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FRESHWATER SYSTEM HEALTH: A HYDRAULIC PERSPECTIVE
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Adaptation of dams and reservoirs to climate change and Environmental Flows

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Abstract

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

1 ADAPTATION OF D&R TO CLIMATE CHANGE

1.1

STEPS	ANALYSES	QUESTIONS
1 Description of the D&R system	1.1 Components & time scales (L&EO)	Which are the potential hazards?
	1.2 Hazards (L&EO)	
	1.3 Indicators (L&EO)	
2 Climate Change assessment	2.1 Climate Change scenarios (M)	Phase 1 Screening (present work)
	2.2 Values of indicators (M)	
3 Vulnerability assessment	3.1 Sensitivity analysis (L&EO)	Which are the potentially significant hazards?
	3.2 Adaptive capacity analysis (L)	
	3.3 Exposure analysis (L&EO)	
	3.4 Vulnerability analysis (L&EO)	
4 Risk assessment	4.1 Probability analysis (L&EO)	Which are the significant hazards?
	4.2 Impacts analysis (L&EO)	
	4.3 Risk analysis (L&EO)	
5 Assessment of adaptation measures	5.1 Identification (L&EO)	Phase 2 Detailed analysis
	5.2 Appraisal (L&EO)	
	5.3 Integration	

Types and categories of climate hazards

1.2

For D&R systems

(1) Mean air temperature increase (HC1) & extreme heat (HC2).

(2) Mean precipitation decrease (WD1), aridity (WD4) & droughts (WD5).

(3) Extreme precipitation (WD2) & flooding (WD3).

Category of Hazard Based on IPCC [13]	Symbol	Type of Hazard
Heat and Cold (HC)	HC1	Mean air temperature (increase)
	HC2	Extreme heat—Heat waves
	HC3	Cold spells and frost
Wet and Dry (WD)	WD1	Mean precipitation (decrease)
	WD2	Extreme precipitation
	WD3	Flooding (fluvial and pluvial)
	WD4	Aridity
	WD5	Drought
	WD6	Wildfires
	WD7	Soil erosion
	WD8	Landslide (incl. mudflows)
	WD9	Land subsidence
	WD10	Water temperature
Wind and Air (WA)	WA1	Mean wind speed (increase)
	WA2	Extreme winds
	WA3	Air quality (change)
Coastal (C)	C1	Relative (mean) sea level (rise)
	C2	Coastal flooding
	C3	Coastal erosion
	C4	Saline intrusion
	C5	Sea water temperature (and marine heat waves)
	C6	Sea water quality (incl. salinity and acidity)
Snow and Ice (SI)	SI1	Snow and land ice
	SI2	Avalanche

Stamou, A., Mitsopoulos, G. & Koutroulis, A. Proposed Methodology for Climate Change Adaptation of Water Infrastructures in the Mediterranean Region. *Environ. Process.* **11**, 12 (2024). https://doi.org/10.1007/s40710-024-00691-w

Components of D&R systems

1.3

Groups of components	Symbol	Component
Input (I)	I	Inflows
Functions (P)	P1 P2 P3 P4	Storage Flood control Hydropower Recreation
Assets (A)	A1 A2 A3 A4	Embankment Spillway Auxiliaries Buildings
Outflow (O)	O1 O2 O3	Water supply Hydropower production **Water releases; E-FLOW**
Supporting infrastructure (S)	S1 S2 S3 S4	Power supply Communications Transportation Personnel

Stamou, A.I.; Mitsopoulos, G.; Sfetsos, A.; Stamou, A.T.; Sideris, S.; Varotsos, K.V.; Giannakopoulos, C.; Koutroulis, A. Vulnerability Assessment of Dams and Reservoirs to Climate Change in the Mediterranean Region: The Case of the Almopeos Dam in Northern Greece. Water 2025, 17, 1289. https://doi.org/10.3390/w17091289

Impacts of climate change on E-FLOW

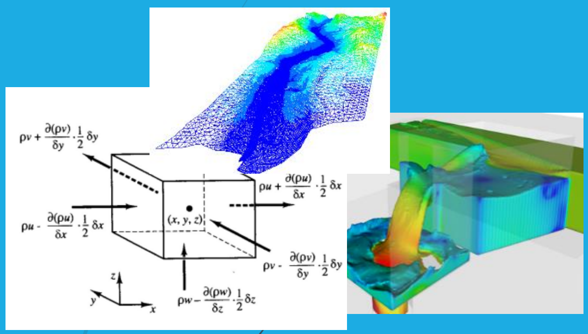
1.4

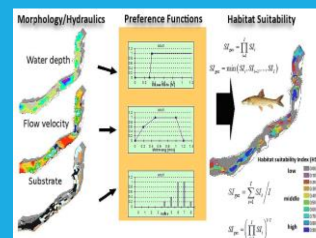
- Mean air temperature increase & extreme heat: increase T, decrease DO and increase the pollution of the reservoir.
- Mean precipitation decrease, aridity & droughts: increase the concentrations of pollutants and sediments in the reservoir.
- Thus, both groups of hazards
  - reduce the water quality of the reservoir and thus of the downstream flow,
  - increase the demand for higher E-FLOW that creates management conflicts for multi-purpose reservoirs.
- Extreme precipitation & flooding increase the downstream flow, create flooding and pollution and deterioration of the substrate (S).

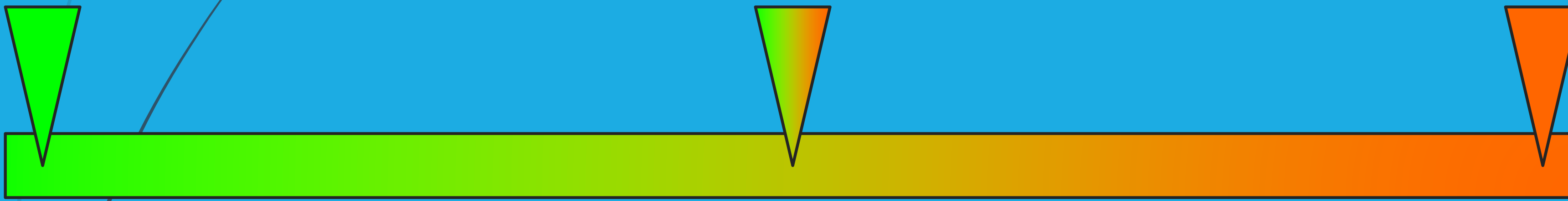
Later: These effects on the E-FLOW can be taken into account via including in the HHM the relevant environmental parameters, such as T, DO and S.

Hydrodynamic Habitat Modeling (HHM)

Interdisciplinary research!







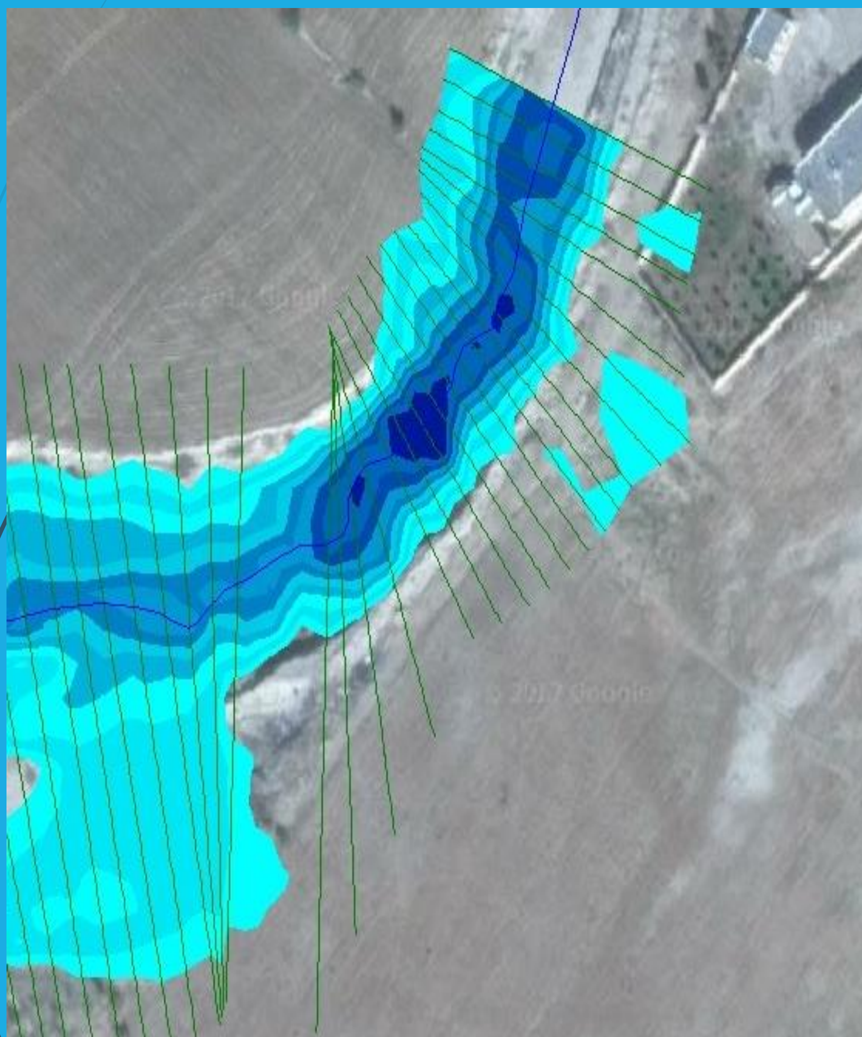
Hydraulics

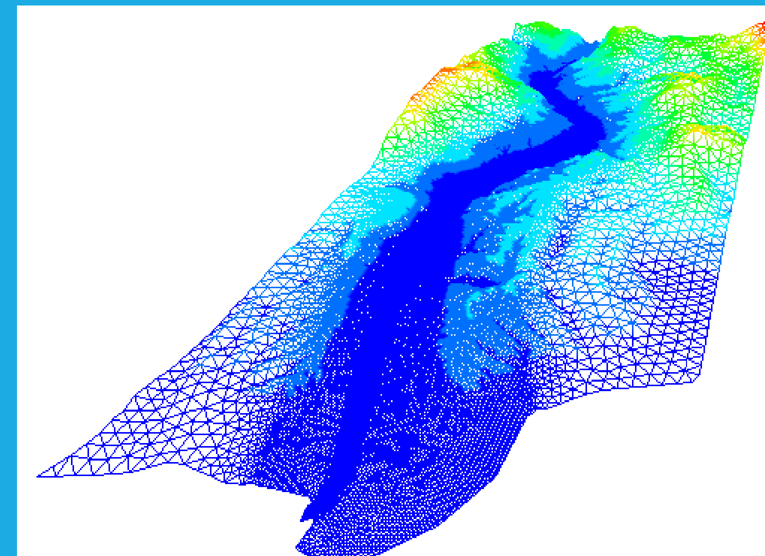
Eco-hydraulics

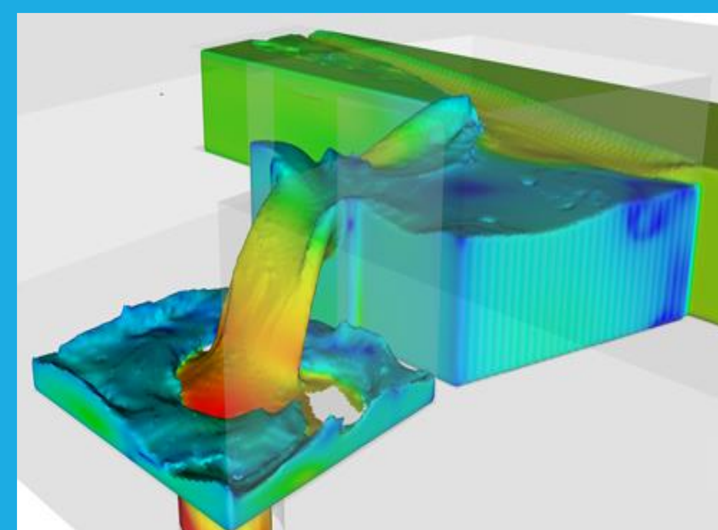
Biology

2 HYDRODYNAMIC MODELS

2.1







Equations of hydrodynamic models

2.2

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$

$$\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial uw}{\partial z} + \frac{1}{\rho}\frac{\partial P}{\partial x} - g_x - \frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) = 0$$

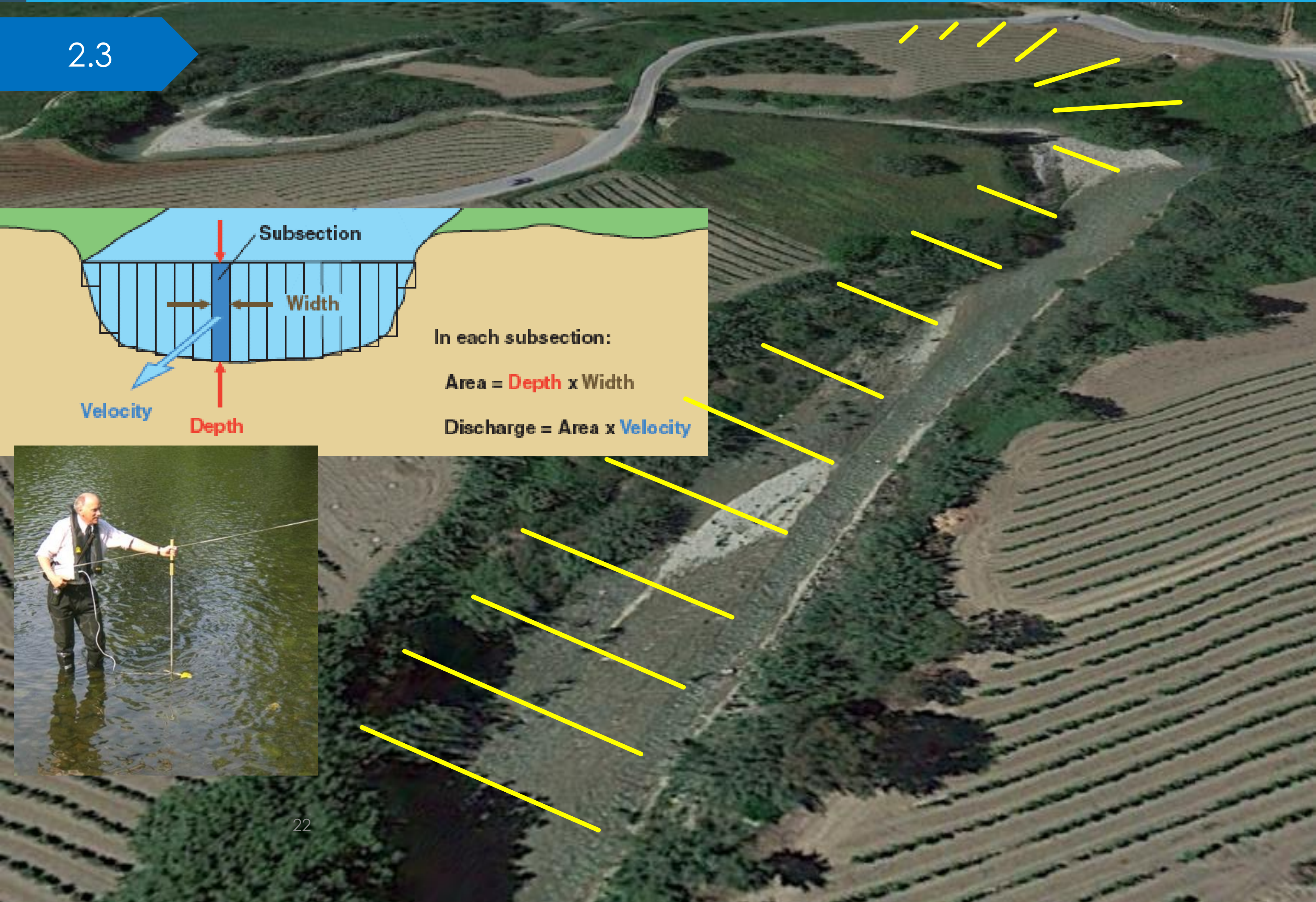
$$\frac{\partial v}{\partial t} + \frac{\partial uv}{\partial x} + \frac{\partial v^2}{\partial y} + \frac{\partial vw}{\partial z} + \frac{1}{\rho}\frac{\partial P}{\partial y} - g_y - \frac{\mu}{\rho}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) = 0$$

$$\frac{\partial w}{\partial t} + \frac{\partial wu}{\partial x} + \frac{\partial wv}{\partial y} + \frac{\partial w^2}{\partial z} + \frac{1}{\rho}\frac{\partial P}{\partial z} - g_z - \frac{\mu}{\rho}\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) = 0$$

Z-wise momentum

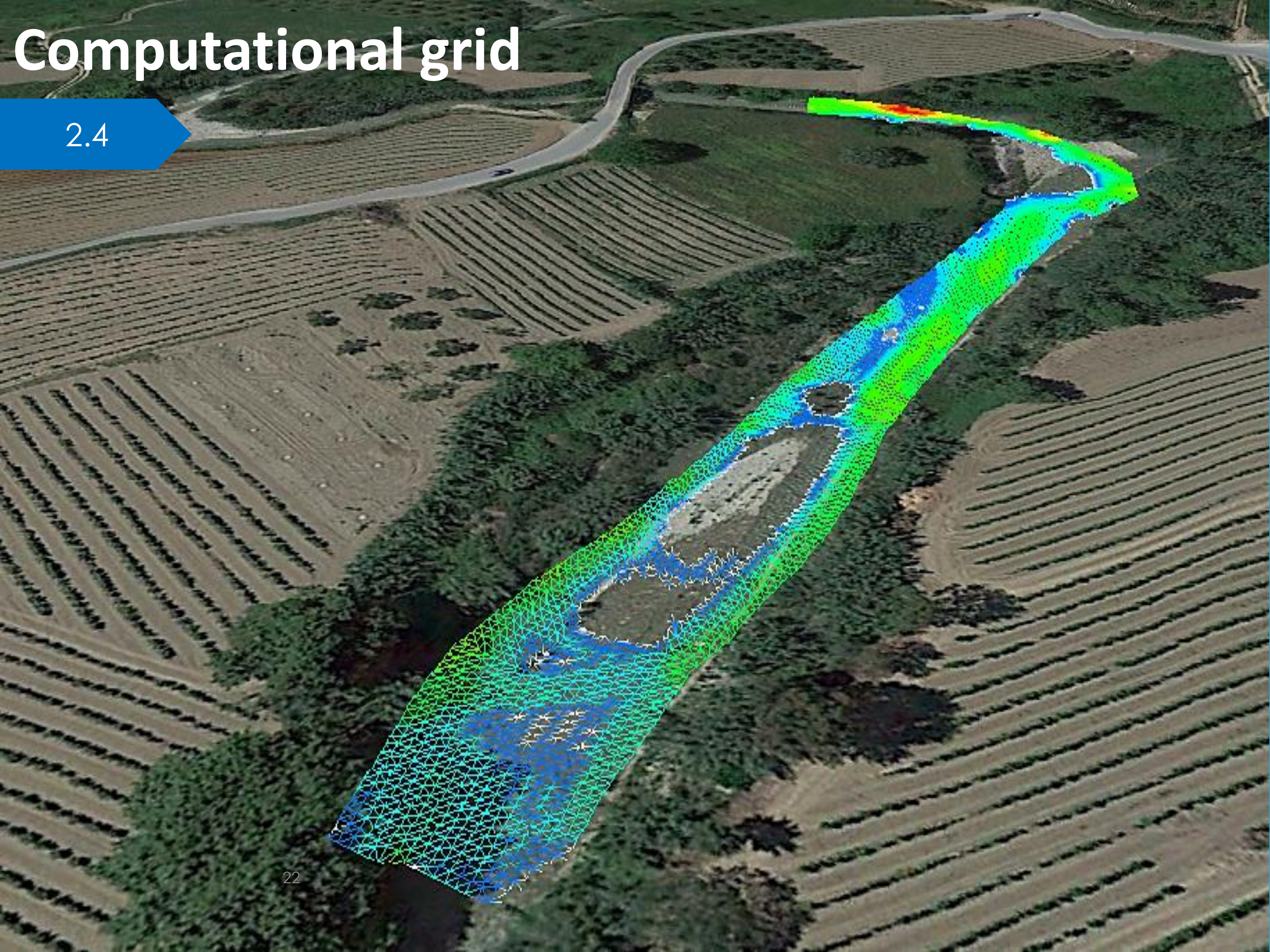
Velocity (V) & water depth (D) measurements

2.3



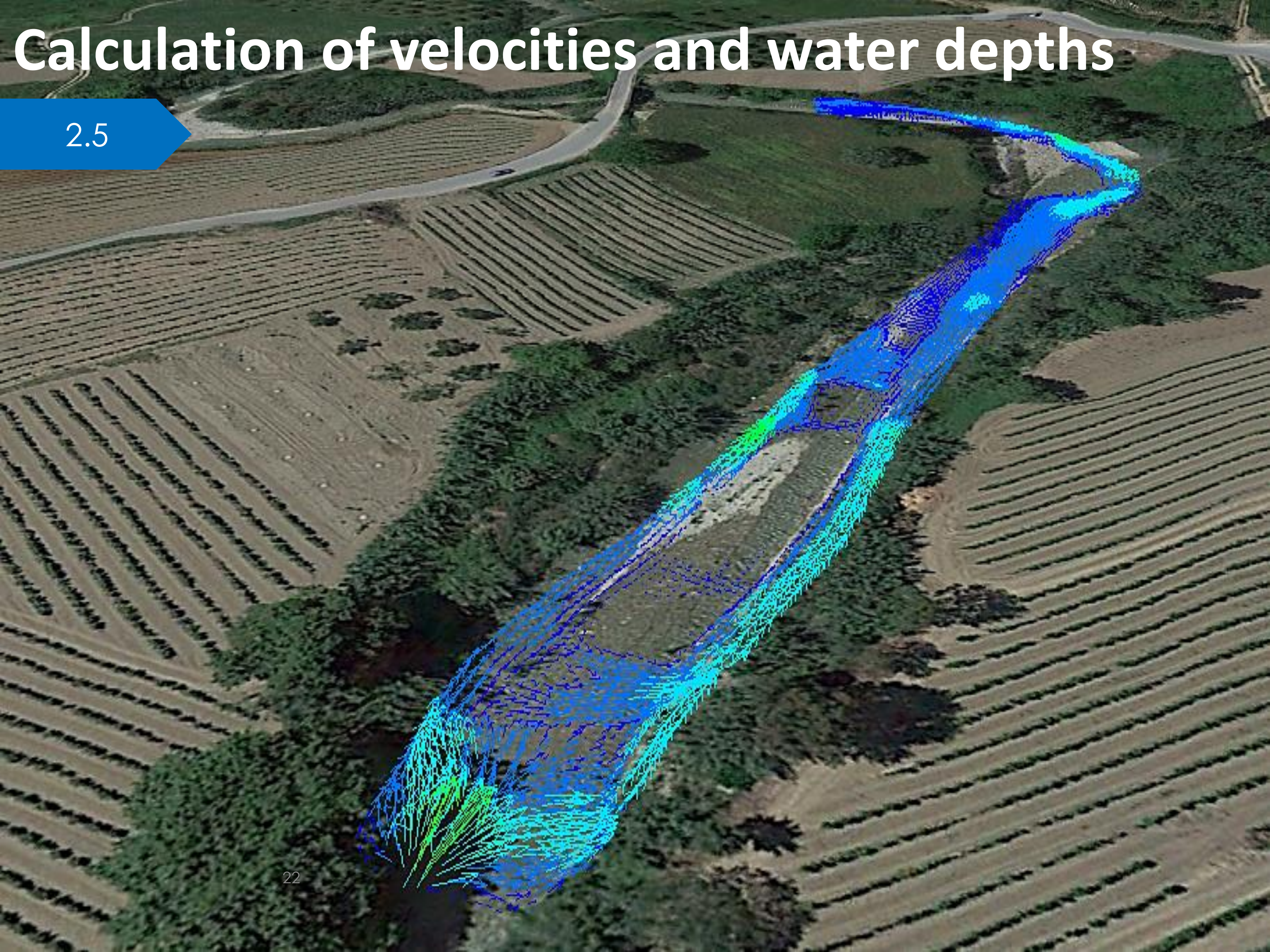
Computational grid

2.4



Calculation of velocities and water depths

2.5



3 HABITAT AND HABITAT MODELS

3.1

- Aquatic habitat. The place -in the river- that is defined by specific
  - hydraulic -> V & D
  - hydromorphological -> S (substrate)
  - physicochemical -> DO, chemicals etc., (see D&R)
- variables

in which one or more species can survive, reproduce and thrive.

3.2

For the habitat model

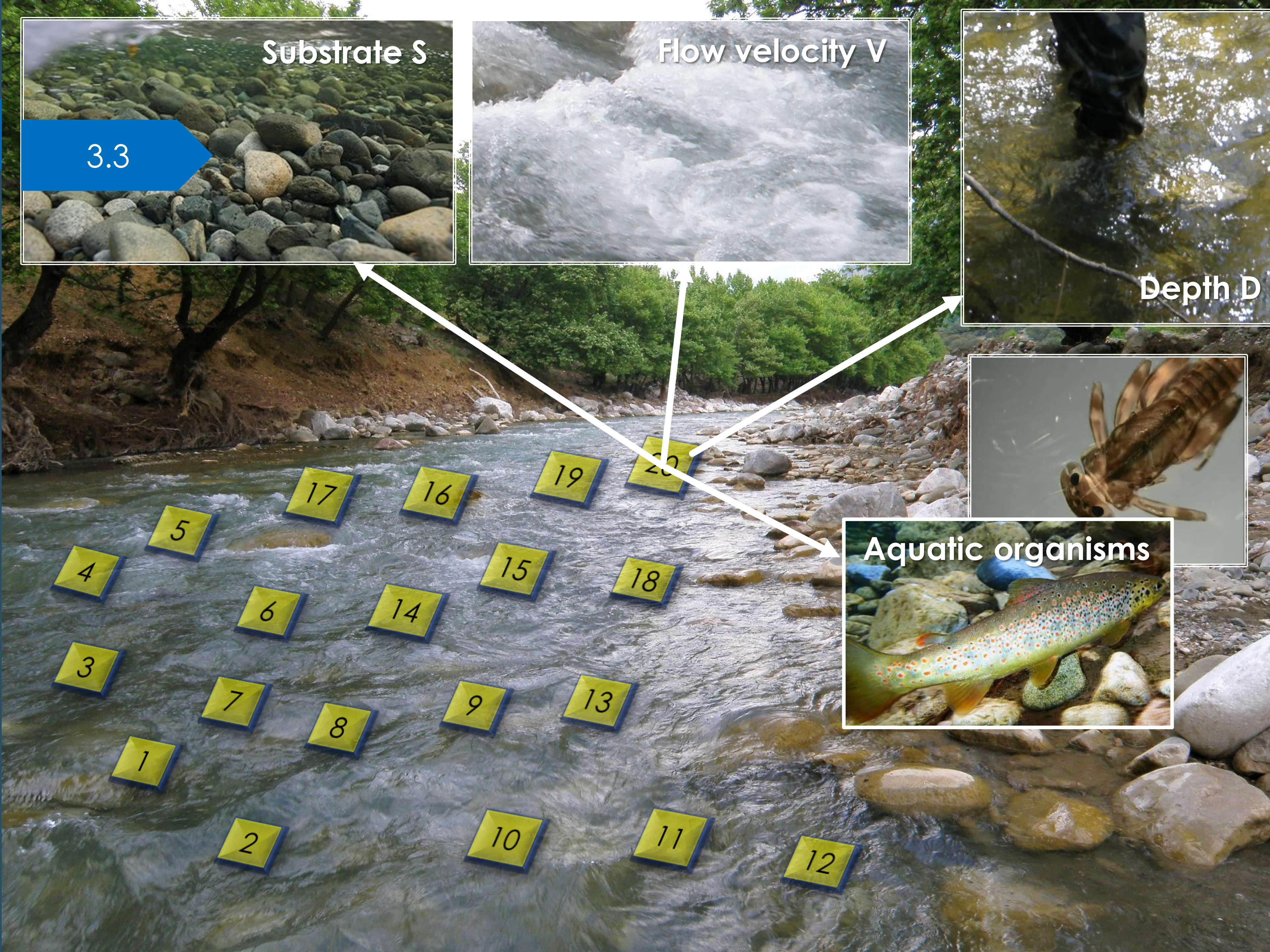
*1. We collect a dataset which relates Variables (V, D, S and T) with Abundance of aquatic organisms**

2. We make transformations to develop Habitat Suitability Curves (HSCs) based on these data

HSCs -> Basis for the habitat model's predictions

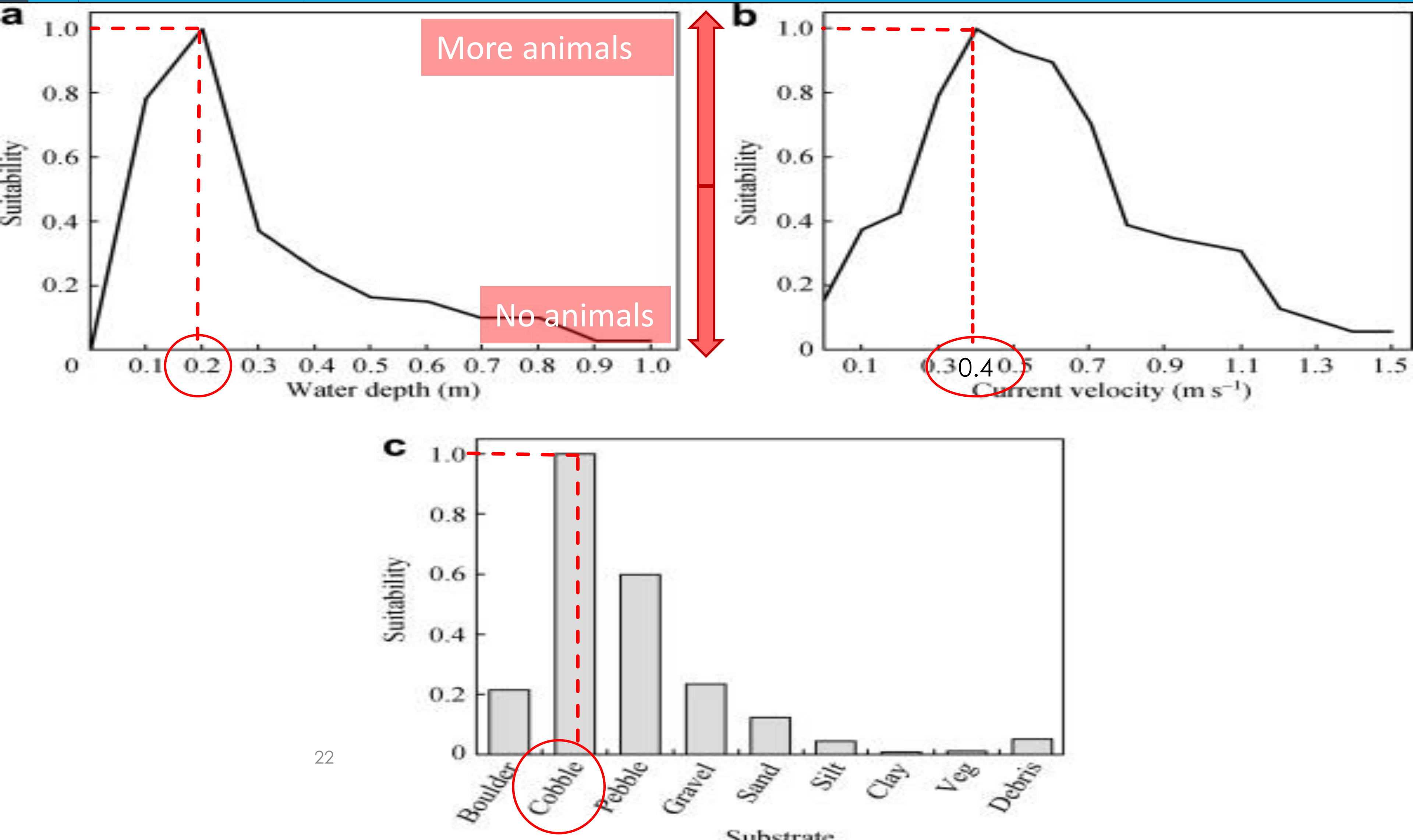
Aquatic organisms

Benthic macroinvertebrates: Aquatic organisms visible to the naked eye, including insect larvae and adults, snails, worms, crustaceans (crabs etc.)


3.3
Substrate S
Flow velocity V
Depth D
Aquatic organisms
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

Habitat suitability for D, V and S

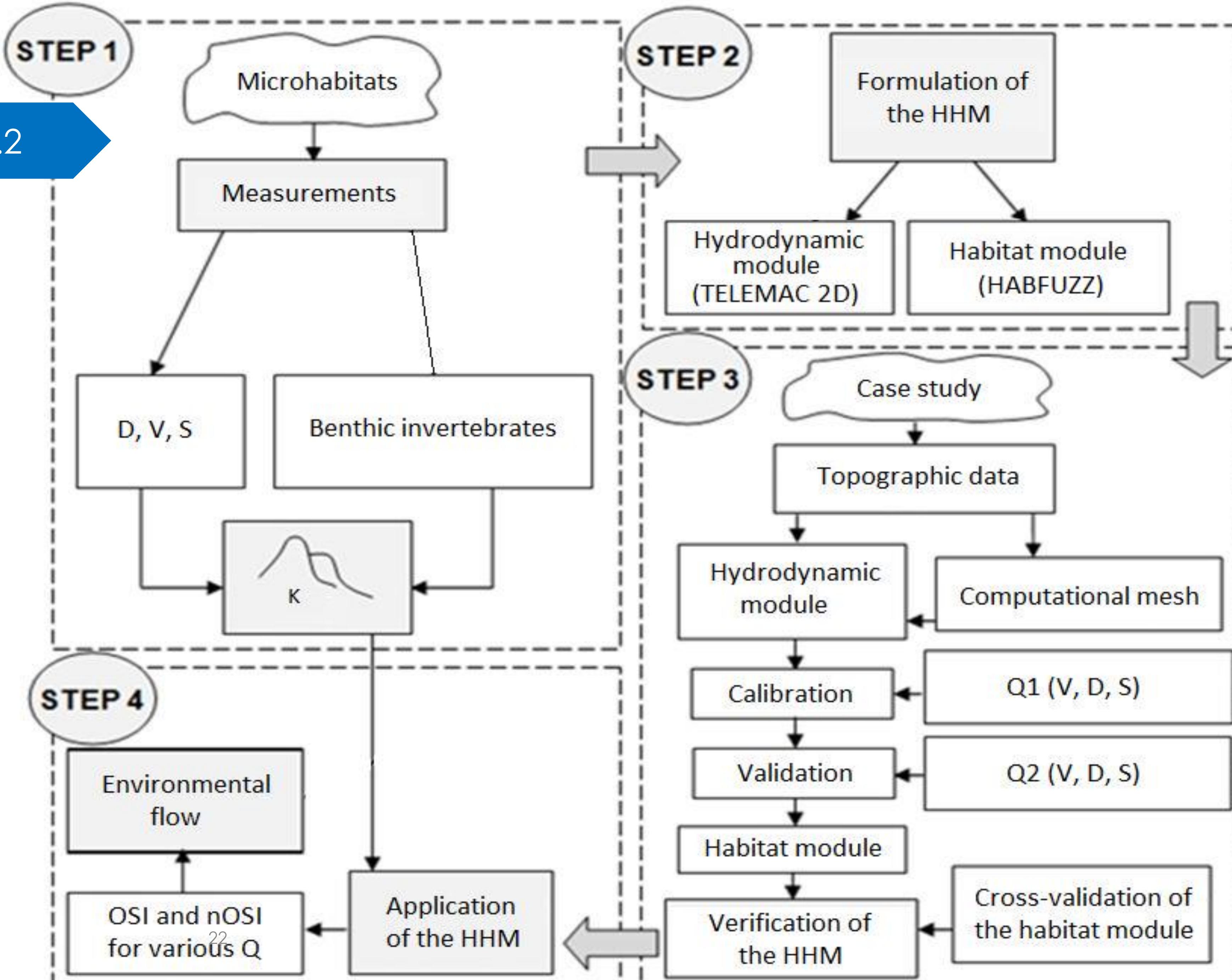
3.4



4 HYDRODYNAMIC HABITAT MODELS (HHM)

4.1

- In the literature, there exist more than 200 methods for assessing E-FLOW that can be categorized as:
- (1) hydrological, (2) hydrodynamic habitat modelling (HHM), and (3) holistic methods combining the first two methods
- The use of HHMs in EFAs has been widely researched worldwide in the past four decades
- New, complex predictive algorithms of enhanced accuracy have been developed for the prediction of habitat suitability
- However, the practical application of HHMs in EFAs is limited worldwide. Main reasons
  - (a) costs,
  - (b) time,
  - (c) expertise and
  - (d) availability of hydroecological data


STEP 1
Microhabitats
Measurements
D, V, S
Benthic invertebrates
K
STEP 2
Formulation of the HHM
Hydrodynamic module (TELEMAC 2D)
Habitat module (HABFUZZ)
STEP 3
Case study
Topographic data
Hydrodynamic module
Computational mesh
Calibration
Q1 (V, D, S)
Validation
Q2 (V, D, S)
Habitat module
Cross-validation of the habitat module
Verification of the HHM
STEP 4
Environmental flow
OSI and nOSI for various Q
Application of the HHM

Weighted Usable Area (WUA)

4.3

$$\text{WUA} = \sum_{i=1}^{n} F[f(V_i), f(D_i), f(S_i)]\, x\, A_i$$

where

$f(V_i), f(D_i)$ and $f(S_i)$ are the calculated suitabilities

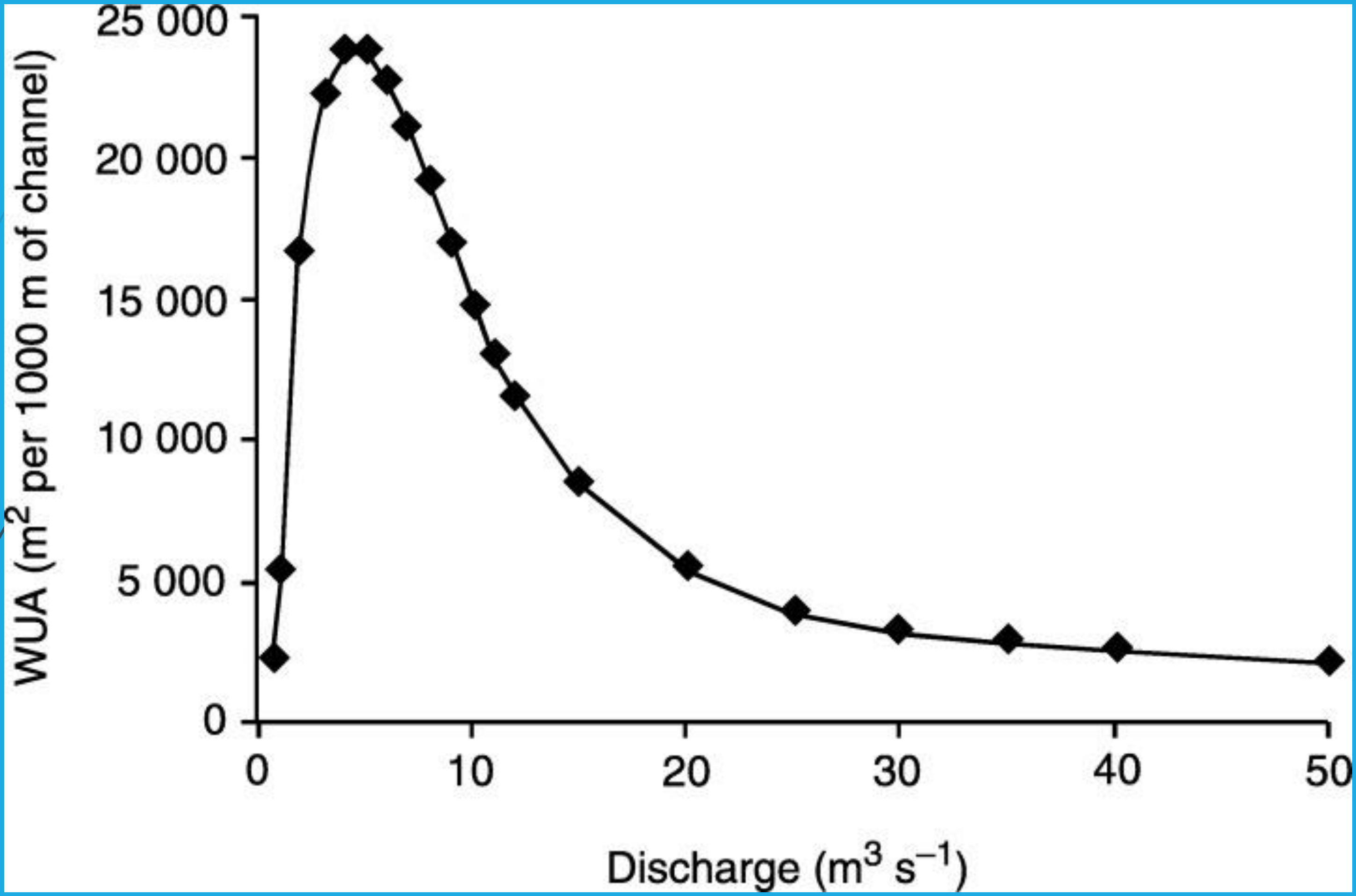
F[ ] the composite suitability factor (maybe a product, a weighted average etc.)

A_i the surface area of each cell of the computational grid

Usually divided by the reach length (km) and expressed in m^2/km

Example of Weighted Usable Area (WUA)

4.4



5 CASE STUDY 1

5.1

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

ELSEVIER

Research article

Determination of environmental flows in rivers using an integrated hydrological-hydrodynamic-habitat modelling approach

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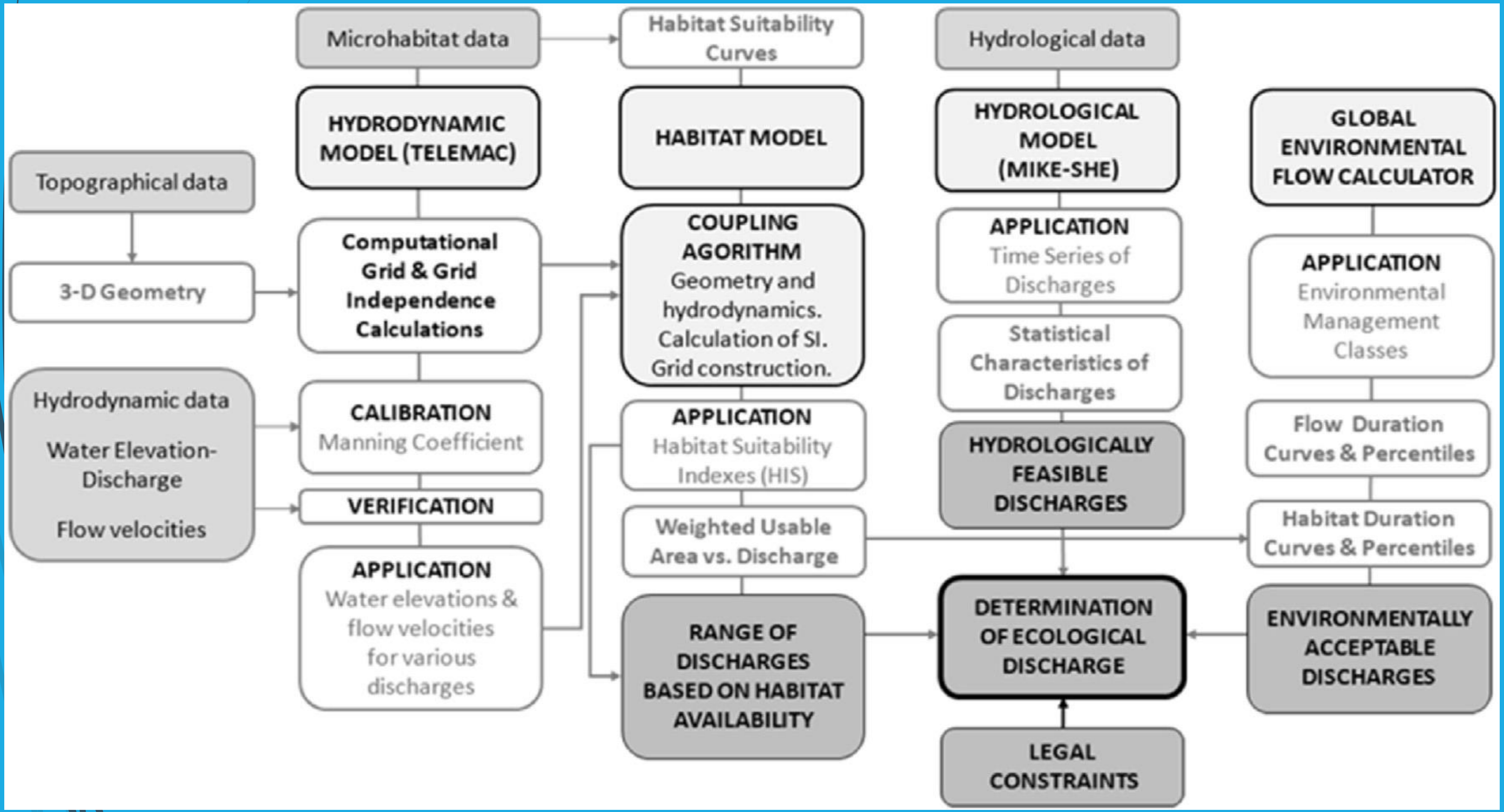
Integrated modelling

ABSTRACT

We propose the novel integrated modelling procedure 3H-EMC for the determination of the environmental flow in rivers and streams; 3H-EMC combines Hydrological, Hydrodynamic and Habitat modelling with the use of the Environmental Management Classes (EMCs) that are defined by the Global Environmental Flow Calculator. We apply 3H-EMC in the Sperchios River in Central Greece, in which water abstractions for irrigation cause significant environmental impacts. Calculations of the hydrodynamic-habitat model, in which the large and the small chub are the main fish species, suggest discharge values that range from 1.0 m^3/s to 4.0 m^3/s. However, hydrological modelling indicates that it is practically difficult to achieve discharges that are higher than approximately 1.0–1.5 m^3/s. Furthermore, legislation suggests significantly lower values (0.4–0.5 m^3/s) that are unacceptable from the ecological point of view. This behaviour shows that a non-integrated approach, which is based only on hydrodynamic-habitat modelling does not necessarily result in realistic environmental flows, and thus an integrated approach is required. We propose the value of 1.0 m^3/s as the "optimum" environmental flow for Sperchios River, because (a) it satisfies the habitat requirements, as expressed by the values of weighted useable area that are equal to 2180 and 1964 m^2 for the large and small chub, respectively, and correspond to 82 and 95% of their respective maximum values, (b) it is consistent with the requirements of Environmental Classes A and B, whose percentiles are higher than 75% for discharge (77.2%) and for habitat availability (>83.5% for the large chub and >85.0% for the small chub), (c) it is practically achievable from the hydrological point of view, and (d) it is higher than the value proposed by the Greek legislation. The proposed modelling approach can be applied to any river or stream using the same or similar modelling tools, which should be linked via suitable coupling algorithms.

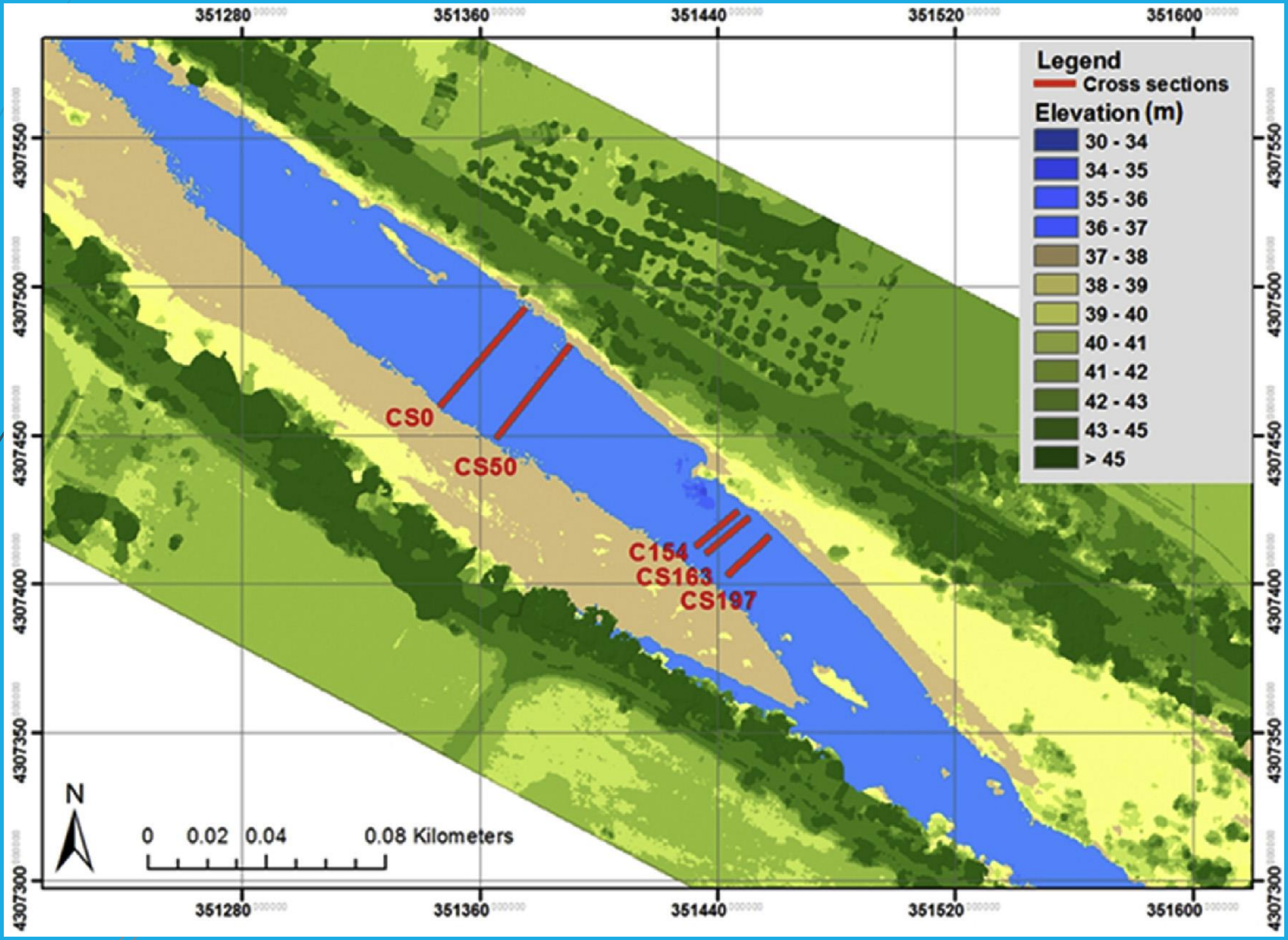
Conceptual diagram - modelling procedure

5.2



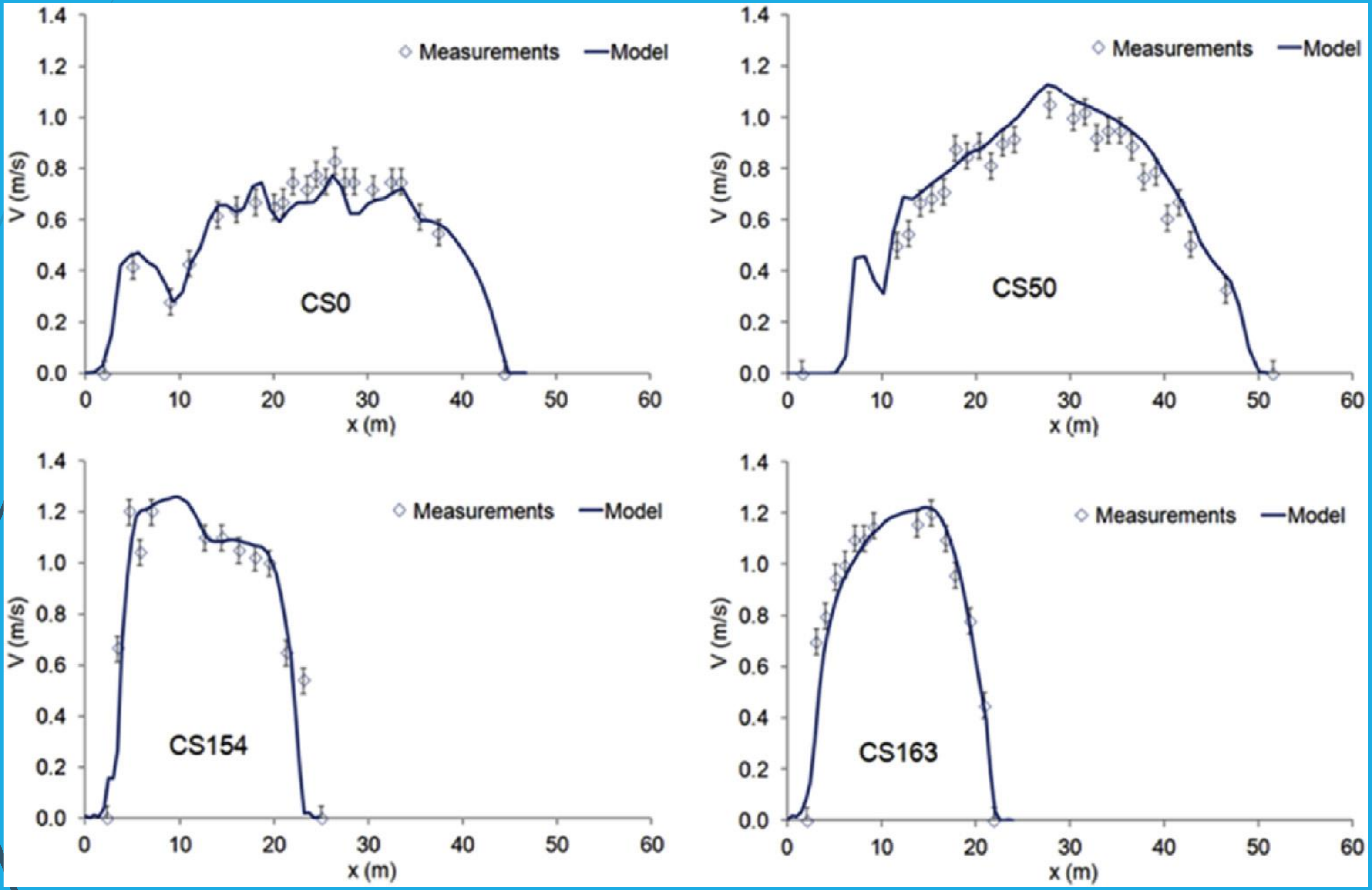
Reach of the river with the main cross sections

5.3



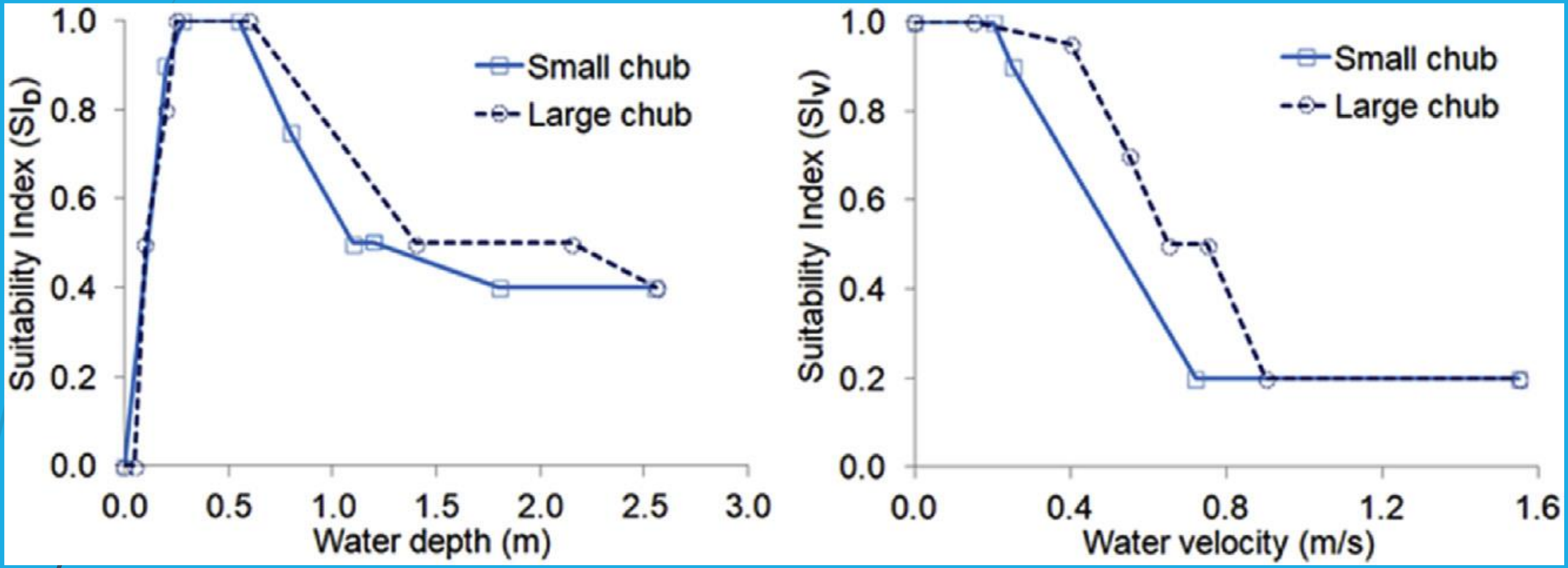
5.4

Calculated flow velocities vs. field measurements at different cross sections



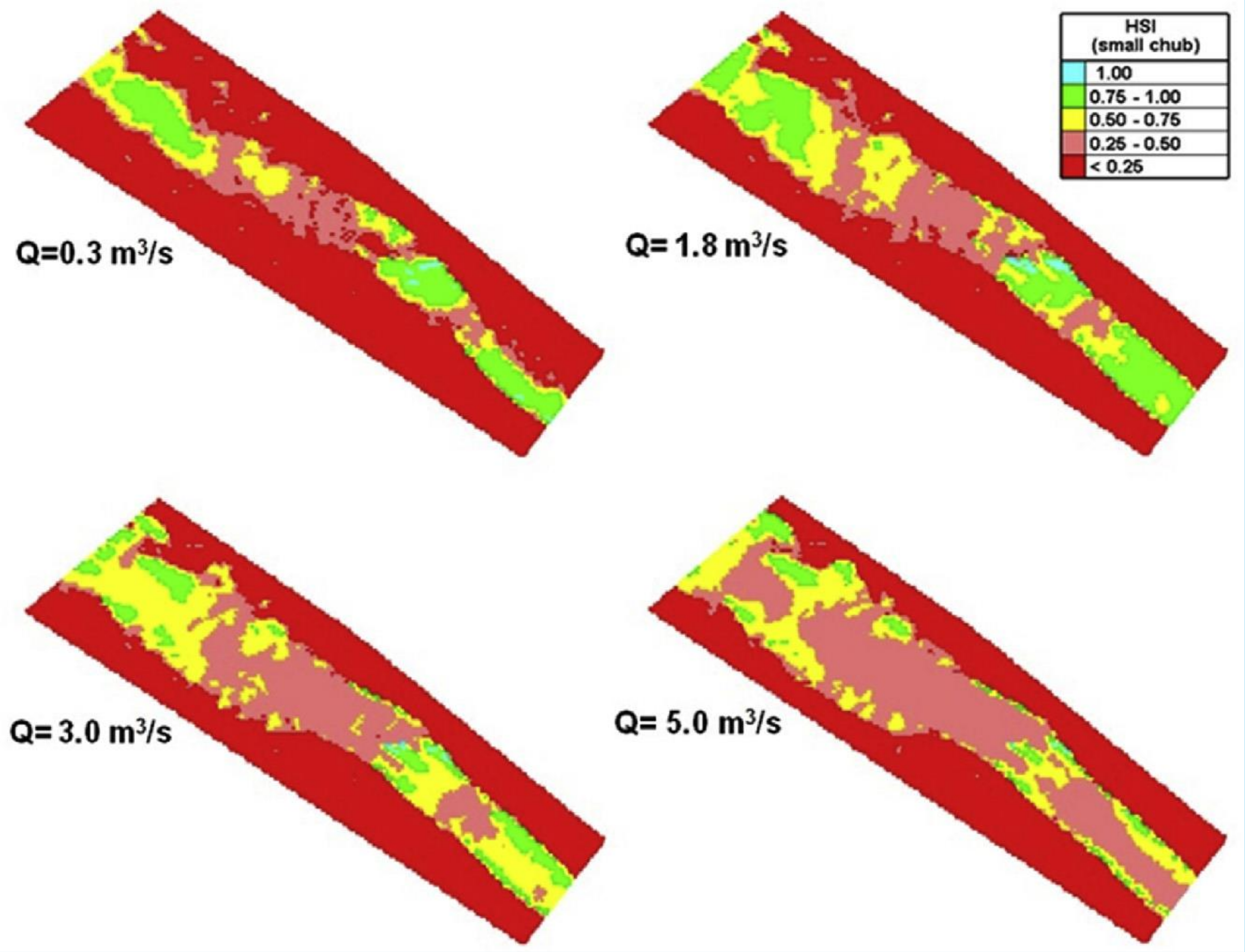
5.5

Habitat Suitability Curves for water depth and average water column velocity



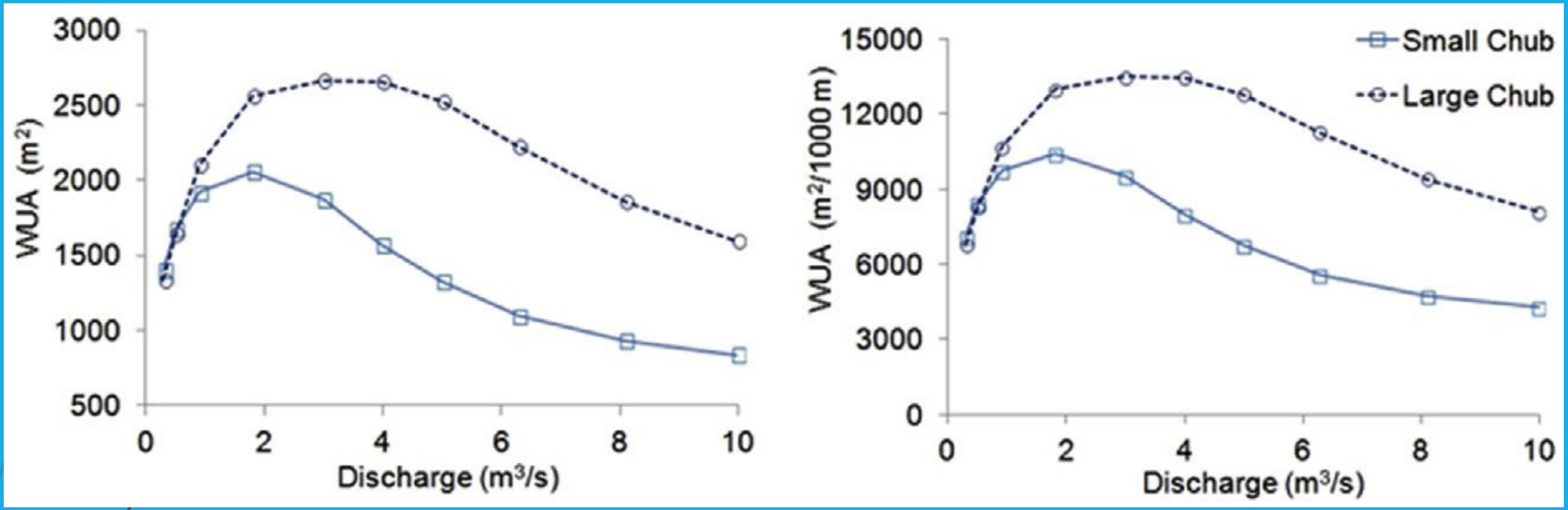
5.6

Calculated Habitat Suitability Index (HSI) for the small chub for various discharges 0.3, 1.8, 3.0 and 5.0 m³/s



Weighted Useable Area

5.7



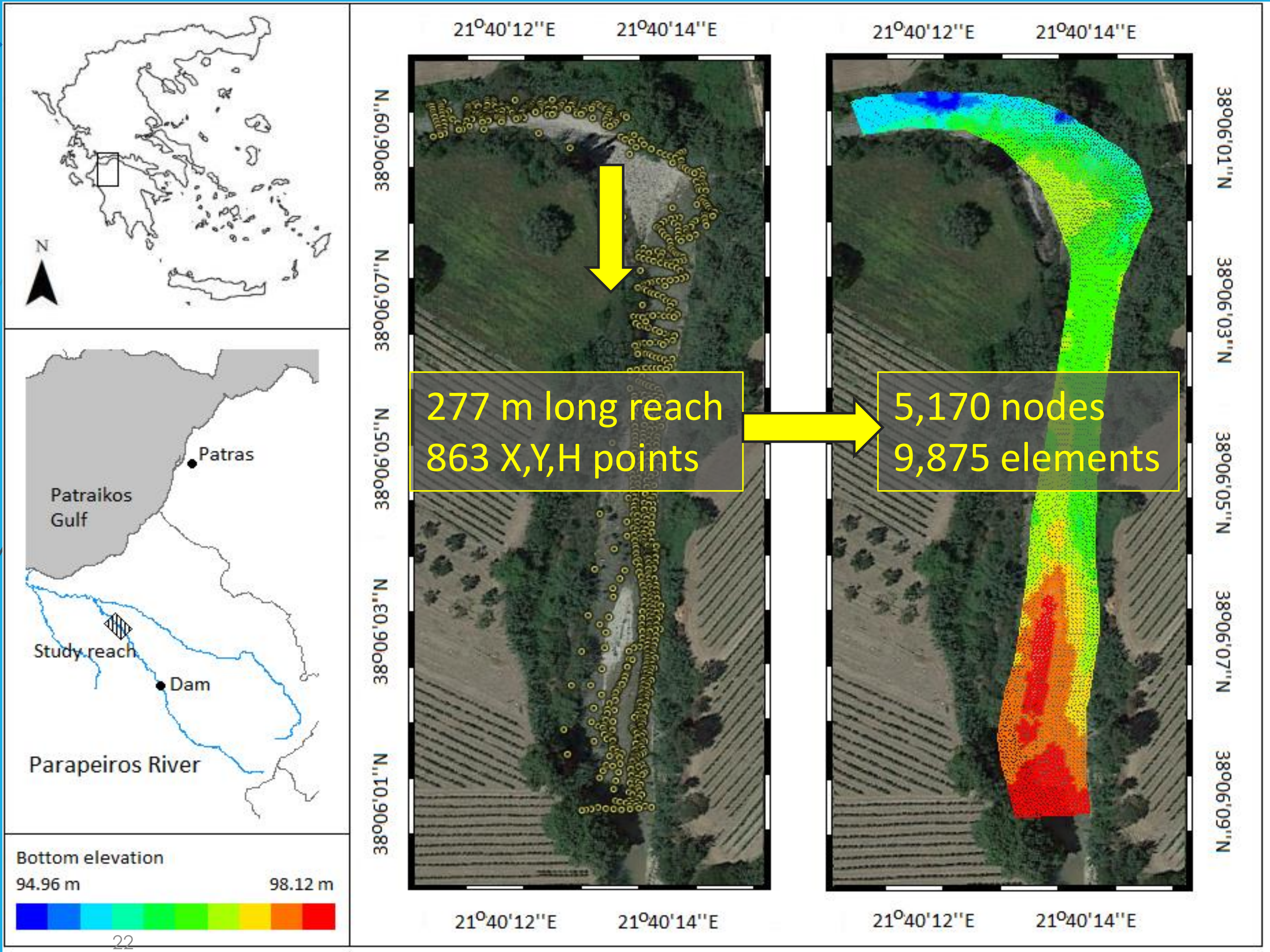
Environmental flow rate = 1.0 m3/s.

- ❖ It satisfies the habitat requirements.
- ❖ It is consistent with the requirements of the Environmental Management Classes A and B.
- ❖ It is higher than the value proposed by the Greek legislation.
- ❖ It is practically achievable from the hydrological point of view.

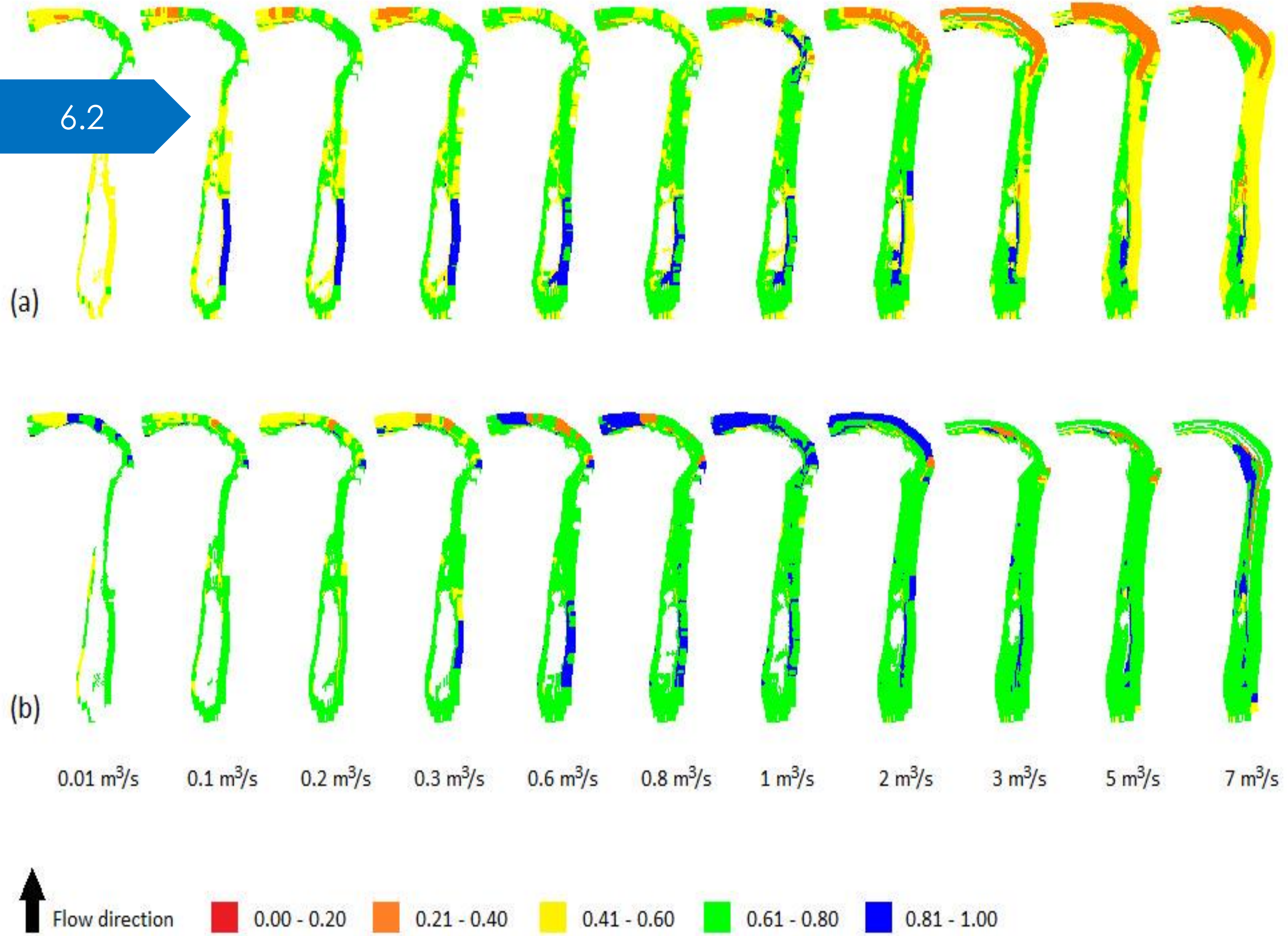
The water deficit during the summer-dry period is expected to be covered by another water source, such as a reservoir and water saving measures.

6 CASE STUDY 2

6.1

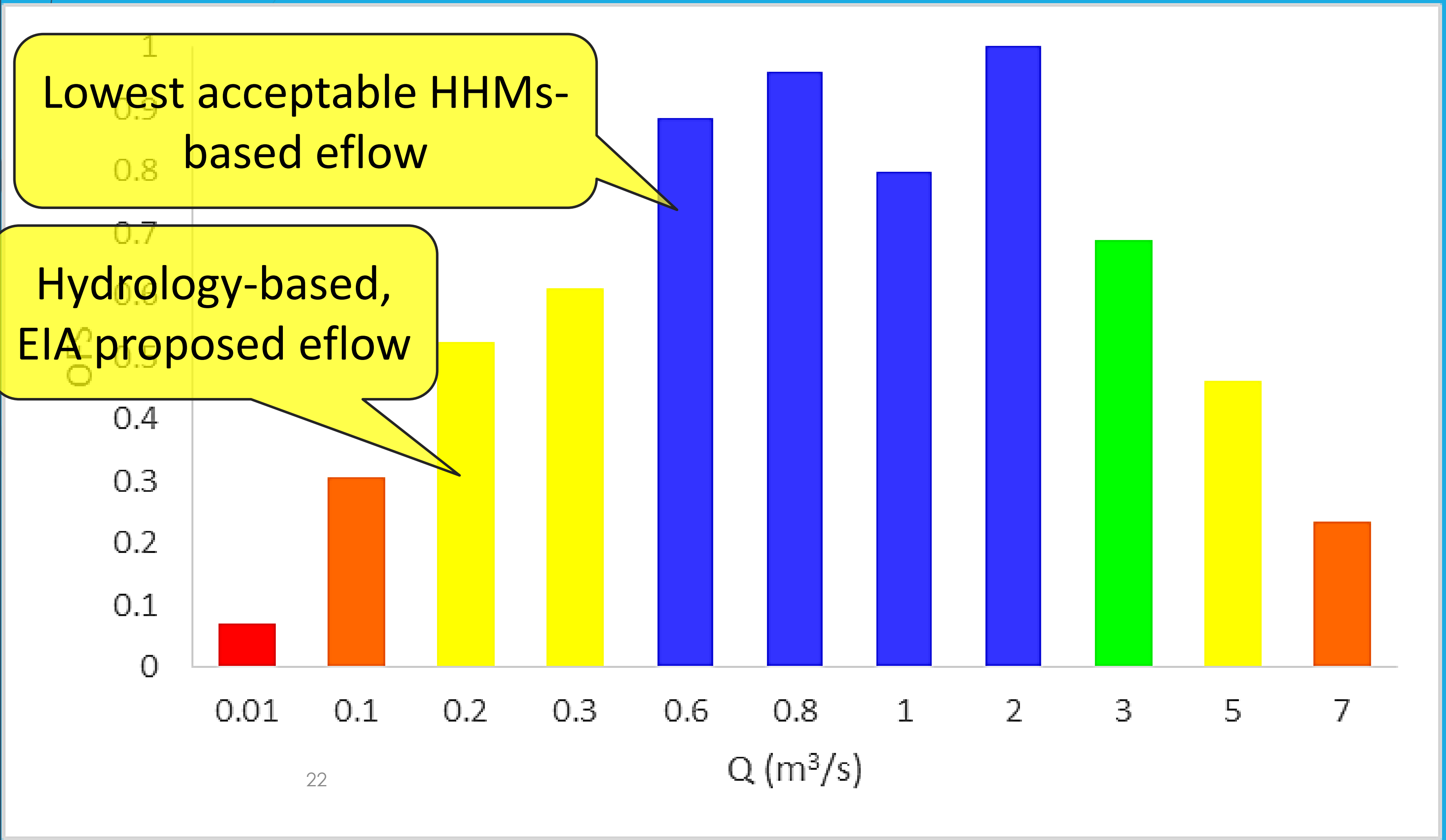


6.2


(a)
(b)
0.01 m³/s
0.1 m³/s
0.2 m³/s
0.3 m³/s
0.6 m³/s
0.8 m³/s
1 m³/s
2 m³/s
3 m³/s
5 m³/s
7 m³/s
Flow direction
0.00 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00

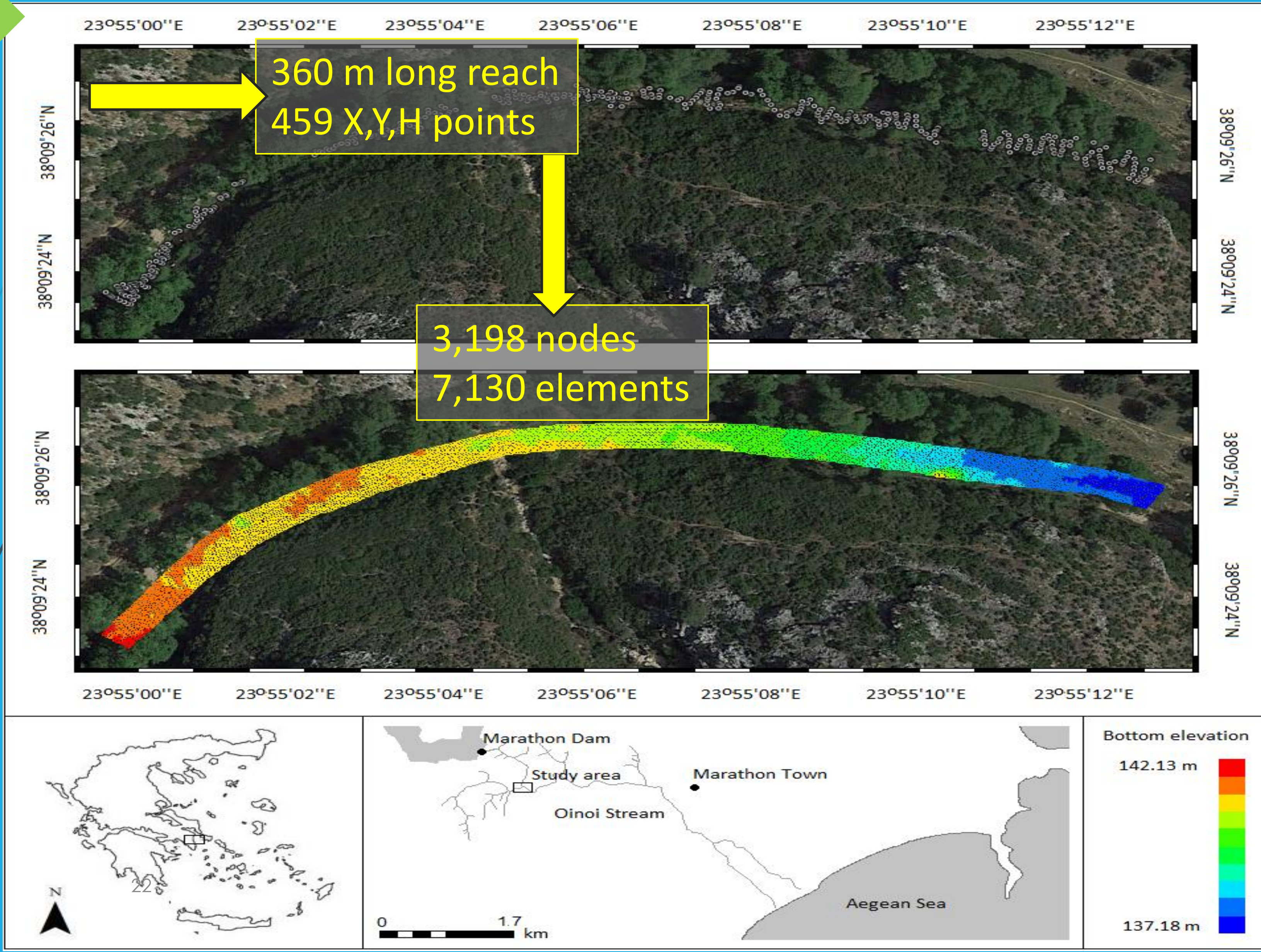
6.3

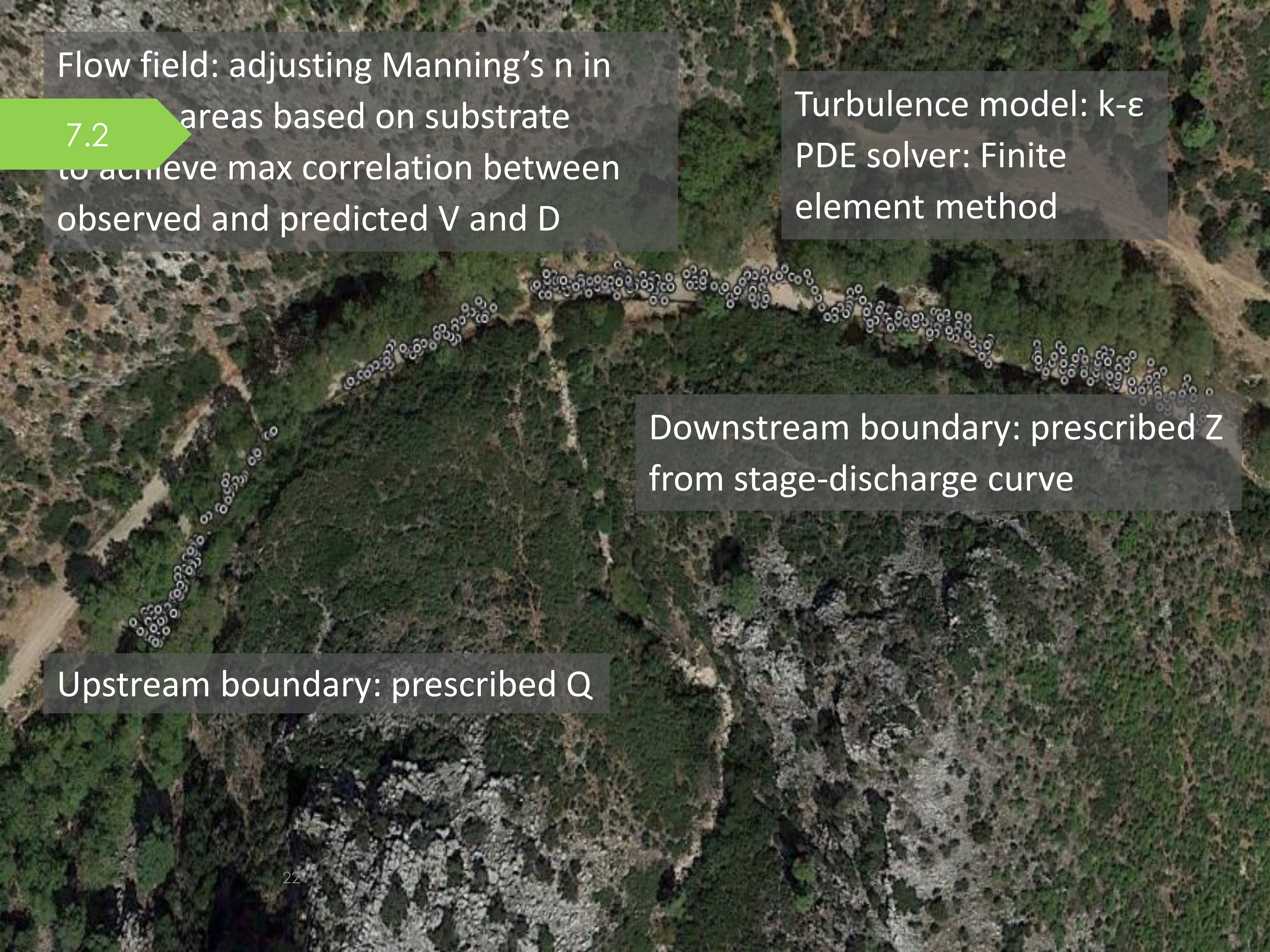
Environmental flow selection



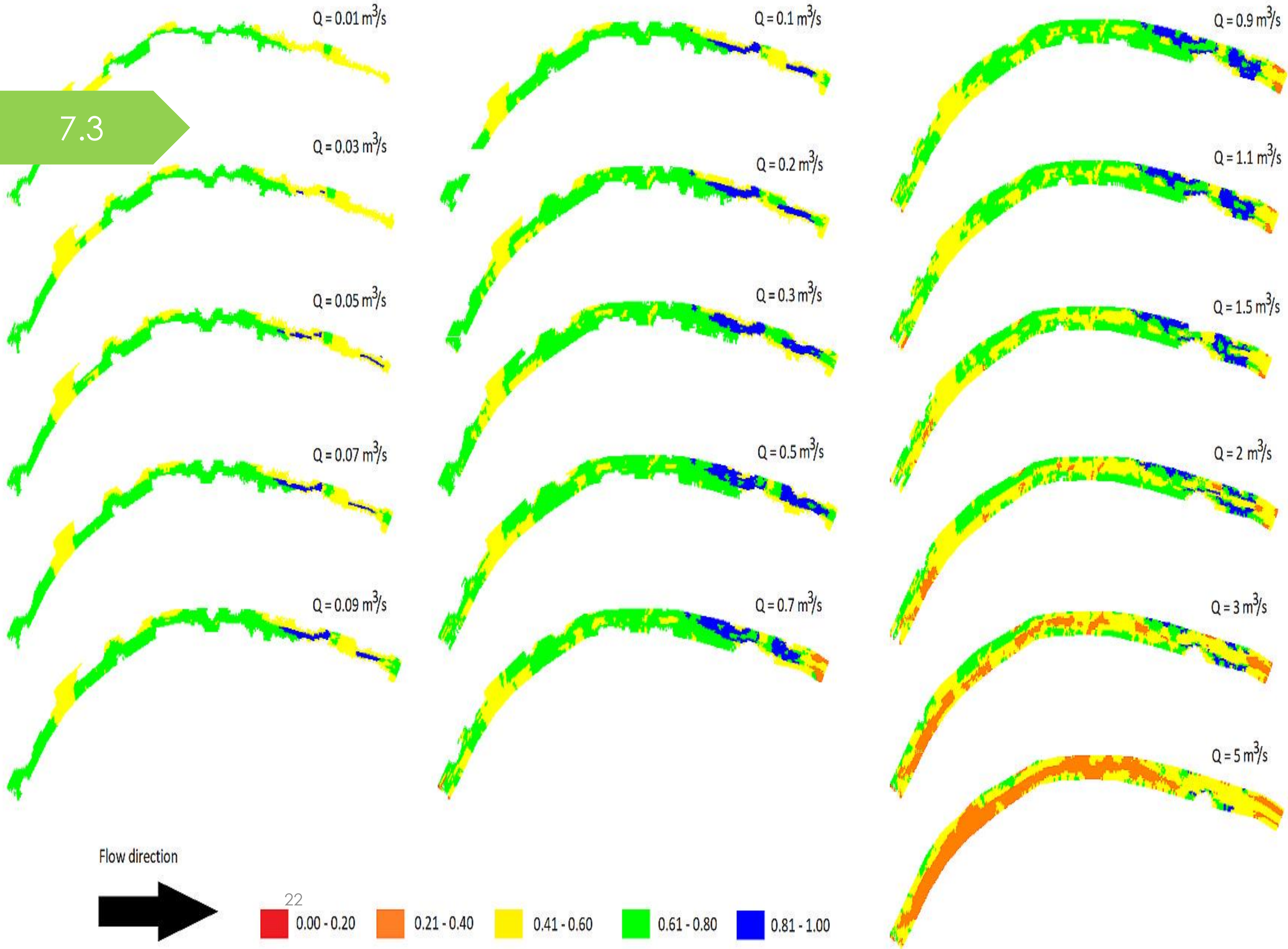
7 CASE STUDY 3

7.1

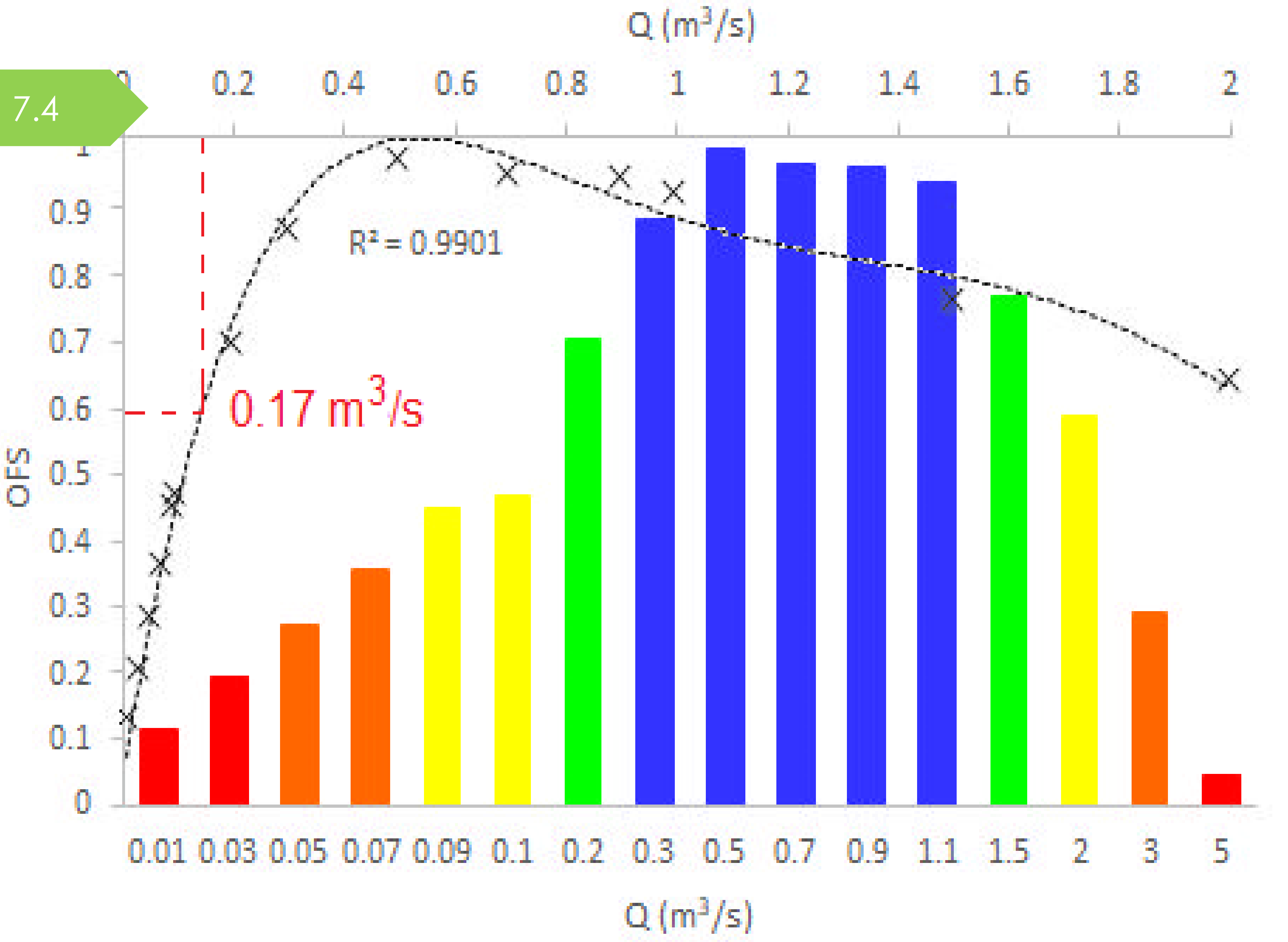




7.2
Flow field: adjusting Manning’s n in
areas based on substrate
to achieve max correlation between
observed and predicted V and D
Turbulence model: k-ε
PDE solver: Finite
element method
Downstream boundary: prescribed Z
from stage-discharge curve
Upstream boundary: prescribed Q


Q = 0.01 m³/s
Q = 0.03 m³/s
Q = 0.05 m³/s
Q = 0.07 m³/s
Q = 0.09 m³/s
Q = 0.1 m³/s
Q = 0.2 m³/s
Q = 0.3 m³/s
Q = 0.5 m³/s
Q = 0.7 m³/s
Q = 0.9 m³/s
Q = 1.1 m³/s
Q = 1.5 m³/s
Q = 2 m³/s
Q = 3 m³/s
Q = 5 m³/s
Flow direction
0.00 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 1.00

7.4


Q (m³/s)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
OFS
R² = 0.9901
0.17 m³/s
0.01
0.03
0.05
0.07
0.09
0.1
0.2
0.3
0.5
0.7
0.9
1.1
1.5
2
3
5
Q (m³/s)

Development of the methodology

Thanks to Dr. Christos Theodoropoulos !

- Theodoropoulos C., Vourka A., Skoulikidis N., Rutschmann P., Stamou A., 2018. Evaluating the performance of habitat models for predicting the environmental flow requirements of benthic macroinvertebrates. Journal of Ecohydraulics 3, 30-44.
- Theodoropoulos C., Vourka A., Stamou A., Rutschmann P., Skoulikidis N., 2017. Response of freshwater macroinvertebrates to rainfall-induced high flows - a hydroecological approach. Ecological Indicators 73, 432-442.
- Theodoropoulos C., Skoulikidis N. and Stamou A., 2016. HABFUZZ | A tool to calculate the hydraulic habitat suitability using fuzzy logic and fuzzy Bayesian inference. Journal of Open Source Software 1 (6).

Applications of the methodology

- Theodoropoulos C., Stamou A., Vardakas L., Papadaki C., Dimitriou E., Skoulikidis N., Kalogianni E., 2020. River restoration is prone to failure unless pre-optimized within a mechanistic ecological framework | Insights from a model-based case study. Water Research 115550.
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- Theodoropoulos C., Skoulikidis N., Rutschmann P., Stamou A., 2018. Ecosystem-based environmental flow assessment in a Greek regulated river with the use of 2D hydrodynamic habitat modelling. River Research and Applications 34, 538-547.