Fish habitat characterization and quantification using LIDAR and conventional topographic information in river survey.

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ABSTRACT

This study presents the application of LIDAR data to the evaluation and quantification of fluvial habitat in river systems, coupling remote sensing techniques with hydrological modeling and ecohydraulics. Fish habitat studies depend on the quality and continuity of the input topographic data. Conventional fish habitat studies are limited by the feasibility of field survey in time and budget. This limitation results in differences between the level of river management and the level of models. In order to facilitate upscaling processes from modeling to management units, meso-scale methods were developed (Maddock & Bird, 1996; Parasiewicz, 2001). LIDAR data of regulated River Cinca (Ebro Basin, Spain) were acquired in the low flow season, maximizing the recorded instream area. DTM meshes obtained from LIDAR were used as the input for hydraulic simulation for a range of flows using GUAD2D software. Velocity and depth outputs were combined with gradient data to produce maps reflecting the availability of each mesohabitat unit type for each modeled flow. Fish habitat was then estimated and quantified according to the preferences of main target species as brown trout (*Salmo trutta*). LIDAR data combined with hydraulic modeling allowed the analysis of fluvial habitat in long fluvial segments which would be time-consuming with traditional survey. LIDAR habitat assessment at mesoscale level avoids the problems of time efficiency and upscaling and is a recommended approach for large river basin management.

Keywords: fish habitat, mesohabitat, hydraulic simulation, ecohydraulics, LIDAR, DTM

1. INTRODUCTION

LIDAR techniques offer a powerful tool applicable to a wide range of hydrological applications, such us flood modeling (Cobby et al., 2001; Dal Cin et al., 2005; Roberts et al., 2007) , water balance (Schmugge et al., 2002) and fluvial geomorphology (Evan-Canfield et al., 2005). Fish habitat studies depend on the quality and continuity of the input topographic data. Conventional fish habitat studies are limited by the feasibility of field survey in time and budget. This limitation results in differences between the level of river management and the level of models; river management mostly operates at catchment or river sector level, while modeling uses the much smaller site level (Borsanyi et al., 2004). In order to facilitate upscaling processes from modeling to management units, intermediary methods between the micro- and the macroscale level were developed (Habitat Mapping (Maddock & Bird, 1996; Maddock, 1999); MesoHABSIM (Parasiewicz, 2001)). Borsányi et al. (2004) proposed a method based on the characterization and mapping of main river hydromorphological units defined according to the surface pattern (wave height), gradient, velocity and depth.

Among the environmental effects caused by dams and reservoirs, the main one is the alteration of the flow regime. Although each use gives rise to different disruptions of the flow regime, in most cases the general effect is a reduction and lamination of floods. However, changes also affect parameters of biological importance, leading to severe alteration of processes that are determined by the volume of water flowing in the river and loss of the complexity and the richness of the populations that these ecosystems support. In order to analyse the effects of flow regulation on fish habitat, we

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selected a fluvial reach in River Cinca downstream of El Grado Dam included in the fluvial segment limited by El Grado Dam and Esera tributary mouth.

The objectives of this research were:

a) to analyze the potential use of LIDAR-derived DTM meshes for the hydraulic simulation of environmental flows and fish habitat
b) to study the performance and limitations of 2 m square pixel LIDAR DTM meshes for fish habitat analysis in low flow conditions.
c) To analyze the potential use of LIDAR DTM meshes compared to traditional topographic survey for hydraulic modeling.

2. METHODS

2.1 Study area

The Cinca River is one of the main tributaries to the Ebro River, in NE Spain. The Ebro Basin is the larger basin in Spain, with a total area of 85.378 km^2, and its administration is under the Ebro Water Authority (Confederación Hidrográfica del Ebro; www.chebro.es), a trans-regional Spanish institution based in Zaragoza. The Ebro Basin yields annually a total of 18.200 hm^3/year in average (maximum 29.700 and minimum of 8.400 hm^3/year), a 17% of spanish national yield. River Cinca is a left bank tributary which basin extends south from the heights of the Pyrenees, covering 9678 km^2 (Figure 1)

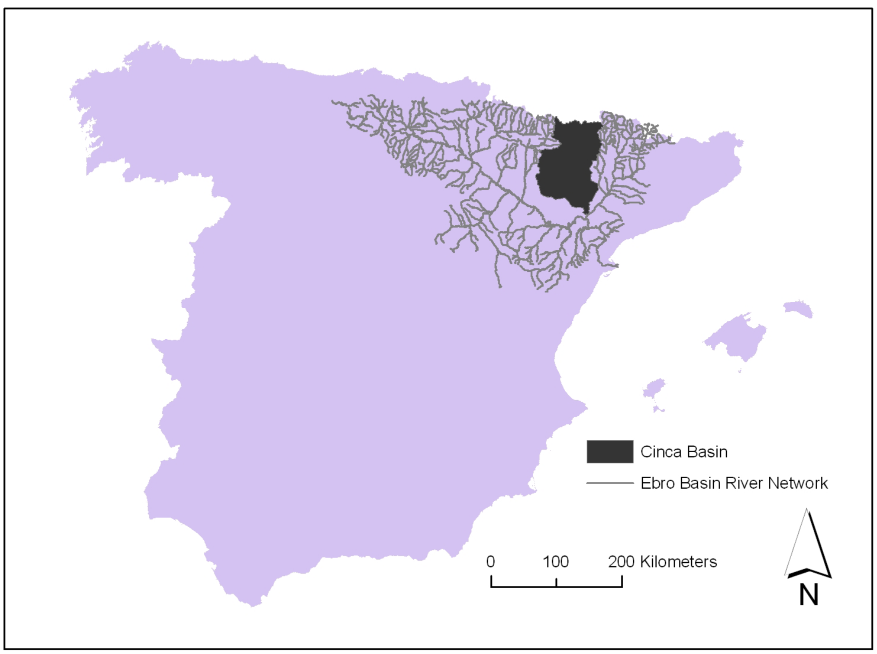

Figure 1-. Location of Cinca Basin in the Ebro Basin (SE Spain)

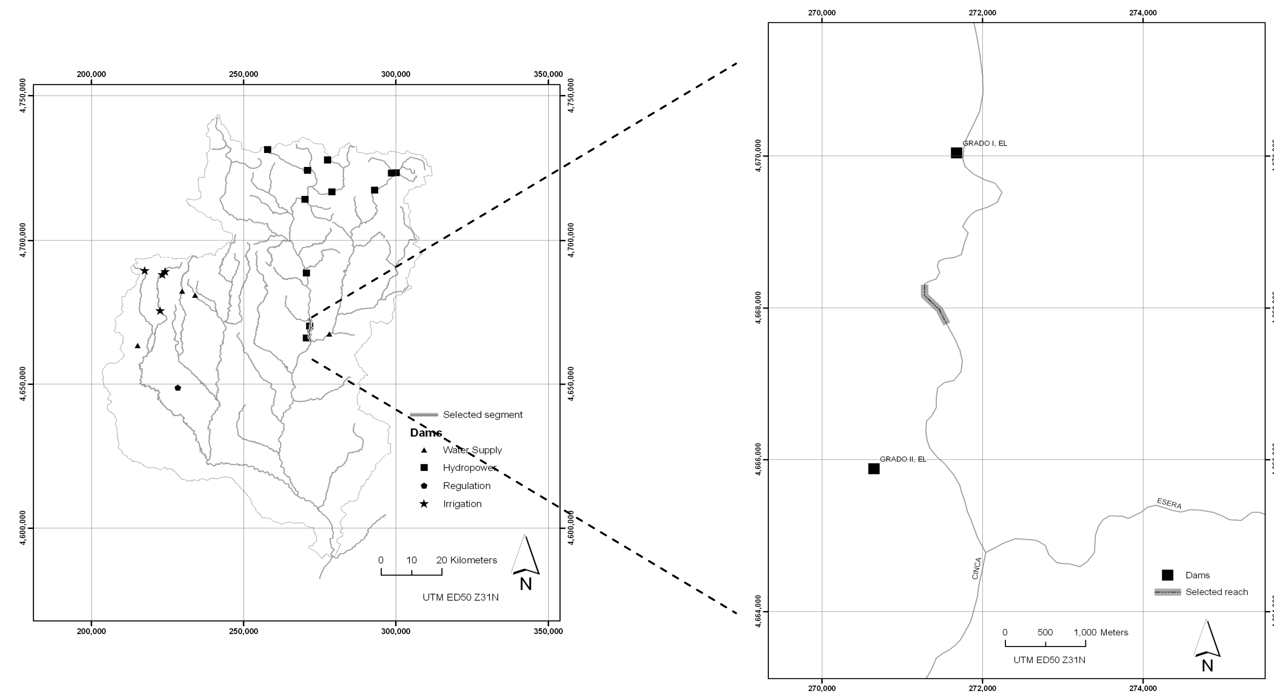

Figure 2-. Detail of selected segment and selected reach in Cinca River

Cinca Basin yields 2571 hm^3/year in average and it is intensively used for hydropower generation and irrigation. The main use is hydropower production (57% of dams), followed by irrigation (19%) and water supply (19%).Figure 2 shows Cinca Basin, main dams and the selected segment and reach where this study was carried out. The selected reach belonged to the segment delimited by the Grado I Dam upstream and the mouth of Esera tributary downstream. The dimensions of the terrain modeled were around 600 x 250 m, with about 37,500 cells of 4 m^2. The reach was dry during the LIDAR survey, so it was not necessary to do bathymetry.

2.2 LIDAR survey

A LIDAR survey was carried out by the Confederación Hidrográfica del Ebro (Water Authority) to study flood risk in medium and lower Cinca valley. The flight went from El Grado I Dam to the mouth of river Cinca, with a total of 107.89 km in length. The survey was conducted by the company Stereocarto using the following equipment (Table 1):

Table 1-. Equipment for LIDAR survey (Stereocarto)

SECTION	EQUIPMENT	MODEL
FLIGHT EQUIPMENT	Plane	CESSNA: 404 TITAN
	Navigation System	Track-Air: Tracker
	Differential GPS	NOVATEL: Millenium
	Inertial INS/DGPS System	Applanix: POS/AV 410
LIDAR SYSTEM	Scanner	Leica ALS50
	Rack	Leica ALS50
	Computer	Leica ALS50
	Software	Inertial analytical navigator
		Kalman filter
		Closed cycle error controller
		Trajectory smoother
		Feedback error controller
		Allignement
AERIAL PHOTOGRAPHY	Camera	Z/I DMC Digital
	Navigation System	ASMS (Airborne Sensor Management System)
	Inertial INS/DGPS System	GPS e INS
	In-flight storage system	FDS (Flight Data Storage)
	Post-processing station	PPS (Post Processing System)

The main characteristics of the survey are presented in Table 2:

Table 2-. Characteristics of LIDAR flight

Parameter	Units	Value
Heigth	m	1500
FOV	º	30 - 40
Laser pulse frequency	hz	60000
Density		1 point/ 2 m^2
Intensity		>256 levels

The flight was done in the dry season in orden to maximize the instream dry recorded area. Field differential GPS units were settled to be closer than 50 km to the plane during the flight. Postprocessing work involved the application of filters and error controllers to get two final products (Figure 3):

- Digital Surface Model (dsm); 2 m pixel grid based on the analysis of the first and last LIDAR pulses
- Digital Terrain Model (dtm); 2 m pixel grid obtained using the last LIDAR pulse.

The final precision values were:

- Horizontal: RMSE < 0.50 m
- Vertical: RMSE 0.15 m

Figure 3 shows the results of LIDAR processing: dsm and dtm grids. The first one includes vegetation and buildings, the second one is restricted to terrain surface, identified with the last laser pulse.

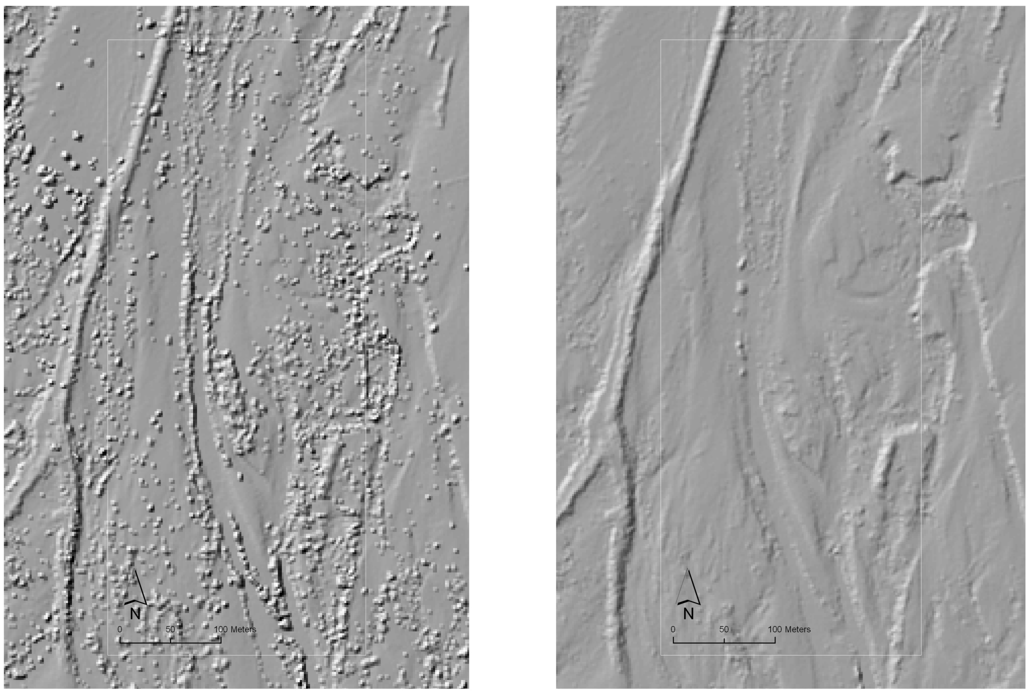

Figure 3-. Grids dsm (left) and dtm (right) for the selected reach (rectangle) in Cinca River

2.3 Hydraulic simulation

For the hydraulic simulation it was used the GUAD 2D model, developed by Inclam S.A.and CPS (University of Zaragoza). GUAD 2D is a model that simulates water depth, level and speed in two dimensions (x, y) for each pixel of a given terrain under certain flow conditions (input hydrograph, output level, roughness). GUAD 2D works iteratively solving the equations of continuity averaging the speed of flow in the water column above each terrain pixel (2D model) (Figure 4). The strength of GUAD 2D allows to simulate floods in more than 1 million pixel areas.

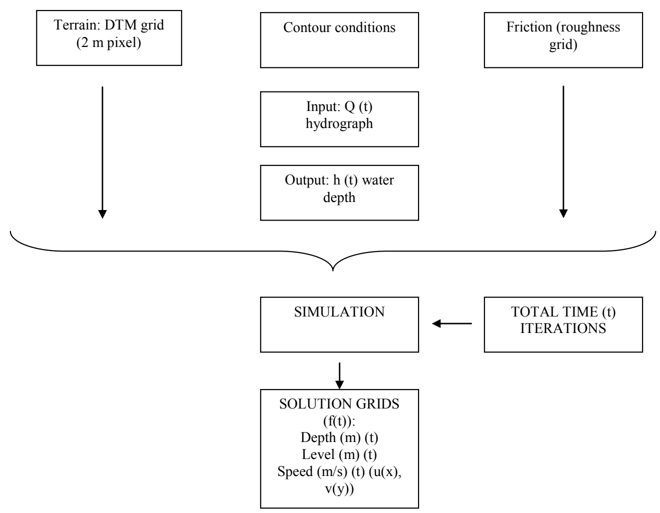

Figure 4-. Scheme for the hydraulic simulation with GUAD 2D

Figure 5 shows the natural mean monthly flows for El Grado gauge station (1912-1974). The selected flows for the simulation were:

- Natural average flow (1912-1974; n=32; El Grado gauge station): 50 m^3/s
- Natural average flow in the dryest month (August): (1912-1974; n=43; El Grado gauge station): 35 m^3/s
- 20% of natural average flow: 10 m^3/s
- 10% of natural average flow: 5 m^3/s

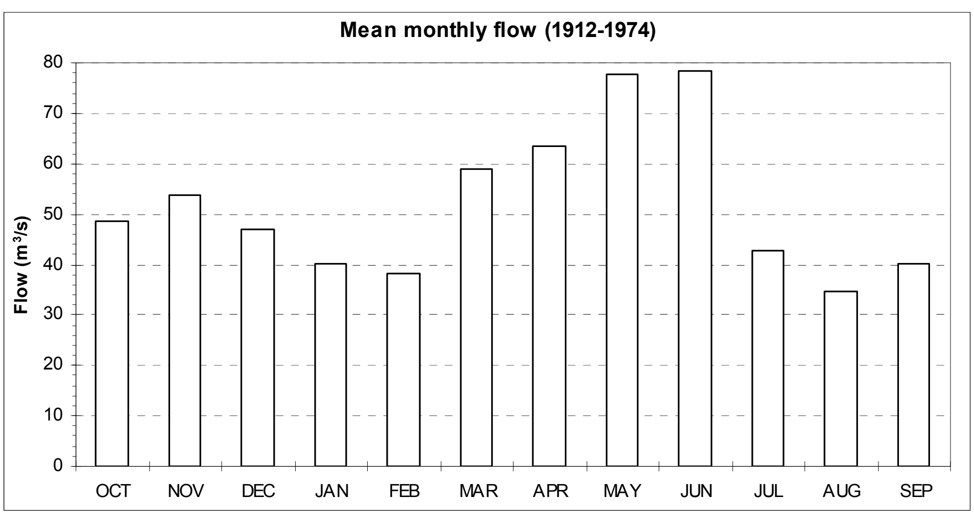

Figure 5-. Mean monthly flow in El Grado (Cinca River)

2.4 Fish habitat evaluation

For the evaluation of fish habitat two different methodologies were applied:

a) Mesohabitat quantification: riffle, shallow glide, deep glide and pool (after Maddock and Bird, 1996)

b) Weighted usable area (WUA) for different stages of brown trout (*Salmo trutta*): adults, juveniles, fry and spawning using preference curves elaborated for Spain by García de Jalón (1999)

The quantification of mesohabitat type was done by reclassification of depth and velocity grids for each modeled flow. The main mesohabitat units are described in Table 3:

Table 3-. Definition of mesohabitat units (after Maddock and Bird, 1996)

Mesohabitat	Depth range (m)	Velocity range (m/s)	Description
Riffle	< 0.5	> 0.8	Relatively steep water surface gradient, coarser bed material, some broken water
Shallow glide	< 0.5	0.2 - 0.8	Relatively smooth, low gradient water.
Deep glide	> 0.5	0.2 - 0.8	Relatively smooth, low gradient water.
Pool	> 0.5	< 0.2	Smooth, low gradient

The preference of each stage of brown trout with respect to depth, velocity and substrate were evaluated using preference curves developed by García de Jalón (1999) and Mayo (2000) for Spain. Figure 6 and Table 4 show respectively adult brown trout preference curves and table for depth, velocity and substrate

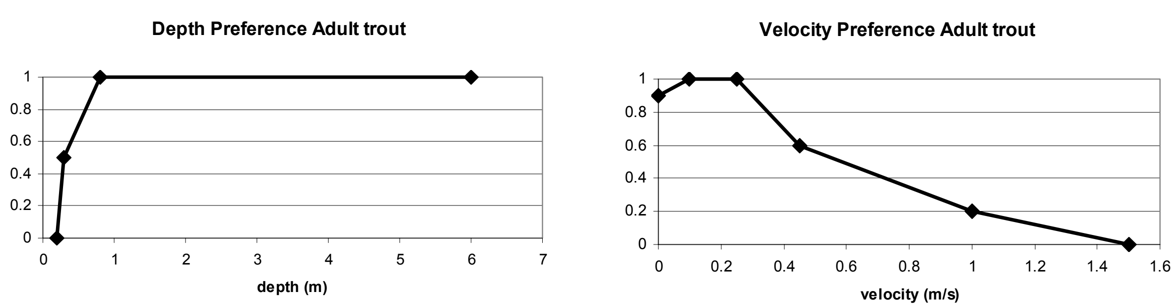

Figure 6-. Depth and velocity preference curves for adult brown trout in Spain (García de Jalón, 1979)

Table 4-. Substrate preferences for adult brown trout in Spain (García de Jalón, 1979)

Substrate	Preference (0-1)
silt, clay	0.3
sand	0.5
gravel	0.9
cobble	1
boulder	1
rock	0.5
aquatic vegetation	0.8
roots, branches	0.2
trees, shrubs	0.2

The river Cinca in the evaluated reach is mainly a gravel bed river. It has been assumed that the bed in the reach is composed mainly of gravel for the calculation of the substrate suitability. Once evaluated the suitability (0-1) of depth (Sd), velocity (Sv) and substrate (Ss) conditions for the development of each brown trout stage, it was calculated the Composite Suitability Index (CSI) for each wetted pixel as the geometric mean of the three indicators:

$$CSI = \sqrt[3]{Sd \bullet Sv \bullet Ss}$$

Finally, the Weighted Usable Area (WUA) (Bovee, 1982) for each brown trout stage under different flow conditions was calculated as an aggregate of the product of the Composite Suitability Index (CSI, range 0-1) evaluated at every pixel and the area of the pixel.

3. RESULTS

3.1 Hydraulic simulation

Depth ranged from a maximum of 0.71 m with 5 m^3/s to a maximum of 1.52 under 50 m^3/s. Velocity ranged from 2,6 m/s with 5 m^3/s to a maximum of 3.3 under 50 m^3/s

3.2 Mesohabitat quantification

The extent of the mesohabitat units varied with different flow scenarios. Table 5 presents the area of the mesohabitat units under different flow scenarios.

Table 5-. Quantification of mesohabitat units for different simulated flows

Mesohabitat	Q = 5 m^3/s	Q = 10 m^3/s	Q = 35 m^3/s	Q = 50 m^3/s
Riffle	0	25,728	39,744	39,744
Shallow glide	41,760	40,048	30,672	31,456
Deep glide	9,728	12,480	14,176	14,592
Pool	464	3,584	3,152	2,832

It can be noted that riffles disappear in the scenario of lowest flow, being almost the same for Q = 35 m^3/s or 50 m^3/s. The area of pools is severely restricted because of the morphology of this braided gravel bed river. Figure 7 presents graphically the results of the mesohabitat simulation

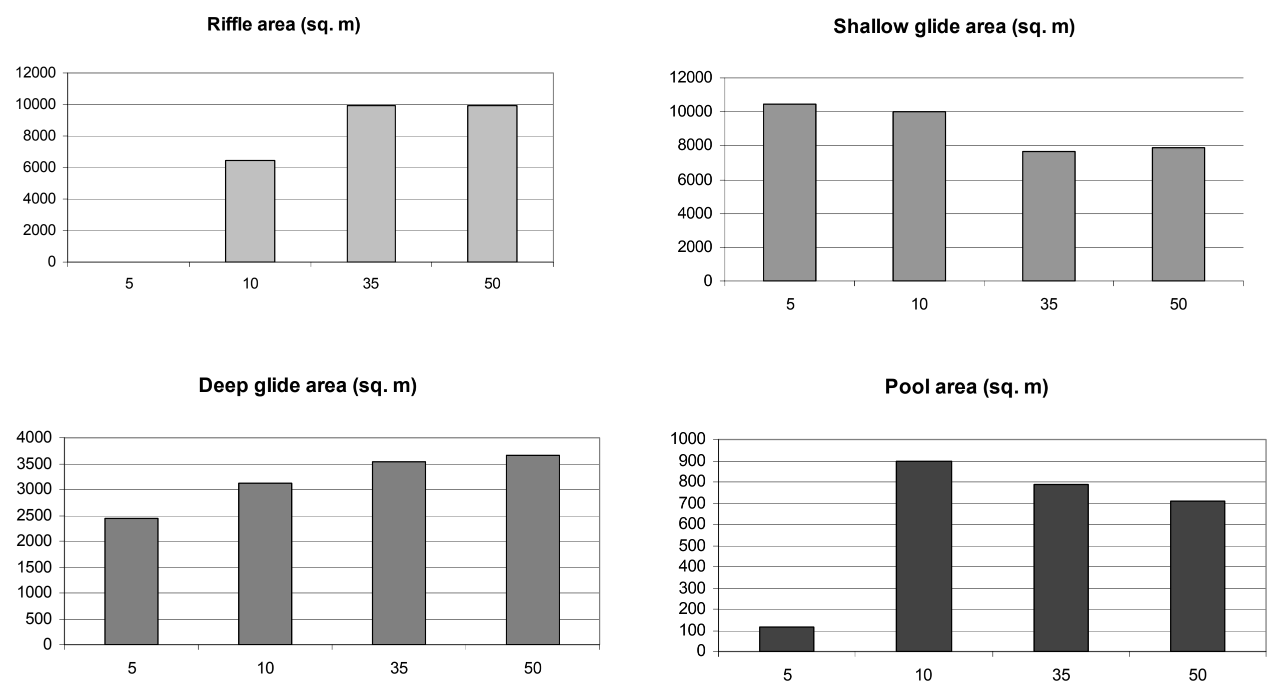

Figure 7-. Graphic quantification of mesohabitat units for different simulated flows

3.3 Brown trout weighted usable area (WUA)

The evaluation of brown trout habitat yielded the below presented results (Table 6):

Table 6-. Quantification of brown trout habitat (Weighted usable area) for different simulated flows

WUA (sq. m)	Q = 5 m^3/s	Q = 10 m^3/s	Q = 35 m^3/s	Q = 50 m^3/s
Adult	8,168	10,780	15,360	15,368
Juveniles	11,556	11,480	9,656	8,944
Fry	13,632	9,580	9,024	8,460
Spawning	12,860	11,976	12,408	11,696

It can be noted that the lowest flow halves the habitat for adult trout compared to the mean natural August flow (Q = 35 m^3/s). On the other hand, higher flows restrict the habitat for juveniles, as velocities increase over tolerable thresholds for individuals in this stage (Figure 8).

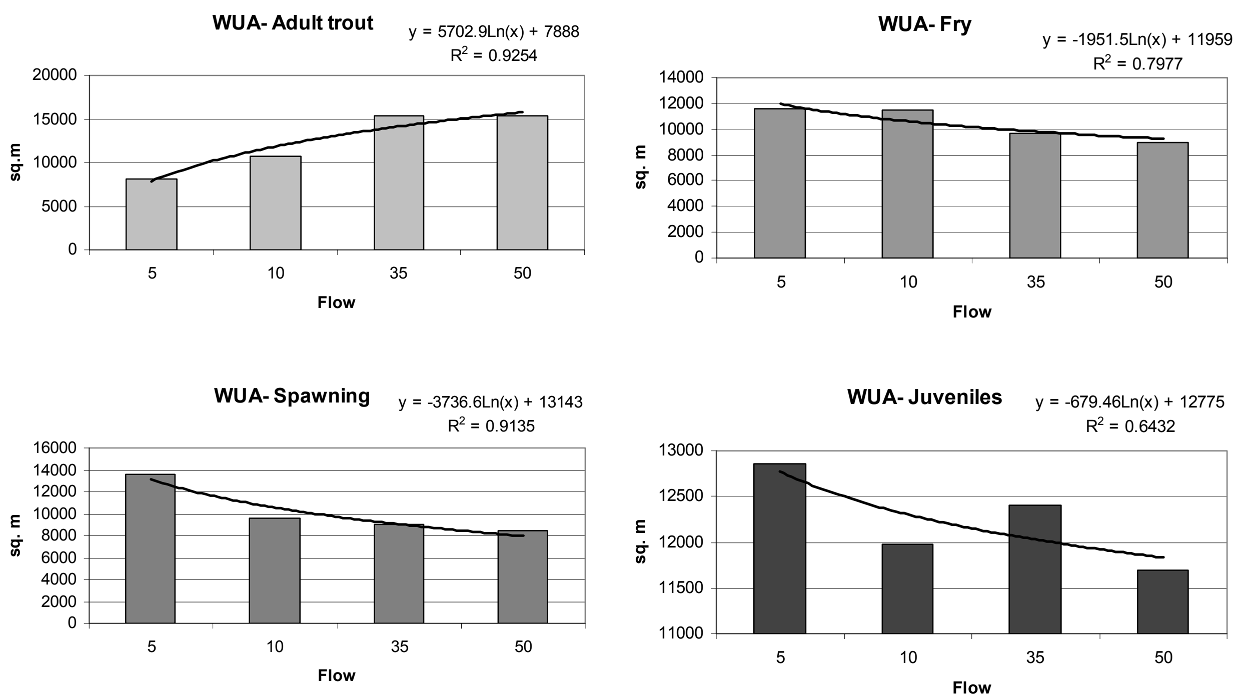

Figure 8-. Graphic quantification of brown trout habitat (Weighted usable area) for different simulated flows and regression expressions

4. CONCLUSIONS

a) The presented study demonstrates the applicability of LIDAR data to fluvial habitat evaluation. For this purpose it is required a specific LIDAR survey design, adapted to the linear shape of the floodplain and riverine system. LIDAR flights must be conducted went river channels are dry, in order to avoid the need to do a complementary bathymetry.

b) The application of this technique requires a strong hydraulic model, such us GUAD 2D, capable of simulating flows in large grids (over 1,000,000 pixels). The combination of LIDAR-derived grids and strong hydraulic models allows the analysis of fluvial habitat in long fluvial segments which would be unfeasible with traditional survey. Reaches over 4 km in length and 250 m in width can be analysed as shown in this study.

c) This methodology presents a clear advantages over conventional topographic surveys in the following aspects:

   a. Saves fieldwork time

   b. LIDAR grids are continuous and evenly distributed in comparison to discontinuous topographic surveys (cross sections, random surveys,…)

   c. LIDAR grids can be used for the evaluation of morphological changes in fluvial systems over time

   d. LIDAR habitat assessment at mesoscale level avoids the problems of time efficiency and upscaling (Maddock, 1999) and is a recommended approach for large river basin management.

d) The main disadvantages of this methodology are:

   a. The limited vertical precision of LIDAR meshes (0.15 m in this case) that affect the performance of hydraulic simulations. This can affect mainly the results of low flow simulations, that are critical for fluvial habitat assessment.

   b. Inability of laser pulses to progress under the water level: if a water table is present, a bathymetry is required to complete river channel topography. This problem can be reduced by planning LIDAR surveys in the dry season, ideally when channels are dry, as it was done in this study.

   c. The costs, that are outweighted by the benefits of the usage and storage of LIDAR data. It is possible to reduce the costs sharing LIDAR information among different land use planning institutions: water authorities, conservation organizations, cadastre, flood risk managers,…

e) The evaluation of fish habitat can be done at different scales: mesohabitat or microhabitat applying different methodologies. If preference curves for a given species are available, the effect of flow regulation on different stages for this species can be assessed with high precision.

f) The analysed reach in River Cinca is a braided gravel reach. Low flows restrict riffle area, halving available habitat for adult trout species. On the other hand, high flows may restrict habitat for juveniles. For this reasons, non-natural peaking may affect all stages of brown trout. A scientifically designed environmental flow regime must be adapted to natural variation, without overpassing tolerance thresholds for sensitive organisms in the fluvial ecosystem.

g) Further research must be done in order to enhance the precision of LIDAR grids to be used in hydraulic simulation. Vertical precision must be enhanced in order to simulate low flow conditions. Triangle-pixel grids may improve the hydraulic simulation, compared to square-pixels grids. Square pixel grids present some death corners that affect the performance of hydraulic simulations. Resampling and interpolation strategies may help to reduce this effects on square-pixel grids.

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