2022, Athens, Greece

Comparative assessment of macroinvertebrate habitat suitability in Mediterranean (Greek) and semi-arid (Moroccan) river reaches

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ABSTRACT

Ecohydraulic models have long been used to determine environmental flows downstream of dams, but the often lack of local habitat suitability curves (HSCs) prevents their wider implementation. To overcome this, ecohydraulic experts often use HSCs developed in ‘foreign’ river reaches. However, this approach may result in unrealistic ecohydraulic outputs. We developed and compared HSCs for freshwater macroinvertebrates from Greek (Mediterranean climate) and Moroccan (semi-arid climate) river reaches, to (i) either support or discourage the use of ‘foreign’ HSCs in ecohydraulic models, and (ii) provide locally developed HSCs for robust ecohydraulic simulations in Greek and Moroccan river reaches. Macroinvertebrates were influenced by water depth and substrate type in the Moroccan river reaches, and by flow velocity and water depth in the Greek river reaches. Moreover, they had different optimal habitat preferences. Our results discourage the use of ‘foreign’ HSCs in ecohydraulic models, especially in areas of different hydro-climatic properties.

1. Introduction

Ecohydraulic models (e.g., those applied to assess environmental flows downstream of dams) require (i) a hydraulic input: flow velocities, water depths and substrate types across the river reach that will be simulated, and (ii) a biological input: habitat suitability curves (HSCs) for aquatic biota, usually fish or benthic macroinvertebrates. If one of these inputs is missing, ecohydraulic simulations cannot be applied. The missing input is usually the biological one, as the development of HSCs in rivers is a costly and time-consuming task (Theodoropoulos et al., 2018). To overcome this frequent lack of HSC data, ecohydraulic experts have often been tempted to use HSCs from other river reaches, potentially with different hydro-climatic properties, and thus different aquatic community structure, often producing unrealistic ecohydraulic outputs (Hudson et al., 2003). Consequently, the development of HSCs for aquatic biota from various river reaches is a crucial step towards applying accurate and ecologically credible ecohydraulic models.

We developed and compared HSCs for freshwater macroinvertebrates from Mediterranean (Greek) and semi-arid (Moroccan) river reaches, to (i) examine potential differences in the habitat preferences of benthic macro-invertebrates from different climatic zones, and (ii) provide a robust biological input for relevant ecohydraulic simulations in Greek and Moroccan river basins, thus overcoming the need to extrapolate HSCs between reaches, which has often led to inaccurate or unrealistic ecohydraulic results.

2. Materials and methods

We measured flow velocity (V; m/s), water depth (D; m) and the type of substrate (S; see Theodoropoulos et al., 2018), and collected macroinvertebrates using a rectangular hand-net from (i) 59 unpolluted microhabitats across the upper Oum Er-Rbia River, Morocco (semi-arid climate) and (ii) 380 unpolluted microhabitats from various streams and rivers of similar hydro-climatic properties in Greece (Mediterranean climate). Each microhabitat was 0.25 x 0.25 m^2 wide. The resulting datasets included observations of V, D, S and macroinvertebrate taxa, which were converted to a community-based habitat suitability index (K) as follows:

$$\mathbf{K_i = 0.4\ n_i + 0.3\ H_i\ + 0.2\ EPT_i + 0.1\ a_i}$$

where K_i is the habitat suitability of the i^{th} microhabitat, n_i, H_i, EPT_i and a_i are the macroinvertebrate taxonomic richness (family level), the Shannon's diversity index, the richness of Ephemeroptera, Plecoptera and Trichoptera and the abundance of the i^{th} microhabitat, respectively. All K_i values were normalized to the 0-1 scale by dividing by the maximum K at each river reach to account for potential spatial and/or temporal autocorrelation. Statistical relationships (p and R^2 values) between hydraulic variables (V, D, S) and K were produced, via generalized linear mixed-effects models using the GAMLSS package (Rigby and Stasinopoulos, 2005) in R version 4.0.1. HSCs were similarly developed using generalized additive models.

3. Results and discussion

In the Moroccan river reaches (semi-arid climate), water depth and substrate type were the major drivers of macroinvertebrate habitat suitability, being statistically significant and strongly correlated with K ($R^2 > 0.5$). In the Greek river reaches (Mediterranean climate), macroinvertebrate K was significantly influenced by water depth and flow velocity (Table 1), however, correlations were weak to moderate ($0.32 \geq R^2 \geq 0.14$).

Table 1. Statistical significance (p) and strength of correlation (pseudo-R^2) between hydraulic variables and macroinvertebrate habitat suitability using generalized linear mixed-effects models (**<0.01; *<0.05).

Hydraulic variables	Habitat suitability | Greece		Habitat suitability | Morocco	
	p	R^2	p	R^2
Flow velocity (m/s)	0.046*	0.14	0.248	0.64
Water depth (m)	3.41e-16**	0.32	0.01**	0.51
Substrate type	0.15	0.13	0.001**	0.81

Macroinvertebrates mostly preferred shallow, rocky habitats (large gravel, small, large stones and boulders; optimal D values between 0.1 m and 0.2 m). In the Greek river reaches, macroinvertebrates preferred slow to moderately flowing waters (with wider optimal V range, from 0.4 m/s to 0.9 m/s), in contrast to the Moroccan reaches, where they mostly preferred moderately flowing waters (with narrower optimal V range, from 0.65 m/s to 0.85 m/s). In the Greek river reaches, they had increased tolerance for suboptimal flow velocities: they could largely tolerate V > 0.7 m/s up to 1 m/s and V < 0.4 m/s (K remained > 0.5). In contrast, in the Moroccan reaches, K became unsuitable (< 0.5) in V < 0.6 and V > 0.8 m/s, as well as in D < 0.05 and D > 0.15 m.

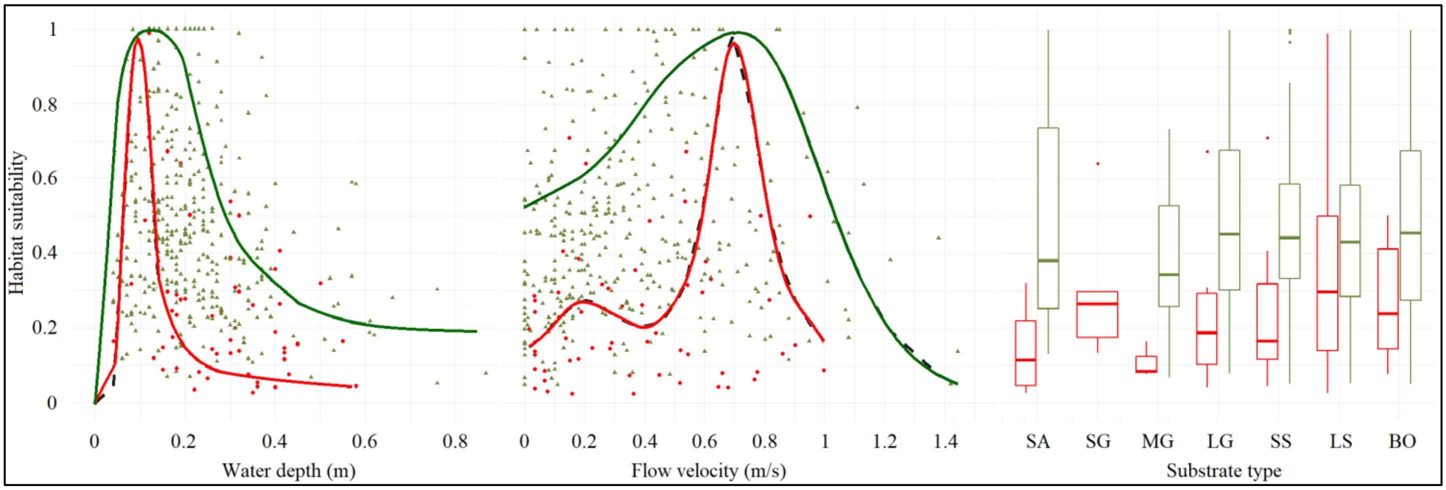

Figure 1. Habitat suitability curves for frehswater macroinvertebrates from the Greek (green; n=380) and Moroccan (red, n=59) river reaches. SA: Sand; SG, MG, LG: Small, medium, large gravel; SS, LS: Small, large stones; BO: Boulders

4. Conclusion

Macroinvertebrates in Mediterranean and semi-arid river reaches were influenced by different hydraulic drivers (D and S in the Moroccan river reaches; D and V in the Greek river reaches). Moreover, their optimal habitat preferences between the two areas were different. We conclude that the use of macroinvertebrate HSCs in river reaches of different hydro-climatic properties will likely produce unrealistic ecohydraulic outputs, which may further lead to inadequate environmental flow recommendations and thus, inadequate freshwater management strategies.

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Link: https://www.iahreuropecongress.org/PDF/IAHR2022_ABSTRACT_BOOK.pdf

Proceedings of the 12th Marine and Inland Waters Research Symposium
(pp. 75-81)

Habitat suitability curves for benthic macroinvertebrates from a large North African river (Oum Er-Rbia, Morocco)

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Abstract

Benthic macroinvertebrates have been widely used as biological indicators, in riverine ecosystems, to provide information on the ecological response to natural and anthropogenic disturbances. Arid and semi-arid north African countries are facing severe climatic pressures, intensified by human activities, but regional research on the biological response to such pressures is limited. In this work, we collected abiotic data and benthic macroinvertebrates (BMs) from the mid-reaches of the Oum Er-Rbia River, Morocco. We used generalized linear mixed-effects models to search for statistically significant relationships between variables, and to develop habitat suitability curves for BMs and major drivers of their community structure (water depth, flow velocity, water temperature, substrate type). BMs habitat suitability was highest in shallow (<0.2 m), fast-flowing (0.5-0.75 m/s), rocky habitats (large stones). The developed habitat suitability curves can be used for implementing ecohydraulic simulations as mitigation tools for the sustainable management and conservation of these vulnerable arid/semi-arid ecosystems.

Keywords: HSCs, GLMMs, Morocco, Semi-arid climate

1. Introduction

Flow variability is a crucial driver of the distribution, abundance and diversity of aquatic communities in riverine ecosystems (Allan, 1995). Among the variety of organisms that have been used for the exploration of the status and the structural-functional characteristics of aquatic ecosystems, research has largely incorporated benthic macroinvertebrates (BMs) as bioindicators, since their immense biodiversity and relevant environmental response can provide valuable information, especially in cases of climatic and human pressures (Karaouzas *et al.,* 2019; Theodoropoulos & Karaouzas, 2021).

Studies have shown that ecosystems in semi-arid to arid regions, such as the North African landscapes, are critically sensitive due to their potential transition to desert-like zones (Kacem *et al.*, 2019; Bedoui, 2020), a phenomenon commonly called desertification (Safriel, 2009). However, research on the response of BMs in arid/semi-arid ecosystems, that would inform proactive and reactive ecological management strategies in these areas, is rather limited.

The purpose of this study was to develop habitat suitability curves (HSCs) for major environmental and hydrological variables that affect the structure and distribution of BMs, ultimately aiming to model the ecohydraulic properties of the largest Moroccan river (Oum Er-Rbia) using BMs as bioindicators. This study could also be used for the implementation of relevant ecohydraulic simulations elsewhere in Morocco, in river basins of similar hydro-ecological properties.

2. Material and Methods

2.1 Study area

Our study area is located upstream of the Al Massira Dam (32° 30'N, 7° 30'W; Morocco), the second largest national artificial reservoir (Bousseba *et al.*, 2020), in the middle reaches of the longest perennial Moroccan river Oum Er-Rbia. The regional climate is described as semi-arid to arid (Bousseba *et al.*, 2020). We sampled BMs, as well as environmental and hydrological variables in 59 microhabitats between the cities of Lamrapta and Kasba Tadla (reach length: 50km; mean elevation: 450 m a.s.l.), in December 2021.

2.2 Data collection and analysis

BMs sampling was carried out in 59 microhabitats, using a 0.25 m x 0.25 m sampler with a mesh size of 500 µm. All samples were preserved in bottles containing 70% ethanol and were transferred to the laboratory for analysis. At each microhabitat, hydraulic variables (V: flow velocity, m/s; D: depth, m) were measured with a OTTC2-1® discharge measurement meter, while temperature (T: ºC), conductivity (C: µs/cm) and pH were recorded with a Hanna HI9828/4-01® water quality multi-parameter probe. Moreover, substrate type (S) was visually identified based on the categories shown in Table 1. Afterwards, microhabitat suitability was calculated using two alternatives (normalized and standardized) of a widely used BM-based habitat suitability index (SI; Theodoropoulos *et al.*, 2018 and references therein), as follows:

$$Ks_i = 0.4n_i + 0.3H_i + 0.2EPT_i + 0.1a_i \ [1]$$

$$Kn_i = 0.4\frac{n_i}{n_{i[max]}} + 0.3\frac{H_i}{H_{i[max]}} + 0.2\frac{EPT_i}{EPT_{i[max]}} + 0.1\frac{a_i}{a_{i[max]}} \; [2]$$

$$Ks_i = \frac{\sum_{i=1}^{N} K_i}{K_{i[max]}} \; [3]$$

where K_i is the habitat suitability of the i^{th} habitat; n_i is the number of the BMs taxa (families); H_i denotes the Shannon's diversity index; EPT_i is the number of Ephemeroptera-Plecoptera-Trichoptera (EPT) taxa; a_i is the abundance of BMs taxa; N is the total number of the i^{th} habitats; while Kn_i and Ks_i express the normalized and the standardized SI, ranging from 0 (unsuitable) to 1 (optimal habitat). Finally, we used generalized linear mixed-effects models (GLMMs) to search for statistically significant relationships between the dependent variable (Ks) and each explanatory abiotic variable (V, D, T, S, pH, C), by simultaneously excluding the effects of other abiotic variables (included as random effects). Significant relationships were identified by calculating the p-value and the Cox-Snell pseudo-R^2 for each model. All analyses were implemented in the non-parametric R package 'Generalized Additive Models for Location, Scale and Shape' (GAMLSS; Rigby & Stasinopoulos, 2005). Moreover, the GLMMs-based SI curves were depicted in the two-dimensional scale, and we additionally applied a smoother function (i.e., GAM) to detect minor local variations of the data. All analyses and visualizations were performed using the R 4.0.5 free software environment for statistical computing and graphics.

Table 2. Substrate type classification scheme applied during sampling (Scheider *et al.*, 2010).

Substrate type (Descriptor)	Grain size (mm)	ID
Silt	0.001-0.0625	1
Sand	0.0625-2	2
Small gravel	2-6	3
Medium gravel	6-20	4
Large gravel	20-60	5
Small stones	60-120	6
Large stones	120-200	7
Boulders	>200	8

3. Results

The K_s index was more robust for our dataset compared to K_n, since statistically significant and strong relationships were observed ($p<0.1$ and pseudo-$R^2>0.6$) for the majority of the abiotic variables (Table 2). As a result, we used the Ks to produce the HSCs with the integration of GLMMs for depth, flow, temperature and the substrate type.

Table 3. Statistical parameters (p-value and pseudo-R^2) of the generalized linear mixed-effects models for the multivariate response of the normalized and standardized suitability index (Kn; Ks) and the explanatory abiotic parameters. The asterisk (*) indicates the level of statistical significance ($p^{**}<0.05$; $p^{*}<0.1$).

Abiotic parameters	**Kn** (normalized SI)		**Ks** (standardized SI)	
	p-value	**pseudo-R^2**	**p-value**	**pseudo-R^2**
Flow* (V; m/s)	0.315	0.46	0.07*	0.72
Depth* (D; m)	0.036**	0.51	0.00005**	0.61
Temperature* (°C)	0.434	0.56	0.0545*	0.6
Substrate* (S)	0.0004**	0.63	0.000765**	0.78
pH	0.409	0.53	0.401	0.59
Conductivity (C)	0.0006**	0.18	0.283	0.73

BMs in the Oum Er-Rbia River had optimal habitat preferences in depths from 0 m to 0.2 m, while in deeper habitats there was a constant decrease of Ks (Fig. 1). Flow velocity suitability was optimal from 0.5 m/s to 0.75 m/s, while lower/higher velocity values indicated less-suitable preferences. Temperature suitability peaked at 13.6°C. Regarding substrate type, large stones (Table 1; ID=7) were characterized as the optimal suitable substrate type. All HSCs (Fig. 1) showed a unique peak ($Ks_{[max]}$), indicating a homogenous reaction to the environmental effects.

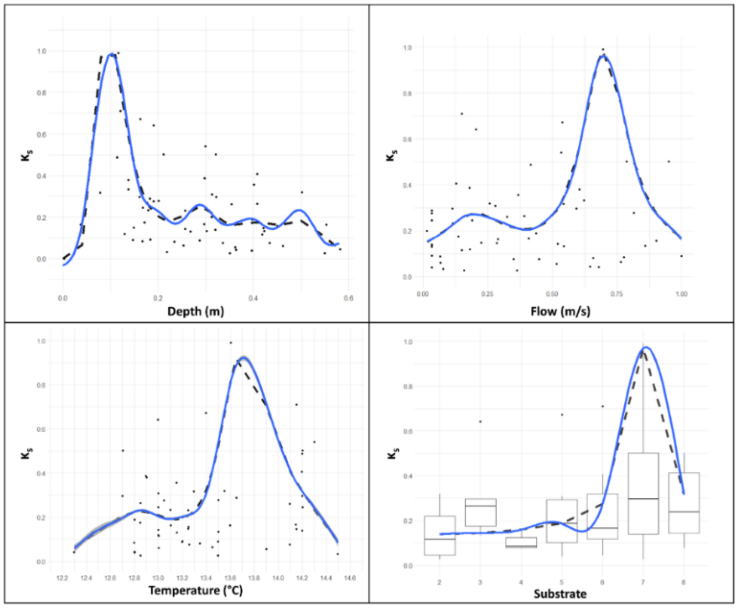

Figure 3. Habitat suitability curves (HSCs; 0-1) for benthic macroinvertebrates in the Oum Er-Rbia River (Morocco; North Africa) based on the standardized suitability index (Ks) for water depth (m), flow velocity (m/s), water temperature (°C) and substrate type (S). The selected curves were produced and statistically validated using the generalized linear mixed-effects models (GLMMs, dashed black line; smoother, blue line; n=59).

4. Discussion

We developed HSCs for BMs in Oum Er-Rbia, the largest perennial river in Morocco, setting for the first time the biological base for ecohydraulic simulations both across the specific river and in the wider North African region. Our comparative analysis between the investigated indices (K_n; K_s) showed that the standardized suitability index (K_s) fitted our dataset best. The response of BMs to depth, flow velocity and substrate is in agreement with previous works in Mediterranean basins (e.g., Greece: Theodoropoulos *et al.*,2018). More specifically, increased suitability was observed in shallow, fast-flowing habitats (Fig. 1), an expected outcome since this abiotic combination can facilitate ecological niches with adequate spatiotemporal supply of energy resources (e.g., detritus) and increased water purification rates (Khudhair *et al.*, 2019). Additionally, the large sized riffle-rocks (i.e., large stones; Table 1) was the optimal substrate, providing stable and constant conditions of substrate and flow, respectively, as well as protection from predators (Ramirez *et al.*, 1998; Theodoropoulos *et al.*, 2018). In accordance with the study of Karaouzas *et al.*, 2019, our analysis validated that BMs communities, and thus their habitat preferences, are highly influenced by hydrological-hydraulic drivers.

North African regions are facing climatic and human-exploitation related pressures, such as desertification (Kacem *et al.*, 2019; Bedoui, 2020), which may harm local human communities (e.g., increase poverty rates) and biodiversity as well (Reynolds *et al.*, 2007). Except for its ecological relevance, the outcome of this study can be used as the biological reference for the implementation of ecohydraulic simulations for mitigating the impacts of climatic pressures and/or for the formulation of conservation strategies for these highly vulnerable aquatic ecosystems.

5. Acknowledgements

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Link: https://symposia.gr/wp-content/uploads/2022/09/Programme-1.pdf

Appendix II: Simulation log files

Ziz river [Optimal Ecological flow: 2 m^3s^{-1}]

Time step	Simulation time (s)	Outflow discharge (m^3s^{-1})	Δ-change
1	**0.162036**	≈0	**0.006028**
2	0.296448	≈0	0.004822
3	0.435817	≈0	0.004826
4	0.580202	≈0	0.004883
5	0.728049	≈0	0.004922
6	0.878248	≈0	0.004932
7	1.030505	≈0	0.004933
8	1.184831	≈0	0.004933
9	1.34124	≈0	0.004935
10	1.499711	≈0	0.004936
11	1.660222	≈0	0.004937
12	1.822777	≈0	0.004937
13	1.987402	≈0	0.004936
14	2.154148	≈0	0.004935
15	2.323088	≈0	0.004933
16	2.494312	≈0	0.004931
17	2.667932	≈0	0.004928
18	2.844072	≈0	0.004926
19	3.022866	≈0	0.004923
20	3.204455	≈0	0.004921
21	3.388977	≈0	0.004918
22	3.57657	≈0	0.004916
23	3.767366	≈0	0.004914
24	3.961494	≈0	0.004912
25	4.159084	≈0	0.004911
26	4.360267	≈0	0.004909
27	4.565184	≈0	0.004907

28	4.77399	≈0	0.004905
29	4.986861	≈0	0.004902
30	5.203999	≈0	0.004899
31	5.425633	≈0	0.004895
32	5.652025	≈0	0.004891
33	5.883471	≈0	0.004886
34	6.120297	≈0	0.004882
35	6.36286	≈0	0.004877
36	6.611546	≈0	0.004872
37	6.866767	≈0	0.004867
38	7.128958	≈0	0.004862
39	7.398578	≈0	0.004858
40	7.676108	≈0	0.004853
41	7.962045	≈0	0.004849
42	8.25689	≈0	0.004846
43	8.561121	≈0	0.004843
44	8.875191	≈0	0.004842
45	9.199483	≈0	0.004843
46	9.534265	≈0	0.004847
47	9.879615	≈0	0.004855
48	10.235283	≈0	0.004868
49	10.600626	≈0	0.004887
50	10.97441	≈0	0.004915
51	11.354695	≈0	0.004938
52	11.739773	≈0	0.004943
53	12.12933	≈0	0.00493
54	12.524381	≈0	0.004938
55	12.924427	≈0	0.004973
56	13.326646	≈0	0.005011
57	13.728001	≈0	0.005042
58	14.126044	≈0	0.005091

59	14.516993	≈0	0.005091
60	14.900922	≈0	0.005004
61	15.284573	≈0	0.004942
62	15.672729	≈0	0.005002
63	16.060737	≈0	0.005099
64	16.441247	≈0	0.005132
65	16.811974	≈0	0.005184
66	17.169523	≈0	0.005123
67	17.51848	≈0	0.004969
68	17.869634	≈0	0.004902
69	18.227832	≈0	0.004938
70	18.590532	≈0	0.005046
71	18.949935	≈0	0.005072
72	19.304245	≈0	0.00507
73	19.653681	≈0	0.005058
74	19.999125	≈0	0.00504
75	20.34182	≈0	0.004951
76	20.687909	≈0	0.004919
77	21.039667	≈0	0.004938
78	21.39583	≈0	0.004982
79	21.753266	≈0	0.004962
80	22.113433	≈0	0.005026
81	22.471767	≈0	0.005009
82	22.829428	≈0	0.004958
83	23.190132	≈0	0.004869
84	23.560573	≈0	0.004869
85	23.94098	≈0	0.004901
86	24.329067	≈0	0.004927
87	24.722899	≈0	0.004986
88	25.11783	≈0	0.004992
89	25.513401	≈0	0.00499

90	25.909763	≈0	0.004934
91	26.311403	≈0	0.00482
92	26.72807	≈0	0.004805
93	27.161674	≈0	0.004894
94	27.604708	≈0	0.00496
95	28.051356	≈0	0.004945
96	28.502953	≈0	0.004904
97	28.963427	≈0	0.004916
98	29.431733	≈0	0.004908
99	29.908853	≈0	0.004847
100	30.401017	≈0	0.004863
101	30.907056	≈0	0.004808
102	31.433298	≈0	0.004831
103	31.977906	≈0	0.004864
104	32.537744	≈0	0.004955
105	33.102678	≈0	0.005057
106	33.661201	≈0	0.004911
107	34.229861	≈0	0.004735
108	34.830315	≈0	0.004714
109	35.467261	≈0	0.004841
110	36.12517	≈0	0.004939
111	36.791177	≈0	0.004905
112	37.470032	≈0	0.004779
113	38.180219	≈0	0.004714
114	38.933573	≈0	0.004763
115	39.724359	≈0	0.004863
116	40.537482	≈0	0.004734
117	41.396334	≈0	0.004665
118	42.316765	≈0	0.00487
119	43.261755	≈0	0.004887
120	44.228682	≈0	0.004592

121	45.281548	≈0	0.004435
122	46.468545	≈0	0.004556
123	47.771244	≈0	0.004843
124	49.116292	≈0	0.004879
125	50.494751	≈0	0.004159
126	52.15195	≈0	0.004393
127	54.038224	≈0	0.004648
128	56.067543	≈0	0.005297
129	57.982972	≈0	0.004599
130	60.065563	≈0	0.004331
131	62.469737	≈0	0.004711
132	65.021469	≈0	0.005131
133	67.508004	≈0	0.004792
134	70.102298	≈0	0.004505
135	72.98164	≈0	0.004199
136	76.410502	≈0	0.004428
137	80.282249	≈0	0.005373
138	83.885072	≈0	0.003779
139	88.652157	≈0	0.004466
140	93.988685	≈0	0.00566
141	98.70311	≈0	0.005338
142	103.118745	≈0	0.004247
143	108.31772	≈0	0.005515
144	113.031483	≈0	0.004607
145	118.147646	≈0	0.004638
146	123.663091	≈0	0.004638
147	129.609251	≈0	0.005229
148	135.295105	≈0	0.004572
149	141.513073	≈0	0.004396
150	148.585056	≈0	0.006009
151	154.469566	≈0	0.004245

152	161.400766	≈0	0.004442
153	169.203205	≈0	0.005678
154	176.073468	≈0	0.004533
155	183.651295	≈0	0.004169
156	192.739786	≈0	0.005116
157	201.622282	≈0	0.004961
158	210.575129	≈0	0.004685
159	220.129512	≈0	0.004384
160	231.027524	≈0	0.005463
161	241.00273	≈0	0.004872
162	251.239762	≈0	0.004381
163	262.924445	≈0	0.00516
164	274.246423	≈0	0.004637
165	286.454816	≈0	0.004969
166	298.740083	≈0	0.004872
167	311.346946	≈0	0.004757
168	324.598788	≈0	0.004443
169	339.511317	≈0	0.005003
170	354.41623	≈0	0.005239
171	368.639884	≈0	0.004401
172	384.797696	≈0	0.004878
173	401.359558	≈0	0.005623
174	416.085938	≈0	0.004635
175	431.972347	≈0	0.004444
176	449.845065	≈0	0.005459
177	466.214809	≈0	0.004686
178	483.680782	≈0	0.004591
179	502.702387	≈0	0.005098
180	521.357508	≈0	0.004908
181	540.360497	≈0	0.004504
182	561.455592	≈0	0.005074

183	582.243639	≈0	0.005355
184	601.652805	≈0	0.004696
185	622.318019	≈0	0.004905
186	643.38193	≈0	0.005118
187	663.958877	≈0	0.004865
188	685.108671	≈0	0.00503
189	706.133273	≈0	0.005128
190	726.634983	≈0	0.00461
191	748.870982	≈0	0.005197
192	770.26322	≈0	0.005012
193	791.60593	≈0	0.004441
194	815.634392	≈0	0.005189
195	838.788431	≈0	0.005097
196	861.503726	≈0	0.005017
197	884.143675	≈0	0.004638
198	908.551881	≈0	0.005288
199	931.631932	≈0	0.004572
200	956.870916	≈0	0.004975
201	982.234182	≈0	0.005366
202	1005.865933	≈0	0.00455
203	1031.835449	≈0	0.005013
204	1057.737939	≈0	0.005309
205	1082.131469	≈0	0.00493
206	1106.871746	≈0	0.005357
207	1129.964596	≈0	0.004854
208	1153.751828	≈0	0.004777
209	1178.647193	≈0	0.0054
210	1201.696969	≈0	0.004692
211	1226.260826	≈0	0.004748
212	1252.129596	≈0	0.005326
213	1276.416692	≈0	0.004471

214	1303.579674	≈0	0.005345
215	1328.990789	≈0	0.005211
216	1353.375311	≈0	0.00444
217	1380.835422	≈0	0.005294
218	1406.769593	≈0	0.00527
219	1431.376792	≈0	0.004682
220	1457.652518	≈0	0.00498
221	1484.033331	≈0	0.005064
222	1510.083075	≈0	0.004907
223	1536.62894	≈0	0.004803
224	1564.262534	≈0	0.005292
225	1590.370417	≈0	0.004644
226	1618.479934	≈0	0.005328
227	1644.860398	≈0	0.005253
228	1669.969791	≈0	0.004465
229	1698.088546	≈0	0.005732
230	1722.615046	≈0	0.005004
231	1747.122717	≈0	0.00422
232	1776.158181	≈0	0.005299
233	1803.556086	≈0	0.005128
234	1830.269967	≈0	0.004657
235	1858.949906	≈0	0.004763
236	1889.059075	≈0	0.005797
237	1915.028286	≈0	0.004431
238	1944.332379	≈0	0.005248
239	1972.249541	≈0	0.004904
240	2000.714848	≈0	0.005319
241	2027.472782	≈0	0.004678
242	2056.072243	≈0	0.004989
243	2084.734886	≈0	0.004536
244	2116.331404	≈0	0.00506

245	2147.552578	≈0	0.005186
246	2177.656354	≈0	0.00482
247	2208.883034	≈0	0.004715
248	2241.99485	≈0	0.004968
249	2275.321685	≈0	0.005195
250	2307.398237	≈0	0.004839
251	2340.544397	≈0	0.004772
252	2375.273197	≈0	0.005184
253	2408.767182	≈0	0.005861
254	2437.342389	≈0	0.004728
255	2467.558854	≈0	0.004825
256	2498.872838	≈0	0.005175
257	2529.12795	≈0	0.005322
258	2557.553686	≈0	0.005047
259	2585.716604	≈0	0.005268
260	2612.448923	≈0	0.005277
261	2637.777976	≈0	0.004643
262	2665.053998	≈0	0.005478
263	2689.950023	≈0	0.005173
264	2714.014596	≈0	0.004927
265	2738.434316	≈0	0.005432
266	2760.912798	0.0010022	0.005198
267	2782.537075	0.00166836	0.005324
268	2802.844332	0.00184419	0.005991
269	2819.791886	0.00129864	0.005755
270	2834.514814	0.161657	0.00421
271	2851.999955	0.189277	0.003689
272	2875.698356	0.220122	0.004337
273	2903.019703	0.271813	0.004457
274	2933.670285	0.31875	0.004608
275	2966.928068	0.365921	0.004618
276	3002.934554	0.408497	0.004755

277	3040.798083	0.446573	0.004679
278	3081.260922	0.478787	0.004808
279	3123.343036	0.524514	0.004756
280	3167.583029	0.565528	0.004821
281	3213.462902	0.593664	0.004829
282	3260.967191	0.621919	0.004829
283	3310.154505	0.670438	0.004792
284	3361.473831	0.702327	0.004788
285	3415.070197	0.735063	0.004824
286	3470.624879	0.765481	0.004838
287	3528.043897	0.790347	0.004906
288	3586.558073	0.81596	0.004876
289	3646.562763	0.854586	0.00477
290	3709.465149	0.893393	0.004803
291	3774.945722	0.9273	0.004814
292	3842.955331	0.959295	0.004795
293	3913.86853	0.989405	0.004801
294	3987.728214	1.01867	0.004797
295	4064.7097	1.04711	0.004795
296	4144.987943	1.07462	0.004794
297	4228.717104	1.101	0.004796
298	4316.001154	1.12685	0.004793
299	4407.056283	1.15391	0.004777
300	4502.364324	1.18016	0.004781
301	4602.043004	1.20562	0.004781
302	4702.043004	1.22935	0.004596
303	4802.043004	1.25141	0.004415
304	4902.043004	1.27206	0.004251
305	5002.043004	1.29154	0.004102
306	5102.043004	1.31	0.003968
307	5202.043004	1.32757	0.003847
308	5302.043004	1.34429	0.003736
309	5402.043004	1.36017	0.003639

310	5502.043004	1.37519	0.003541
311	5602.043004	1.38934	0.003456
312	5702.043004	1.40267	0.003387
313	5802.043004	1.41524	0.003316
314	5902.043004	1.42705	0.003235
315	6002.043004	1.43809	0.003156
316	6102.043004	1.44836	0.003092
317	6202.043004	1.45796	0.003036
318	6302.043004	1.46701	0.002986
319	6402.043004	1.4756	0.00294
320	6502.043004	1.48382	0.002899
321	6602.043004	1.49172	0.00286
322	6702.043004	1.49934	0.002824
323	6802.043004	1.50671	0.002789
324	6902.043004	1.51386	0.002756
325	7002.043004	1.52078	0.002725
326	7102.043004	1.5275	0.002694
327	7202.043004	1.53402	0.002665
328	7302.043004	1.54034	0.002636
329	7402.043004	1.54646	0.002608
330	7502.043004	1.55241	0.002581
331	7602.043004	1.55816	0.002554
332	7702.043004	1.56374	0.002527
333	7802.043004	1.56914	0.002502
334	7902.043004	1.57437	0.002476
335	8002.043004	1.57944	0.002451
336	8102.043004	1.58437	0.002426
337	8202.043004	1.58915	0.002402
338	8302.043004	1.59381	0.002378
339	8402.043004	1.59834	0.002354
340	8502.043004	1.60275	0.00233
341	8602.043004	1.60706	0.002307
342	8702.043004	1.61126	0.002284

343	8802.043004	1.61536	0.002261
344	8902.043004	1.61938	0.002239
345	9002.043004	1.62331	0.002216
346	9102.043004	1.62715	0.002194
347	9202.043004	1.63092	0.002172
348	9302.043004	1.63462	0.002151
349	9402.043004	1.63824	0.002129
350	9502.043004	1.6418	0.002108
351	9602.043004	1.6453	0.002087
352	9702.043004	1.64874	0.002066
353	9802.043004	1.65212	0.002046
354	9902.043004	1.65545	0.002025
355	10002.043	1.65872	0.002005
356	10102.043	1.66195	0.001985
357	10202.043	1.66513	0.001965
358	10302.043	1.66826	0.001946
359	10402.043	1.67135	0.001926
360	10502.043	1.6744	0.001907
361	10602.043	1.6774	0.001888
362	10702.043	1.68037	0.001869
363	10802.043	1.68329	0.001851
364	10902.043	1.68618	0.001832
365	11002.043	1.68903	0.001814
366	11102.043	1.69185	0.001796
367	11202.043	1.69463	0.001778
368	11302.043	1.69738	0.00176
369	11402.043	1.7001	0.001743
370	11502.043	1.70278	0.001725
371	11602.043	1.70544	0.001708
372	11702.043	1.70806	0.001691
373	11802.043	1.71065	0.001674
374	11902.043	1.71322	0.001657
375	12002.043	1.71575	0.001641

376	12102.043	1.71826	0.001625
377	12202.043	1.72074	0.001608
378	12302.043	1.7232	0.001592
379	12402.043	1.72562	0.001576
380	12502.043	1.72803	0.001561
381	12602.043	1.73041	0.001545
382	12702.043	1.73276	0.00153
383	12802.043	1.73509	0.001514
384	12902.043	1.7374	0.001499
385	13002.043	1.73969	0.001484
386	13102.043	1.74196	0.00147
387	13202.043	1.7442	0.001455
388	13302.043	1.74643	0.001441
389	13402.043	1.74863	0.001426
390	13502.043	1.75081	0.001412
391	13602.043	1.75297	0.001398
392	13702.043	1.75512	0.001384
393	13802.043	1.75724	0.00137
394	13902.043	1.75934	0.001357
395	14002.043	1.76143	0.001343
396	14102.043	1.76349	0.00133
397	14202.043	1.76554	0.001317
398	14302.043	1.76756	0.001303
399	14402.043	1.76957	0.00129
400	14502.043	1.77156	0.001278
401	14602.043	1.77354	0.001265
402	14702.043	1.77549	0.001252
403	14802.043	1.77743	0.00124
404	14902.043	1.77935	0.001228
405	15002.043	1.78125	0.001215
406	15102.043	1.78313	0.001203
407	15202.043	1.785	0.001191
408	15302.043	1.78685	0.00118

409	15402.043	1.78868	0.001168
410	15502.043	1.7905	0.001156
411	15602.043	1.7923	0.001145
412	15702.043	1.79408	0.001133
413	15802.043	1.79585	0.001122
414	15902.043	1.7976	0.001111
415	16002.043	1.79934	0.0011
416	16102.043	1.80106	0.001089
417	16202.043	1.80276	0.001078
418	16302.043	1.80445	0.001068
419	16402.043	1.80612	0.001057
420	16502.043	1.80778	0.001047
421	16602.043	1.80943	0.001036
422	16702.043	1.81105	0.001026
423	16802.043	1.81267	0.001016
424	16902.043	1.81427	0.001006
425	17002.043	1.81585	≈0
426	17102.043	1.81742	≈0
427	17202.043	1.81898	≈0
428	17302.043	1.82052	≈0
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430	17502.043	1.82357	≈0
431	17602.043	1.82507	≈0
432	17702.043	1.82655	≈0
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435	18002.043	1.83094	≈0
436	18102.043	1.83237	≈0
437	18202.043	1.83379	≈0
438	18302.043	1.8352	≈0
439	18402.043	1.8366	≈0
440	18502.043	1.83798	≈0

441	18602.043	1.83935	≈0
442	18702.043	1.84071	≈0
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444	18902.043	1.84339	≈0
445	19002.043	1.84471	≈0
446	19102.043	1.84602	≈0
447	19202.043	1.84732	≈0
448	19302.043	1.8486	≈0
449	19402.043	1.84988	≈0
450	19502.043	1.85114	≈0
451	19602.043	1.85239	≈0
452	19702.043	1.85363	≈0
453	19802.043	1.85486	≈0
454	19902.043	1.85607	≈0
455	20002.043	1.85728	≈0
456	20102.043	1.85848	≈0
457	20202.043	1.85966	≈0
458	20302.043	1.86083	≈0
459	20402.043	1.862	≈0
460	20502.043	1.86315	≈0
461	20602.043	1.86429	≈0
462	20702.043	1.86542	≈0
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467	21202.043	1.87093	≈0
468	21302.043	1.872	≈0
469	21402.043	1.87307	≈0
470	21502.043	1.87412	≈0
471	21602.043	1.87516	≈0

472	21702.043	1.87619	≈0
473	21802.043	1.87721	≈0
474	21902.043	1.87823	≈0
475	22002.043	1.87923	≈0
476	22102.043	1.88022	≈0
477	22202.043	1.88121	≈0
478	22302.043	1.88218	≈0
479	22402.043	1.88315	≈0
480	22502.043	1.8841	≈0
481	22602.043	1.88505	≈0
482	22702.043	1.88599	≈0
483	22802.043	1.88692	≈0
484	22902.043	1.88784	≈0
485	23002.043	1.88875	≈0
486	23102.043	1.88966	≈0
487	23202.043	1.89055	≈0
488	23302.043	1.89144	≈0
489	23402.043	1.89232	≈0
490	23502.043	1.89319	≈0
491	23602.043	1.89405	≈0
492	23702.043	1.8949	≈0
493	23802.043	1.89575	≈0
494	23902.043	1.89659	≈0
495	24002.043	1.89742	≈0
496	24102.043	1.89824	≈0
497	24202.043	1.89906	≈0
498	24302.043	1.89987	≈0
499	24402.043	1.90067	≈0
500	**24502.043**	**1.90146**	**≈0**

≈0: *Value less than* $1*10^{-3}$

Oum Er Rbia river [Optimal Ecological Flow: 2 m^3s^{-1}]

Time step	Simulation time (s)	Outflow discharge (m^3s^{-1})	Δ-change
1	0.162036	≈0	0.003905
2	0.296448	≈0	0.007696
3	0.435817	≈0	0.01311
4	0.580202	≈0	0.0086
5	0.728049	≈0	0.00552
6	0.878248	≈0	0.003658
7	1.030505	≈0	0.002729
8	1.184831	≈0	0.00271
9	1.34124	≈0	0.002786
10	1.499711	≈0	0.002568
11	1.660222	≈0	0.002309
12	1.822777	≈0	0.001953
13	1.987402	≈0	0.001564
14	2.154148	≈0	0.001962
15	2.323088	≈0	0.002527
16	2.494312	≈0	0.003216
17	2.667932	≈0	0.003994
18	2.844072	≈0	0.004758
19	3.022866	≈0	0.006741
20	3.204455	≈0	0.007448
21	3.388977	≈0	0.00802
22	3.57657	≈0	0.009884
23	3.767366	≈0	0.02827
24	3.961494	≈0	0.014875
25	4.159084	≈0	0.01435
26	4.360267	≈0	0.009002
27	4.565184	≈0	0.007081
28	4.77399	≈0	0.006241
29	4.986861	≈0	0.005849

30	5.203999	≈0	0.005664
31	5.425633	≈0	0.005685
32	5.652025	≈0	0.005533
33	5.883471	≈0	0.005714
34	6.120297	≈0	0.005532
35	6.36286	≈0	0.005744
36	6.611546	≈0	0.005403
37	6.866767	≈0	0.005428
38	7.128958	≈0	0.005279
39	7.398578	≈0	0.005145
40	7.676108	≈0	0.005253
41	7.962045	≈0	0.005144
42	8.25689	≈0	0.005074
43	8.561121	≈0	0.005004
44	8.875191	≈0	0.005057
45	9.199483	≈0	0.00494
46	9.534265	≈0	0.00489
47	9.879615	≈0	0.004826
48	10.235283	≈0	0.004713
49	10.600626	≈0	0.004829
50	10.97441	≈0	0.004821
51	11.354695	≈0	0.004818
52	11.739773	≈0	0.004701
53	12.12933	≈0	0.004967
54	12.524381	≈0	0.004824
55	12.924427	≈0	0.004688
56	13.326646	≈0	0.004822
57	13.728001	≈0	0.004786
58	14.126044	≈0	0.00471
59	14.516993	≈0	0.004839
60	14.900922	≈0	0.004909

61	15.284573	≈0	0.005122
62	15.672729	≈0	0.004957
63	16.060737	≈0	0.005198
64	16.441247	≈0	0.005036
65	16.811974	≈0	0.005234
66	17.169523	≈0	0.00522
67	17.51848	≈0	0.005352
68	17.869634	≈0	0.005392
69	18.227832	≈0	0.005379
70	18.590532	≈0	0.005798
71	18.949935	≈0	0.005554
72	19.304245	≈0	0.005603
73	19.653681	≈0	0.00551
74	19.999125	≈0	0.005706
75	20.34182	≈0	0.005815
76	20.687909	≈0	0.005479
77	21.039667	≈0	0.005814
78	21.39583	≈0	0.005522
79	21.753266	≈0	0.005779
80	22.113433	≈0	0.005528
81	22.471767	≈0	0.005668
82	22.829428	≈0	0.005303
83	23.190132	≈0	0.005141
84	23.560573	≈0	0.005246
85	23.94098	≈0	0.005398
86	24.329067	≈0	0.00531
87	24.722899	≈0	0.00543
88	25.11783	≈0	0.00516
89	25.513401	≈0	0.005117
90	25.909763	≈0	0.005308
91	26.311403	≈0	0.005455

92	26.72807	≈0	0.005652
93	27.161674	≈0	0.006093
94	27.604708	≈0	0.006452
95	28.051356	≈0	0.007266
96	28.502953	≈0	0.007523
97	28.963427	≈0	0.007723
98	29.431733	≈0	0.007322
99	29.908853	≈0	0.007215
100	30.401017	≈0	0.007155
101	30.907056	≈0	0.00745
102	31.433298	≈0	0.00739
103	31.977906	≈0	0.007753
104	32.537744	≈0	0.008294
105	33.102678	≈0	0.008083
106	33.661201	≈0	0.007281
107	34.229861	≈0	0.006906
108	34.830315	≈0	0.007443
109	35.467261	≈0	0.008448
110	36.12517	≈0	0.009019
111	36.791177	≈0	0.009484
112	37.470032	≈0	0.009207
113	38.180219	≈0	0.008471
114	38.933573	≈0	0.00806
115	39.724359	≈0	0.007618
116	40.537482	≈0	0.007409
117	41.396334	≈0	0.007163
118	42.316765	≈0	0.007352
119	43.261755	≈0	0.008689
120	44.228682	≈0	0.007978
121	45.281548	≈0	0.007164
122	46.468545	≈0	0.006915

123	47.771244	≈0	0.006784
124	49.116292	≈0	0.006694
125	50.494751	≈0	0.006815
126	52.15195	≈0	0.007365
127	54.038224	≈0	0.007502
128	56.067543	≈0	0.007121
129	57.982972	≈0	0.007286
130	60.065563	≈0	0.007211
131	62.469737	≈0	0.007745
132	65.021469	≈0	0.007261
133	67.508004	≈0	0.007437
134	70.102298	≈0	0.007264
135	72.98164	≈0	0.007758
136	76.410502	≈0	0.00837
137	80.282249	≈0	0.007718
138	83.885072	≈0	0.007341
139	88.652157	≈0	0.0073
140	93.988685	≈0	0.007296
141	98.70311	≈0	0.007277
142	103.118745	≈0	0.007312
143	108.31772	≈0	0.007822
144	113.031483	≈0	0.007965
145	118.147646	≈0	0.008379
146	123.663091	≈0	0.00841
147	129.609251	≈0	0.008114
148	135.295105	≈0	0.00774
149	141.513073	≈0	0.007742
150	148.585056	≈0	0.008163
151	154.469566	≈0	0.00809
152	161.400766	≈0	0.007842
153	169.203205	≈0	0.007759

154	176.073468	≈0	0.007676
155	183.651295	≈0	0.007514
156	192.739786	≈0	0.007726
157	201.622282	≈0	0.007639
158	210.575129	≈0	0.007772
159	220.129512	≈0	0.008158
160	231.027524	≈0	0.008452
161	241.00273	≈0	0.008303
162	251.239762	≈0	0.008092
163	262.924445	≈0	0.007935
164	274.246423	≈0	0.008095
165	286.454816	≈0	0.00826
166	298.740083	≈0	0.00833
167	311.346946	≈0	0.008567
168	324.598788	≈0	0.008571
169	339.511317	≈0	0.008351
170	354.41623	≈0	0.008934
171	368.639884	≈0	0.00932
172	384.797696	≈0	0.00853
173	401.359558	≈0	0.008179
174	416.085938	≈0	0.008444
175	431.972347	≈0	0.009095
176	449.845065	≈0	0.009001
177	466.214809	≈0	0.008654
178	483.680782	≈0	0.008503
179	502.702387	≈0	0.008474
180	521.357508	≈0	0.008858
181	540.360497	≈0	0.008524
182	561.455592	≈0	0.01051
183	582.243639	≈0	0.009048
184	601.652805	≈0	0.008831

185	622.318019	≈0	0.008974
186	643.38193	≈0	0.00887
187	663.958877	≈0	0.008609
188	685.108671	≈0	0.009051
189	706.133273	≈0	0.009246
190	726.634983	≈0	0.008875
191	748.870982	≈0	0.008765
192	770.26322	≈0	0.008999
193	791.60593	≈0	0.009354
194	815.634392	≈0	0.009134
195	838.788431	≈0	0.009661
196	861.503726	≈0	0.010516
197	884.143675	≈0	0.0122
198	908.551881	≈0	0.013415
199	931.631932	≈0	0.015677
200	956.870916	0.515	0.010872
201	982.234182	0.558	0.009413
202	1005.865933	0.483	0.007728
203	1031.835449	0.749	0.007174
204	1057.737939	0.673	0.006641
205	1082.131469	0.791	0.006195
206	1106.871746	0.846	0.005412
207	1129.964596	0.917	0.004968
208	1153.751828	1.04	0.004569
209	1178.647193	1.03	0.003789
210	1201.696969	1.07	0.003554
211	1226.260826	1.11	0.003399
212	1252.129596	1.14	0.00327
213	1276.416692	1.17	0.003167
214	1303.579674	1.20	0.003077
215	1328.990789	1.22	0.002999
216	1353.375311	1.25	0.002934

217	1380.835422	1.27	0.002886
218	1406.769593	1.28	0.002846
219	1431.376792	1.30	0.002772
220	1457.652518	1.32	0.002718
221	1484.033331	1.34	0.002658
222	1510.083075	1.36	0.002605
223	1536.62894	1.38	0.002557
224	1564.262534	1.39	0.00251
225	1590.370417	1.41	0.002462
226	1618.479934	1.42	0.002411
227	1644.860398	1.44	0.002358
228	1669.969791	1.46	0.002306
229	1698.088546	1.47	0.002256
230	1722.615046	1.49	0.002207
231	1747.122717	1.50	0.00216
232	1776.158181	1.51	0.002113
233	1803.556086	1.53	0.002068
234	1830.269967	1.54	0.00202
235	1858.949906	1.55	0.001975
236	1889.059075	1.56	0.001929
237	1915.028286	1.57	0.001885
238	1944.332379	1.58	0.001841
239	1972.249541	1.59	0.001798
240	2000.714848	1.60	0.001755
241	2027.472782	1.61	0.001714
242	2056.072243	1.62	0.001673
243	2084.734886	1.63	0.001633
244	2116.331404	1.64	0.001594
245	2147.552578	1.65	0.001556
246	2177.656354	1.66	0.001518
247	2208.883034	1.66	0.001481
248	2241.99485	1.67	0.001445
249	2275.321685	1.68	0.00141

250	2307.398237	1.69	0.001376
251	2340.544397	1.69	0.001342
252	2375.273197	1.70	0.001309
253	2408.767182	1.71	0.001276
254	2437.342389	1.71	0.001245
255	2467.558854	1.72	0.001214
256	2498.872838	1.72	0.001184
257	2529.12795	1.73	0.001154
258	2557.553686	1.74	0.001125
259	2585.716604	1.74	0.001097
260	2612.448923	1.75	0.001069
261	2637.777976	1.75116	0.001042
262	2665.053998	1.75616	0.001016
263	2689.950023	1.76102	≈0
264	2714.014596	1.76575	≈0
265	2738.434316	1.77036	≈0
266	2760.912798	1.77484	≈0
267	2782.537075	1.77921	≈0
268	2802.844332	1.78345	≈0
269	2819.791886	1.78758	≈0
270	2834.514814	1.79159	≈0
271	2851.999955	1.79548	≈0
272	2875.698356	1.79927	≈0
273	2903.019703	1.80296	≈0
274	2933.670285	1.80654	≈0
275	2966.928068	1.81003	≈0
276	3002.934554	1.81342	≈0
277	3040.798083	1.81672	≈0
278	3081.260922	1.81993	≈0
279	3123.343036	1.82305	≈0
280	3167.583029	1.8261	≈0
281	3213.462902	1.82906	≈0

282	3260.967191	1.83194	≈0
283	3310.154505	1.83474	≈0
284	3361.473831	1.83748	≈0
285	3415.070197	1.84014	≈0
286	3470.624879	1.84272	≈0
287	3528.043897	1.84524	≈0
288	3586.558073	1.8477	≈0
289	3646.562763	1.85009	≈0
290	3709.465149	1.85242	≈0
291	3774.945722	1.85469	≈0
292	3842.955331	1.85691	≈0
293	3913.86853	1.85907	≈0
294	3987.728214	1.86117	≈0
295	4064.7097	1.86323	≈0
296	4144.987943	1.86523	≈0
297	4228.717104	1.86718	≈0
298	4316.001154	1.86908	≈0
299	4407.056283	1.87093	≈0
300	4502.364324	1.87274	≈0
301	4602.043004	1.87455	≈0
302	4702.043004	1.87634	≈0
303	4802.043004	1.87805	≈0
304	4902.043004	1.8797	≈0
305	5002.043004	1.88132	≈0
306	5102.043004	1.88288	≈0
307	5202.043004	1.88439	≈0
308	5302.043004	1.88586	≈0
309	5402.043004	1.88729	≈0
310	5502.043004	1.88867	≈0
311	5602.043004	1.89002	≈0
312	5702.043004	1.89132	≈0

313	5802.043004	1.89258	≈0
314	5902.043004	1.8938	≈0
315	6002.043004	1.89499	≈0
316	6102.043004	1.89614	≈0
317	6202.043004	1.89725	≈0
318	6302.043004	1.89833	≈0
319	6402.043004	1.89938	≈0
320	6502.043004	1.90039	≈0
321	6602.043004	1.90138	≈0
322	6702.043004	1.90234	≈0
323	6802.043004	1.90327	≈0
324	6902.043004	1.90417	≈0
325	7002.043004	1.90505	≈0
326	7102.043004	1.90591	≈0
327	7202.043004	1.90674	≈0
328	7302.043004	1.90754	≈0
329	7402.043004	1.90832	≈0
330	7502.043004	1.90908	≈0
331	7602.043004	1.90982	≈0
332	7702.043004	1.91054	≈0
333	7802.043004	1.91124	≈0
334	7902.043004	1.91191	≈0
335	8002.043004	1.91257	≈0
336	8102.043004	1.91321	≈0
337	8202.043004	1.91383	≈0
338	8302.043004	1.91443	≈0
339	8402.043004	1.91501	≈0
340	8502.043004	1.91558	≈0
341	8602.043004	1.91613	≈0
342	8702.043004	1.91667	≈0
343	8802.043004	1.91719	≈0

344	8902.043004	1.91769	≈0
345	9002.043004	1.91818	≈0
346	9102.043004	1.91866	≈0
347	9202.043004	1.91912	≈0
348	9302.043004	1.91955	≈0
349	9402.043004	1.92	≈0
350	9502.043004	1.92041	≈0
351	9602.043004	1.92082	≈0
352	9702.043004	1.92122	≈0
353	9802.043004	1.92161	≈0
354	9902.043004	1.92198	≈0
355	10002.043	1.92235	≈0
356	10102.043	1.9227	≈0
357	10202.043	1.92304	≈0
358	10302.043	1.92338	≈0
359	10402.043	1.9237	≈0
360	10502.043	1.92402	≈0
361	10602.043	1.92432	≈0
362	10702.043	1.92462	≈0
363	10802.043	1.92491	≈0
364	10902.043	1.92519	≈0
365	11002.043	1.92546	≈0
366	11102.043	1.92572	≈0
367	11202.043	1.92598	≈0
368	11302.043	1.92622	≈0
369	11402.043	1.92647	≈0
370	11502.043	1.9267	≈0
371	11602.043	1.92693	≈0
372	11702.043	1.92715	≈0
373	11802.043	1.92736	≈0
374	11902.043	1.92757	≈0

375	12002.043	1.92777	≈0
376	12102.043	1.92797	≈0
377	12202.043	1.92816	≈0
378	12302.043	1.92834	≈0
379	12402.043	1.92852	≈0
380	12502.043	1.9287	≈0
381	12602.043	1.92886	≈0
382	12702.043	1.92903	≈0
383	12802.043	1.92919	≈0
384	12902.043	1.92934	≈0
385	13002.043	1.92949	≈0
386	13102.043	1.92964	≈0
387	13202.043	1.92978	≈0
388	13302.043	1.92992	≈0
389	13402.043	1.93005	≈0
390	13502.043	1.93018	≈0
391	13602.043	1.9303	≈0
392	13702.043	1.93043	≈0
393	13802.043	1.93054	≈0
394	13902.043	1.93066	≈0
395	14002.043	1.93077	≈0
396	14102.043	1.93088	≈0
397	14202.043	1.93098	≈0
398	14302.043	1.93108	≈0
399	14402.043	1.93118	≈0
400	14502.043	1.93128	≈0
401	14602.043	1.93137	≈0
402	14702.043	1.93146	≈0
403	14802.043	1.93155	≈0
404	14902.043	1.93163	≈0
405	15002.043	1.93172	≈0

406	15102.043	1.9318	≈0
407	15202.043	1.93187	≈0
408	15302.043	1.93195	≈0
409	15402.043	1.93202	≈0
410	15502.043	1.93209	≈0
411	15602.043	1.93216	≈0
412	15702.043	1.93223	≈0
413	15802.043	1.9323	≈0
414	15902.043	1.93236	≈0
415	16002.043	1.93242	≈0
416	16102.043	1.93248	≈0
417	16202.043	1.93254	≈0
418	16302.043	1.93259	≈0
419	16402.043	1.93265	≈0
420	16502.043	1.9327	≈0
421	16602.043	1.93275	≈0
422	16702.043	1.9328	≈0
423	16802.043	1.93285	≈0
424	16902.043	1.9329	≈0
425	17002.043	1.93294	≈0
426	17102.043	1.93298	≈0
427	17202.043	1.93303	≈0
428	17302.043	1.93307	≈0
429	17402.043	1.93311	≈0
430	17502.043	1.93315	≈0
431	17602.043	1.93319	≈0
432	17702.043	1.93322	≈0
433	17802.043	1.93326	≈0
434	17902.043	1.93329	≈0
435	18002.043	1.93333	≈0
436	18102.043	1.93336	≈0

437	18202.043	1.93339	≈0
438	18302.043	1.93342	≈0
439	18402.043	1.93345	≈0
440	18502.043	1.93348	≈0
441	18602.043	1.93351	≈0
442	18702.043	1.93354	≈0
443	18802.043	1.93356	≈0
444	18902.043	1.93359	≈0
445	19002.043	1.93361	≈0
446	19102.043	1.93364	≈0
447	19202.043	1.93366	≈0
448	19302.043	1.93368	≈0
449	19402.043	1.9337	≈0
450	19502.043	1.93373	≈0
451	19602.043	1.93375	≈0
452	19702.043	1.93377	≈0
453	19802.043	1.93379	≈0
454	19902.043	1.93381	≈0
455	20002.043	1.93382	≈0
456	20102.043	1.93384	≈0
457	20202.043	1.93386	≈0
458	20302.043	1.93388	≈0
459	20402.043	1.93389	≈0
460	20502.043	1.93391	≈0
461	20602.043	1.93392	≈0
462	20702.043	1.93394	≈0
463	20802.043	1.93395	≈0
464	20902.043	1.93397	≈0
465	21002.043	1.93398	≈0
466	21102.043	1.93399	≈0
467	21202.043	1.93401	≈0

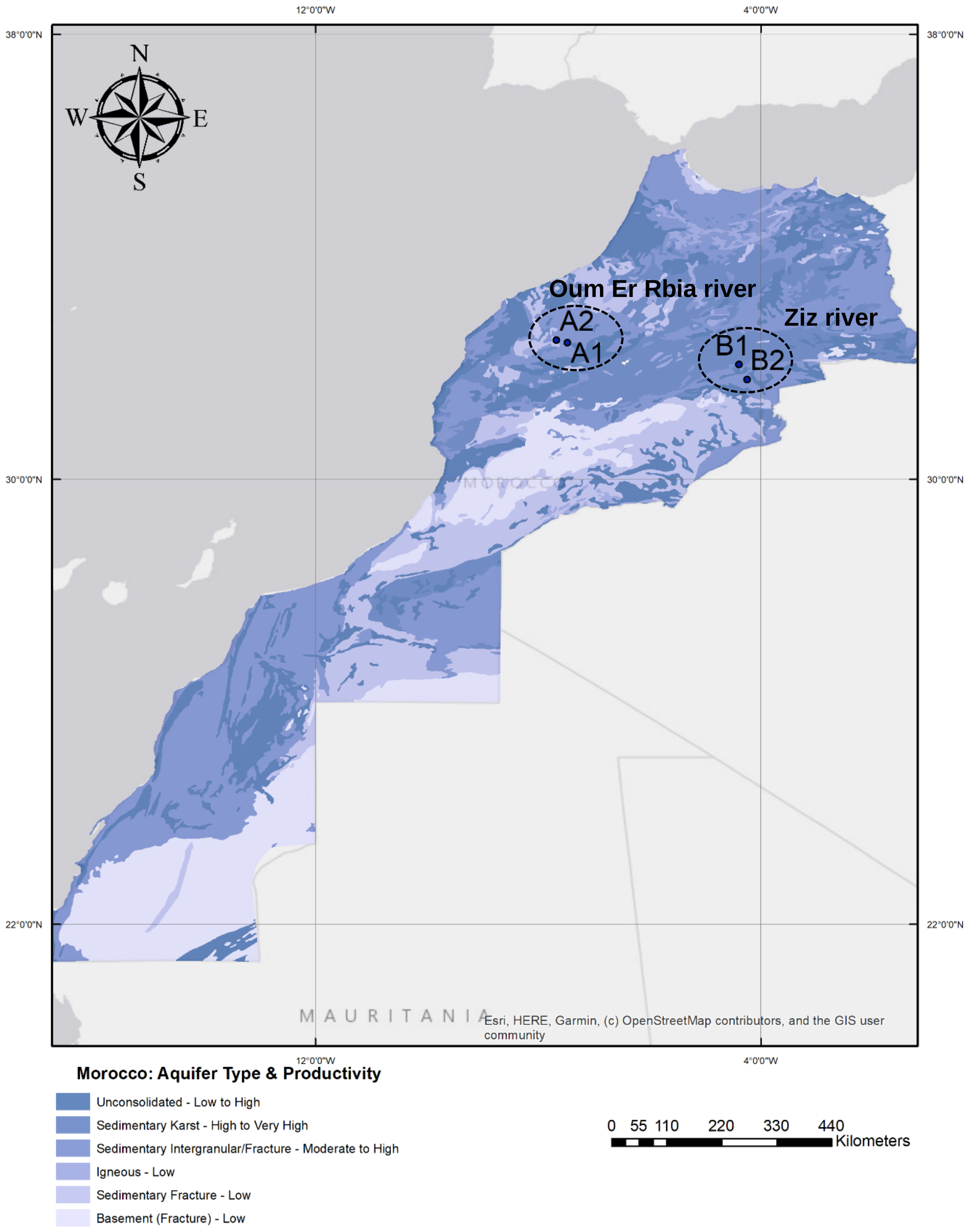
468	21302.043	1.93402	≈0
469	21402.043	1.93403	≈0
470	21502.043	1.93404	≈0
471	21602.043	1.93405	≈0
472	21702.043	1.93407	≈0
473	21802.043	1.93408	≈0
474	21902.043	1.93409	≈0
475	22002.043	1.9341	≈0
476	22102.043	1.93411	≈0
477	22202.043	1.93412	≈0
478	22302.043	1.93412	≈0
479	22402.043	1.93413	≈0
480	22502.043	1.93414	≈0
481	22602.043	1.93415	≈0
482	22702.043	1.93416	≈0
483	22802.043	1.93417	≈0
484	22902.043	1.93417	≈0
485	23002.043	1.93418	≈0
486	23102.043	1.93419	≈0
487	23202.043	1.9342	≈0
488	23302.043	1.9342	≈0
489	23402.043	1.93421	≈0
490	23502.043	1.93422	≈0
491	23602.043	1.93422	≈0
492	23702.043	1.93423	≈0
493	23802.043	1.93423	≈0
494	23902.043	1.93424	≈0
495	24002.043	1.93425	≈0
496	24102.043	1.93425	≈0
497	24202.043	1.93426	≈0
498	24302.043	1.93426	≈0

499	24402.043	1.93427	≈0
500	**24502.043**	**1.93427**	**≈0**

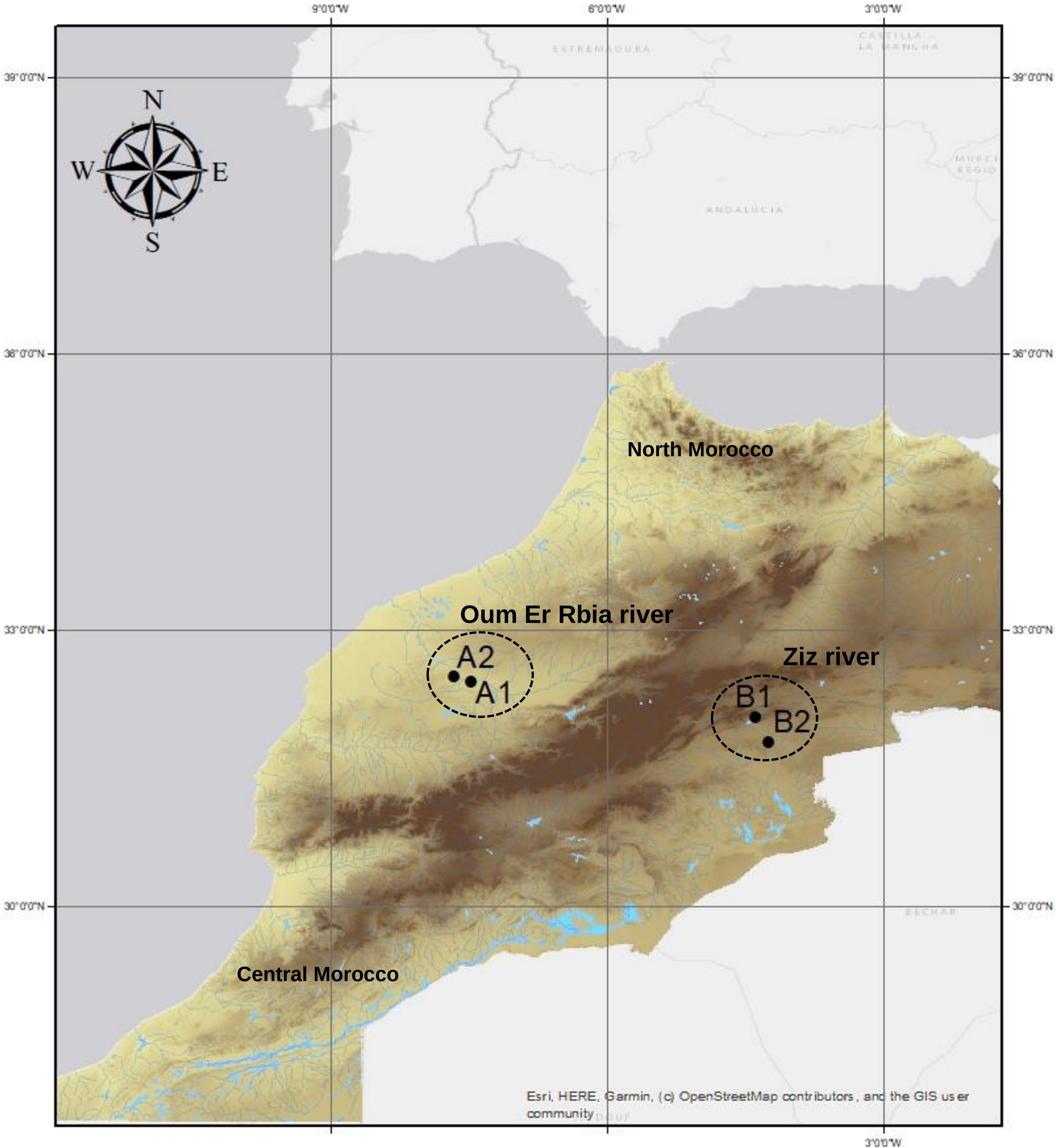
≈0: *Value less than* $1*10^{-3}$

Appendix III: Chartography of sampling sites

1. Aquatic types and Productivity complete map of Morocco (A1, B1; A2, B2 | Upstream, Downstream sampling site)



2. Elevation of North-East Morocco (A1, B1; A2, B2|Upstream, Downstream sampling site)



Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Digital Elevation Model (DEM) of North-East Morocco in meters (m), derived by the NASA Shuttle Radar Topographic Mission (SRTM)