DESIGN AND CONSTRUCTION OF THE WESTERN BREAKWATER FOR THE OUTER PORT AT PUNTA LANGOSTEIRA (A CORUÑA, SPAIN)

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This paper describes the design process, hydraulic stability tests and construction of the Cubipod® armored Western breakwater at Punta Langosteira (Outer Port of A Coruña, Spain), located on the Atlantic coast of Spain. The environmental, geotechnical, economic and logistic conditions favored randomly-placed Cubipods for single-layer armoring of the trunk. 3D hydraulic stability tests were carried out to validate the final design of the Western Breakwater; two models were tested with single- and double-layer Cubipod armors in the trunk and roundhead, respectively. Single-layer 25- and 30-tonne Cubipod® armors were used for the trunk section and a double-layer 45-tonne Cubipod® armor was used for the roundhead. During this project, new challenges were overcome, such as constructing a transition between single and double-layer armors, and manufacturing and handling of 45-tonne Cubipods. The transition in the armor thickness was solved by modifying the filter thickness under the main armor, to ensure a homogeneous external armor profile. Breakwater construction finished in November 2016 with no significant problem or delay in the original schedule.

Keywords: Hydraulic Stability; Armor Unit; Cubipod; Construction; Single-layer; Double-layer; Breakwater

INTRODUCTION

This paper describes the design and construction works for the 1.35 km-long Western Breakwater in the Outer Port at Punta Langosteira (A Coruña, Spain) completed during 2016. The Western Breakwater is the secondary breakwater sheltering the harbor from mainly northern and western storms. The 3.35 km-long main breakwater of this harbor was completed in 2011; Burcharth et al. (2015) described the construction of the double-layer 150-tonne cube armored breakwater, designed to withstand a design storm with H_s[m]=15 and T_p[s]=18.

Two parallel groins (South and North breakwaters), perpendicular to the coastline with single-layer Cubipod® armor of W[t]=25 and 15 (see Corredor et al., 2014), were completed in 2013 to protect the water intake of the Sabón thermal power station. The new Western Breakwater was designed as an extension of the existing 0.45 km-long South Breakwater. As shown in Fig. 1, the Western Breakwater has two alignments, the first being 0.85 km-long in an ESE-WNW direction and the second, 0.47 km-long in a SSE-NNW direction. The maximum water depth of the Western Breakwater at low water level (LWL) is h[m]=22; tidal range is Δh[m]=5.0.

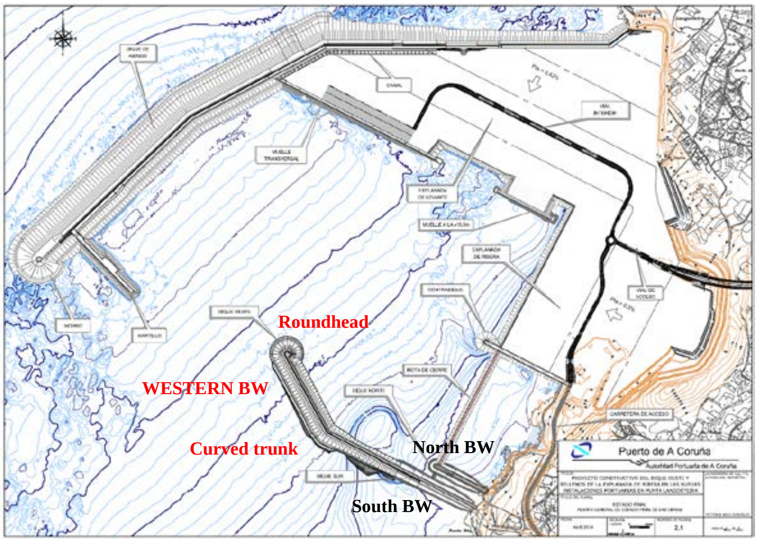

Figure 1. Western breakwater in the Outer Port of A Coruña at Punta Langosteira. Source: Port Authority of A Coruña, Spain.

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ORIGINAL ARMOR DESIGN

The original breakwater was designed by the Port Authority of A Coruña, following a Level III probabilistic approach as included in Spanish ROM standards recommendations (see Maciñeira et al., 2015), and design storms (start of damage, IDa, and ultimate limit state, ULS) for the Western breakwater were calculated and later validated with 1/51 small-scale tests. Fig.2 shows a wave propagation case used to estimate harbor agitation before the construction of this new breakwater; diffraction on the main breakwater strongly affects the waves attacking the secondary breakwater. Four points (see Fig. 2) along the Western breakwater were considered (first straight trunk, curved trunk, second straight trunk and roundhead) and the following failure modes were tested: hydraulic stability of armor layer and toe berm, overtopping and forces on crown-wall.

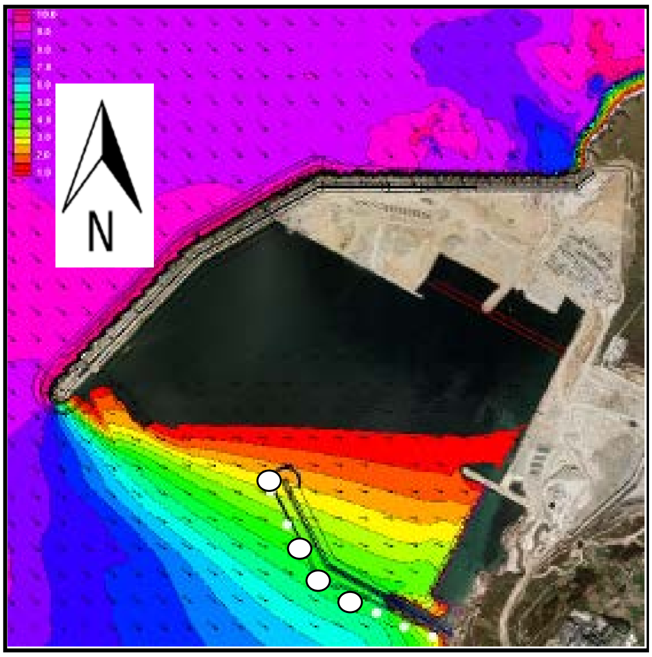

Figure 2. Wave agitation in the Outer Port of A Coruña at Punta Langosteira.

Located in partially-breaking wave conditions, the Western breakwater (0<h[m]<22) was originally designed with conventional H/V=1.5 double-layer randomly-placed 25-tonne cube armor in the straight trunks and 50-tonne cube armors in the curved trunk and roundhead (see Fig. 3). The toe berm was also validated with 12.5-tonne and 25.0-tonne cubes. The original design was validated with 3D 1/51 small-scale tests carried out in the GEAMA-CITEEC wave basin (32.0x34.0x1.2 m) at the A Coruña University (Spain).

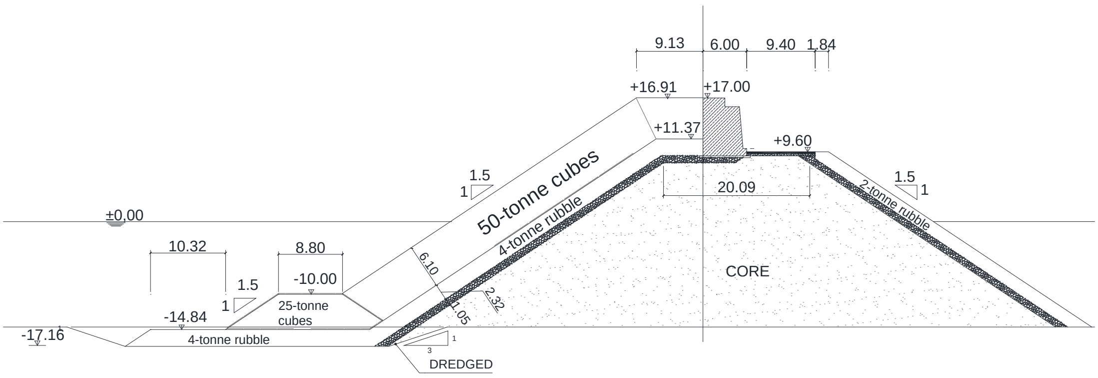

Figure 3. Original double-layer 50-tonne cube curved trunk cross section.

During the bidding process, double-layer and single-layer armoring using different armor units were admitted for the trunk, while only double-layer armoring was allowed for the roundhead. Changes in the toe berm and filter-layers were also allowed. 3D physical tests for the curved trunk and roundhead were required to validate each alternative design, which had to withstand the prescribed design storms for the Ultimate Service Limit or Initiation of Damage (IDa with 1% armor damage) and Ultimate Limit State (ULS with 10% armor damage), with return periods T_R(years)>200 and 5000, respectively.

CUBIPOD® ARMOR DESIGN AND 3D MODEL TESTS

The contractors' joint venture, *UTE Dique Oeste*, proposed an alternative armor design with Cubipod® units. This design was characterized by two clear advantages: (1) the reduction in the concrete consumption with the single-layer Cubipod® armoring in the trunk section, and (2) the re-use of the Cubipod® units previously placed in the roundheads of the South and North breakwaters.

In order to calculate the Cubipod® unit weights, a preliminary design-by-analogy was made with the cube armor solution, considering the stability coefficients (K_D) reported by Medina and Gómez-Martín (2012). The new Cubipod® armor design was validated with the corresponding 3D tests in the same wave basin as the original design made by the A Coruña Port Authority, using the same model scale and wave conditions.

The stability coefficients for double-layer cube and single-layer Cubipod® armors in the trunk section are K_D=6.0 and 12.0 (see Medina and Gómez-Martín, 2012 and 2016), respectively; therefore, a single-layer 25-tonne Cubipod® armor (50x6.0/12.0=25) is suitable to protect the entire trunk of the Western Breakwater. This solution allows for a breakwater that withstands higher design storms and significantly reduces the concrete consumption; additionally, this solution involves re-using most of the 25-tonne Cubipods placed in the existing South Breakwater.

The roundhead stability coefficients for double-layer cube and Cubipod® armors are K_D=5.0 and 7.0 (see Medina and Gómez-Martín, 2012 and 2016), respectively; a double-layer 36-tonne Cubipod® armor (50x5.0/7.0=36) would be sufficient to protect the roundhead. The Cubipod® armored design was validated with 1/51-scale 3D model tests; the available Cubipod® models in the laboratory were equivalent to 24- and 42-tonne Cubipod® units at prototype scale.

Given the basin dimensions, two models were tested (roundhead and curved trunk) in the GEAMA-CITEEC wave basin (32.0x34.0x1.2 m.) under unidirectional waves. The first one included the roundhead and half the second alignment, and the second considered the curved trunk and part of the adjacent alignment (see Santos et al., 2016).

The new breakwater design was protected with a H/V=1.5, single-layer 24-tonne Cubipod® armor in the curved trunk and a double-layer 42-tonne Cubipod® armor in the roundhead. JONSWAP (γ=3.3) wave spectra, with peak periods T_p[s]=15 and 18 and Δh[m]=0.0 and 5.0, were generated with increasing significant wave heights exceeding Hs[m]=5.15 and 5.85 (IDa and ULS) to validate the roundhead armoring, and H_s[m]=6.75 and 8.75 (IDa and ULS) to validate the straight and curved trunks armoring. Overtopping, wave loads and hydraulic stability of armor layer and toe berm were studied during the tests.


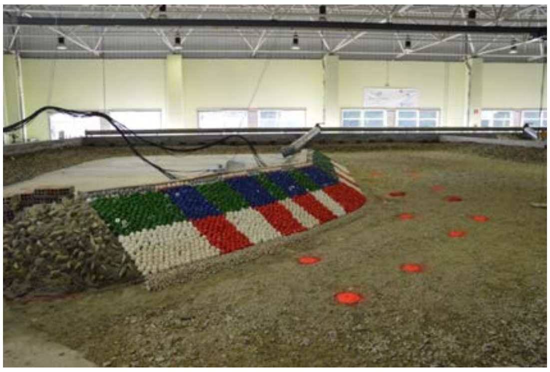

Figure 4. Model I: roundhead armored with double-layer 42-tonne Cubipods, and Model II: straight and curved trunk armored with single-layer 24-tonne Cubipods.

Fig. 4 shows the roundhead under wave attack and the curved trunk area after construction. The roundhead withstood 7.1≤H_s[m]≤7.7 (>5.85m) with damage D<10%, the straight and curved trunks reached Hs[m]=9.2 (>8.75m) without damage (N_{od}=0), and the transition single- to double-layer withstood H_s[m]≥9.1 (>8.25m) without damage (N_{od}=0). In order to study the resilience of the single-layer Cubipod® armor, accumulated armor damage was measured when significant wave height was increased above the design storm. Test conditions were progressively worsened above ULS design storm; Hs[m]=11.1 (>8.75m) which caused only IDa to the first straight trunk close to the curved trunk section. The rock toe berm with W[t]=4 did not show any damage, and the overtopping discharges were admissible with q[l/m/s]=1 (IDa) for Hs[m]=7.18 (>6.75m) and q[l]=10 (ULS) for Hs[m]=9.1 (>8.25).

The Western Breakwater was finally protected with a single-layer 25-tonne Cubipod® armor in the straight trunk, a single-layer 30-tonne Cubipod armor in the curved trunk and a double-layer 45-tonne Cubipod® armor in the roundhead. Five hundred 25-tonne and nine hundred 15-tonne Cubipod® units were recovered from the South and North breakwaters protecting the water intake of the power station, as the Western Breakwater provided sheltering for this area. Re-used 25-tonne Cubipods were placed in the armor slope and re-used 15-tonne units were placed in the armor berm crest where wave action is not as intense (See Fig. 5).

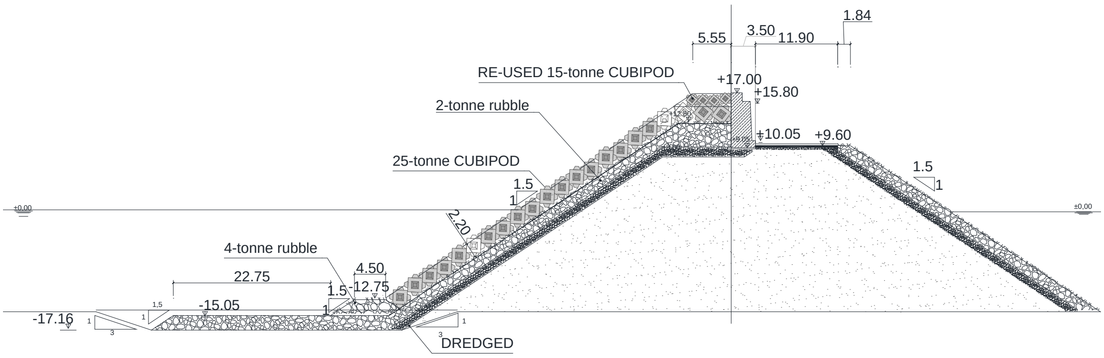

Figure 5. Single-layer 25-tonne Cubipod® trunk cross section.

WESTERN BREAKWATER CONSTRUCTION

Cubipod® armored breakwater with re-used units.

Two parallel groins, South and North Breakwaters, were completed in 2013 to protect the water intake of the Sabón thermal power station (see Corredor et al., 2014). The South Breakwater (0.45 km-long) became the first phase of the 1.35 km-long Western Breakwater. The second phase of the Western Breakwater required 6,670 new 25-tonne, 30-tonne and 45-tonne Cubipod® units, and also 1,360 re-used 15-tonne and 25-tonne units, taken from the two groins, which became sheltered by the Western Breakwater. Regarding the LWL, water depth ranged 0<h[m]<8.3 in the first phase and 8.3<h[m]<22 in the second phase.

In total, five hundred 25-tonne Cubipods and eight hundred and sixty 15-tonne Cubipods were re-used in the Western Breakwater. The 25-tonne Cubipods were recovered from the roundhead and lee side of the South Breakwater and were used in the first alignment of the Western Breakwater. The 15-tonne Cubipods were recovered from the North and lee side of the South Breakwaters, and placed at the crest berm of the new breakwater, once the crown wall was completed (summer 2016), where the wave forces are lower than in the slope.

Cubipod® manufacturing and stacking.

In the block yard, 6,760 new 25-tonne, 30-tonne and 45-tonne Cubipods were produced. Six 19 m^3, five 12.8 m^3 and fourteen 10.6 m^3 articulated vertical formworks were used to manufacture twenty one 45-tonne, seventeen 30-tonne and forty nine 25-tonne Cubipod® units per day (1,100 m^3/day), using 3.5 bases per vertical formwork and 24 hours/day work cycles. Six hours after vibration, vertical formworks were lifted and placed on a new base; 24 hours after vibration, Cubipod® units were moved to the stacking area and the base was prepared for a new formwork. Fig. 6 shows the production line with 45-tonne Cubipod® formworks, lifting a vertical formwork (6 hours after vibration of the concrete) and Cubipods waiting for 24 hours in the bases before being transferred to the stack.

The manufacturing of 25-tonne Cubipods began in April 2015; one month later, the armor of the roundhead of the South Breakwater was dismantled, the Cubipod® units recovered and the core, filter and armor layer advanced at an approximate ratio of 400 meters/month.

Figure 6. 45-tonne Cubipod® formworks in the production line.

In order to minimize the stacking area, up to five levels of stacking were used. Concrete mixer trucks moved along the central elevated platform to pour the concrete into the molds aligned beside the elevated track. Up to three and half bases for each vertical mold were installed on both sides of the track. Fig. 7 shows an aerial view of the extensive block yard and production line, with different size stacking. Double pressure clamps were used to handle and stake Cubipod® units in the block yard.

Figure 7. Aerial view of the Cubipod® block yard (July 7th, 2015)

Finally, once the specified characteristic compression strength (28 days) is reached, the last handling operation in the block yard is to move the cured units onto flat bed platform trucks to be transported to the placement site. Fig. 8 shows wheeled cranes loading a Cubipod unit onto a flat bed platform in the block yard.

Figure 8. Loading Cubipods onto flat bed platform truck to be transported to the placement site.

Cubipod® transition from single-layer to double-layer armor.

A transition from single-layer to double-layer Cubipod® armor is needed. The thickness of the under-layer is increased to compensate for the change in armor thickness and to maintain the continuity and homogeneity of the external profile of the armor. Because the under-layer is placed in advance and armor units must be placed on the under-layer, the armor advances approximately in a 45º wedge shape. To place the 2-tonne rocks on the larger Cubipod® units, the single-layer Cubipod® armor (with thicker under-layer) must advance with a 45º wedge shape, and the double-layer Cubipod® armor must advance in the opposite direction with a 45º wedge shape. When the thicker under-layer touches the interior bottom row of double-layer Cubipod® units, under-layer rocks are placed on the first layer of Cubipods, and the single-layer Cubipod® armor is placed on the transition to obtain a homogeneous external armor profile. Fig. 9 shows the transition from single-layer to double-layer 25-tonne Cubipod® armor in the Western Breakwater.

Figure 9. Transition from single-layer to double-layer 25-tonne Cubipod® armor.

Cubipod placement in the armor.

Single-pressure clamps designed specifically for each unit size were used to place Cubipod® units on the armor slope. These clamps are different from the double-pressure clamps used to handle units in the block yard, and allow better placement performance and recovery of placed units. In a working day, on average, the crawler crane equipped with single-pressure clamps placed 4 to 6 Cubipod® units/hour.

Before placing Cubipods in the armor, an adequate diamond-type placement grid was defined to be used in crawler cranes equipped with differential GPS. Each unit was placed in specific X-Y coordinates following a prescribed order of placement (see Pardo et al., 2014) to obtain a final armor porosity p=41%. The initial armor porosity will depend on the placement grid and the climatic conditions during placement. The random orientation of units is easy to obtain, as Cubipod® units tend to self-arrange on the slope, covering the slope with uniform placing density. Fig. 10 shows the single pressure clamps, placing 25-tonne Cubipods in the Western Breakwater.

Figure 10. Placing 25-tonne Cubipods in the Western Breakwater.

The core of the breakwater, under-layer and most of the submerged section of the armor were constructed in only 3 months, from May to August 2015 (see Fig. 11), the armor without crown wall was completed in October 2015 (see Fig. 12), before the winter season. The crown wall, pavements and crest berm with re-used Cubipods were constructed during the summer of 2016, and work on Western Breakwater was finished during November 2016 (see Fig. 13).

Figure 11. Western Breakwater during construction (September 5th, 2015).

Figure 12. Western Breakwater during construction (October 29th, 2015).

Fig. 13 shows an aerial view of the Western Breakwater when completed.

Figure 13. Western Breakwater (November 16th, 2016).

SUMMARY AND CONCLUSIONS

This paper describes the design and construction of the Cubipod®-armored Western Breakwater at Punta Langosteira. This breakwater completes the 1.35 km-long secondary breakwater of the Outer Port of A Coruña (Spain), which is necessary to shelter the new harbor. The Western Breakwater was constructed in two phases; the first phase was the 0.45 km-long South Breakwater, completed in early

2013, and the second phase is the Western Breakwater that was initiated in May 2015 and finished in November 2016.

The original design of the Western Breakwater, following a Level III probabilistic approach as included in Spanish ROM standards Recommendations and validated with 3D physical model tests, involved a conventional H/V=1.5 double-layer randomly-placed 25-tonne cube armor in the straight trunks and 50-tonne cube armor in the curved trunk and roundhead.

During the bidding process, double-layer or single-layer armoring and different armor units were acceptable for the trunk, while only double-layer armoring was allowed for the roundhead. The contractors' joint venture *UTE Dique Oeste*, winner of the bidding process, proposed an alternative armor design with single- and double-layer Cubipod® units validated with 3D tests. Two models (curved trunk and roundhead) were tested at 1/51 scale in the GEAMA-CITEEC wave basin (32.0x34.0x1.2 meters) with unidirectional waves, as well as a methodology and facilities similar to those used to validate the original design. All models showed null or negligible armor damage for wave storms above the design storm prescribed for ULS.

The final design was protected with a H/V=1.5, single-layer 25-tonne Cubipod® armor in the straight trunk, single-layer 30-tonne Cubipod® armor in the curved trunk, and a double-layer 45-tonne Cubipod® armor in the roundhead. 3D small-scale tests proved that this design was able to withstand higher-than-design storm conditions with the maximum water depth at the toe of the roundhead being h[m]=27 (HWL). The new design reduced concrete consumption by 50%.

The second phase of the Western Breakwater required 6,670 new 25-tonne, 30-tonne and 45-tonne Cubipod® units, as well as 1,360 re-used 15-tonne and 25-tonne units, taken from the South and North Breakwaters, which became sheltered by the Western Breakwater. 25-tonne single-layer Cubipod® armor units were placed in the straight trunk, single-layer 30-tonne Cubipods were placed in the curved trunk, and double-layer 45-tonne units were used in the roundhead. The thickness of the 2-tonne rock filter layer was progressively increased for the transition from single- to double-layer.

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REFERENCES

Burcharth, H.F., Maciñeira, E. and Noya, F. 2015. Design, construction and performance of the main breakwater of the new outer port at Punta Langosteira, A Coruña, Spain, in *Design of Coastal Structures and Sea Defenses*, Ed. Y.C. Kim, World Scientific.

Corredor, A., Santos, M., Peña, E., Maciñeira, E., Gómez-Martín, M.E. and Medina, J.R. 2014. Single-layer Cubipod armored breakwaters in Punta Langosteira (Spain). *Proc. of 34th Int. Conf. on Coastal Eng.*, ASCE, 34(2014): structures.12.

Maciñeira, E., Peña, E., Bajo, V., Sande, J. and Noya, F. 2015. Probabilistic design of the secondary breakwater in the new harbour basin of the outer port of A Coruña. *Proc. Coastal Structures and Solutions to Coastal Disasters Joint Conference*, ASCE 2015, 9-11 Sep. 2015, Boston-Mass. (in press).

Medina, J.R. and Gómez-Martín, M.E. 2012. K_D and safety factors of concrete armor units. *Proc. of 33rd Int. Conf. on Coastal Eng.*, ASCE, 33(2012), structures.29.

Medina, J.R. and Gómez-Martín, M.E. 2016. *Cubipod® Manual 2016*. Valencia: Universitat Politècncia de València. http://hdl.handle.net/10251/72391.

Pardo, V., Herrera, M.P., Molines, J. and Medina, J.R. 2014. "Placement tests, porosity and randomness of cube and Cubipod armor layer". *J. Waterway, Port, Coastal, Ocean Eng.*, 140(5), 04014017.

Santos, M., Corredor, A., Maciñeira, E., Bajo, V., Gómez-Martín, M.E. and Medina, J.R. 2016. Innovative aspects in design and construction of the western breakwater for the outer port of A Coruña at Punta Langosteira (Spain). *RIBAGUA – Revista Iberoamericana del Agua* 3 (2) 89–100 (in Spanish). http://dx.doi.org/10.1016/j.riba.2016.07.005.