Integrated modelling of CSO discharges in the Miño River at Lugo (Spain)

Jose Anta[1], María Bermúdez[2], Luis Cea[3], Joaquín Suárez[4], Jerónimo Puertas[5]

[1] University of A Coruña, Spain, jose.anta@udc.es
[2] University of A Coruña, Spain, mbermudez@udc.es
[3] University of A Coruña, Spain, lcea@udc.es
[4] University of A Coruña, Spain, jsuarez@udc.es
[5] University of A Coruña, Spain, jpuertas@udc.es

ABSTRACT

In this study an integrated modelling of the Lugo sewer network was developed in order to analyze the CSO impacts over the Miño river. Sewer network modelling was performed with the SWMM software package, while a 2D shallow water code was used for river quality modelling. Emission Standards (CSO spill frequency/volume) and Environmental Quality Standards presented in the Urban Pollution Manual were applied to evaluate the receiving water quality. The main results show that the studied river is not suitable for salmonid fishery in terms of dissolved oxygen concentrations, whereas total ammonia limitations were verified throughout the reach.

KEYWORDS

Combined sewer, integrated modelling, receiving water impact, shallow water model, water quality modelling

1 INTRODUCTION

New approaches for urban drainage planning and designing include in some way the analysis of environmental impacts of Combined and/or Separate Sewer Overflows (CSOs or SSOs) discharges into aquatic receiving media. Ambient Water Quality based impact Assessment (WQA) incorporates integrated modeling of the whole urban drainage system, including the wastewater treatment plants (WWTPs) and receiving water bodies.

The Water Framework Directive (WFD, 2000) delegates the responsibility of decision and implementation of local regulations to preserve the receiving waters to the state members. The reduction of the amount of pollution released from the sewer systems can be reached by decreasing the number of stormwater overflows (EUREAU, 2010). Nevertheless, this indicator of water quality impact must be used with care because of the complex interactions between the CSO tank outflow, the amount of flow conducted to the WWTP and the receiving water behavior (Lau et al., 2002). On the other hand, the evaluation of more appropriate indicators such as pollutant concentration in the receiving waters can lead to complex computations (Freni et al., 2010).

In Europe, most of the current guidelines for CSO design recommend long-term simulation approaches and some of them demand water quality modeling at different detail levels, depending on the receiving water and the catchment properties (see among others reviews of de Toffol, 2007 and Blumensaat et al., 2011). In Spain, no national guidelines for WQA have been adopted. At regional and local levels, some authorities have promoted simplified guidelines based on dilution rates in relation to dry weather flows or specifying an acceptable annual CSO spill frequency (Puertas et al., 2008). Recently, some water authorities have promoted WQA strategies and guidelines for sewer system design including integrated modeling approaches (Hernáez et al., 2011).

In this paper we present an integrated modeling of the sewer system of Lugo (Galicia, Spain), which includes the river Miño receiving waters. The Stormwater Management Model (SWMM) was used in the sewer system, while river impact modeling was undertaken using the Turbillon code a code developed by the Environmental and Water Engineering Research Team (GEAMA). This is a 2D finite volume shallow water code with an advection-dispersion pollutant water quality module. In the study the output of the sewer model was used as the input for a river model. The work is focused on methodological application of these codes to analyze the receiving water impacts by using water quality indicators and also the traditional CSO spill frequency/volume emission standards.

2 METHODS

2.1 Integrated modelling approach

In order to analyse the receiving water impacts to the Miño river at the city of Lugo, an integrated model of sewer system and the river was developed using two sub-models: (i) the sewer system model and (ii) the river quantity and quality model.

The sewer system was modelled using the well-known EPA Storm Water Management Model (SWMM) (US-EPA, 2004). The SWMM model is able to estimate rainfall-runoff transformations and flow routing within the sewer system and CSO tanks. The SWMM software allows quality modelling of the surface build-up and wash-off processes, the chemical fate of particular pollutants by specifying decay coefficients but is not able to model different sediment erosion and transport within the sewer network. Due to these limitations, no water quality modelling was performed with SWMM. In order to supply the discharge CSO pollutographs to the river quality model, data from the Casás subcatchment CSO discharge characterization was used (see details in Section 3).

The river model simulates the nitrogen and oxygen cycles in the receiving water body. On the one hand, the hydrodynamic model solves the 2D unsteady depth-averaged turbulent shallow water equations to compute the water depth and the two horizontal components of the depth-averaged velocity. A detailed description of the shallow water numerical schemes implemented in the solver can be found in Cea et al. (2006).

On the other hand, the water quality module solves the mass transport equation for the constituents included in Figure 1, as follows (see elsewhere, e.g. Fisher et al. 1979):

$$\frac{\partial hC}{\partial t}+\frac{\partial uhC}{\partial x}+\frac{\partial vhC}{\partial y}=\frac{\partial}{\partial x}\left(h\left(\frac{\Gamma}{\rho}+\frac{\nu_t}{S_{c,t}}\right)\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(h\left(\frac{\Gamma}{\rho}+\frac{\nu_t}{S_{c,t}}\right)\frac{\partial C}{\partial y}\right)+S_C \qquad (1)$$

where C is the constituent concentration, *u* and *v* are the depth-averaged horizontal components of the water velocity, ρ is the water density, ν_t is the eddy viscosity computed with the depth-averaged mixing length turbulence model, Γ is the molecular diffusion coefficient, S_{ct} is the turbulent Schmidt number and S_C models the interactions which can occur between the different water-quality constituents considered in the model (Figure 1).

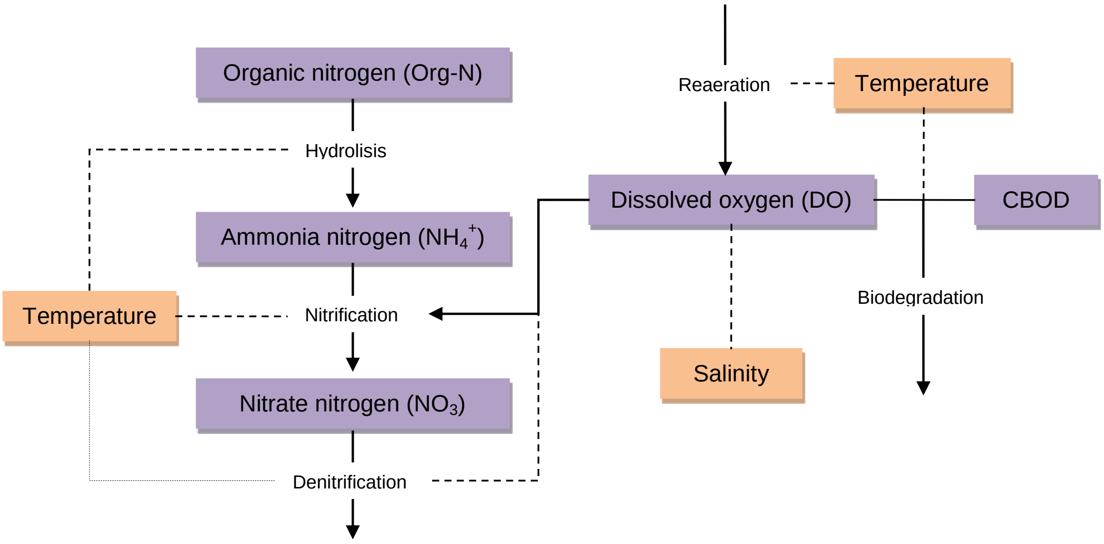

Figure 1. Flow chart of kinetic processes between variables included in the model.

The kinetic expressions used to describe the different reactions can be found in references such as Chapra et al. (1997), while a more detailed description of the water quality module is available in Cea et al. (2009, 2011)

2.2 Water quality standards

The EU Water Frameworks Directive suggests two different approaches to determine the water quality indicators from CSO impacts. The first approach consists in defining the Emission Standards (ES) that are based on achieving some of the following goals: pollutant mass retention (% of pollutant per year), overflow volume retention (% of volume per year), limited overflow frequency (number of spills per year), first flush capture, etc. The ES include neither ecological parameters of the receiving media nor water quality objectives.

On the other hand, the Water Quality Assessment (WQA) methodologies specifically account for the physical, chemical and biological characteristics of the receiving water bodies. These aspects have been defined in the Environmental Quality Standards (EQS). Maybe the most relevant contribution to define a proper EQS approach was given by the Urban Pollution Management (UPM) procedure (FWR, 1998), which defines the concentration-duration-frequency thresholds that should not violated in order to reach the acceptable ecological status of the receiving waters. These thresholds are called the Fundamental Intermittent Standards (FIS), and depend on the ecosystem and pollutant being analysed.

In this work, salmonid fishery FIS EQS standards for dissolved oxygen (DO) and total ammonia (NH_4^+) concentrations have been adopted (Table 3). Regarding the ES, the number of CSO spills and the percentage of captured runoff were selected to evaluate the impact on water quality.

3 INTEGRATED MODELLING OF LUGO SEWER SYSTEM

3.1 Site description

The combined sewer system of the city of Lugo broadly consists of two main catchments draining to the river Miño and to the Chanca-Rato-Fervedoira tributary river. The annual average river flow at Lugo is approximately 60 m^3/s in the Miño river and 0.5 m^3/s in the tributary. The total urban catchment area is about 1280 ha. Following the river reaches Two sewer trunks, which run parallel to the Miño river and its tributaries, convey wastewater flows to the city WWTP (Figure 2).

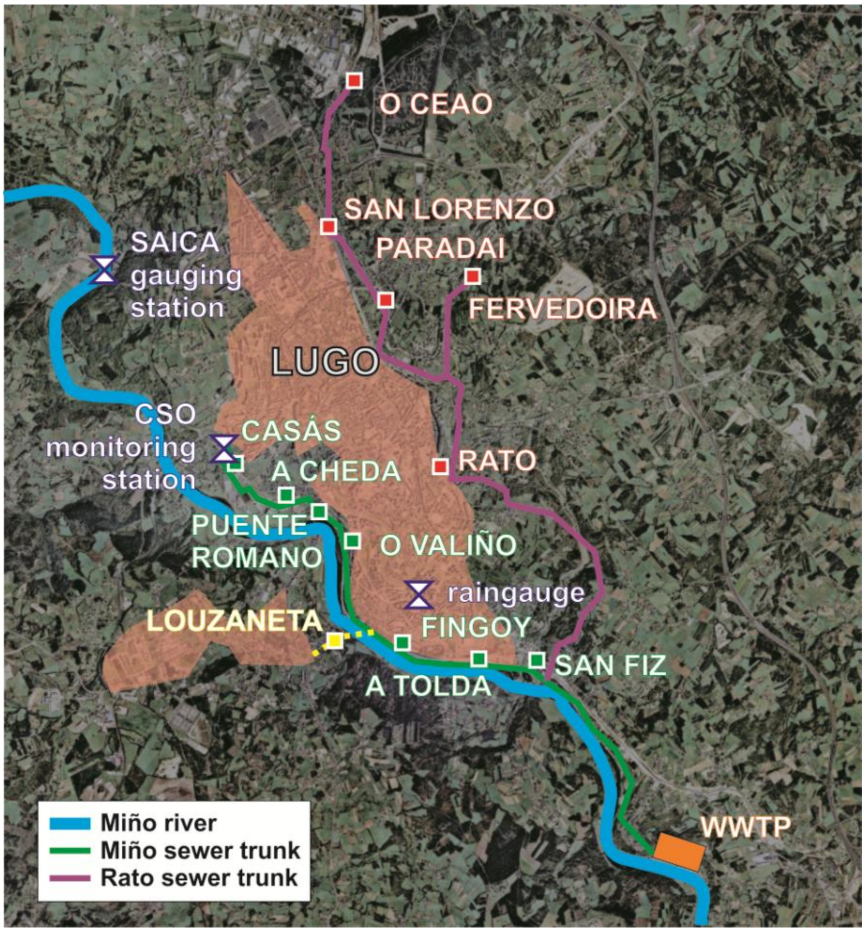

Figure 2. Lugo case study.

The construction of new sewer infrastructures of the city, including the WWTP and CSO tanks, was accomplished by 1997. In order to size the sewer system and CSO tanks, different methodologies were applied according to the best state-of-the-art knowledge at the time of the design. Thus, the Rato-Chanca-Fervedoria structures were sized following the old CHMS guidelines (CHN, 1995). The 12 tanks of this reach have a specific storage volume ranging roughly from 3 to 10 m^3/net-ha (Table 1). The 7 CSO tanks from river Miño reach were designed using computer modelling tools with the objective of reducing the number of spills to the river. An approximate design threshold of 20-30 spills per year had to be achieved with specific volumes ranging from 20 to 50 m^3/net-ha. Lastly, the integrated modelling approach presented in this paper was employed for sizing of the Louzaneta CSO tank. In all the cases, the maximum discharge to the WWTP is 6.7 times the average daily dry weather flow.

In this study, the presented methodology is applied to Lugo city sewer system. The model is comprised of the sewer system, 8 km of the river Miño and the tributary Rato-Chanca-Fervedoria reach, but neglects Lugo WWTP. The simulation period covers the year 2008, which is the pluviometric average year according to the Technical Regulations for Galician Hydraulic Works (Hernáez et al., 2011). During this year the total precipitation was 1008 mm with 220 rain events. Rainfall data were collected close to the downtown with a tipping bucket gauge with a 10 min frequency.

Table 1. Summary of the catchment and main CSO tank parameters of the Lugo sewer system.

Sytem	Catchment	Area (ha)	% Imp.	Averaged Slope (-)	CSO tank (m^3/net ha)
Rato	Montirón	4.5	70%	3.2%	2.9
	O Rato	50.9	93%	5.7%	9.2
	Arq. Lugo-260	3.2	40%	14.4%	7.0
	O Portiño	24.7	64%	10.0%	12.6
	Fervedoira	57.0	70%	2.7%	3.9
	Sagrado corazón	36.5	90%	6.2%	15.3
	Paradai	84.7	80%	4.9%	8.9
	San Lorenzo	102.4	73%	3.4%	4.1
Miño	Casás	146.2	85%	4.4%	31.4
	A Cheda	96.5	82%	5.7%	19.2
	Puente Romano	42.9	40%	6.6%	52.8
	O Valiño	52.6	81%	7.5%	26.4
	Fingoy	18.6	72%	11.2%	18.2
	A Tolda	95.8	74%	4.6%	39.4
	San Fiz	55.4	56%	6.6%	35.5
Louzaneta	Louzaneta	380.5	27%	5.6%	43.3

3.2 Sewer system modelling

The SWMM code (v5.020) was employed to develop the hydraulic model of the Lugo sewer system. The system geometry was taken from the municipal water company's GIS data and was considered unaffected by errors. The model has 153 subcatchments with an average surface of 8 ha. Parameters governing runoff generation were adopted from the shape and average slope of each subcatchment.

The Horton equation was used to calculate infiltration, although the model outputs are not very sensitive to this process as the catchments are mainly impervious (see Table 1). Conduict flow routing was simulated using the dynamic wave model. The storage units were simulated as an in-line chamber with the layout plan of the CSO tanks being built in Lugo. The rating curves of weirs and the outflows valves of the constructed devices were used in the model.

In order to reduce the model output uncertainties, a calibration procedure was performed. An area-velocity SIGMA 950 flowmeter was placed at the Casás CSO tank. The calibration consisted in the adjustment of the impervious area, depression storage and Manning parameters of the tributary subcatchments to the Casás CSO tank. A manual procedure was performed to minimize the event volume errors of a 3 rainy events record (Dec. 2009). During the calibration period volume errors were about 1.5% to 5%. The obtained parameters were then applied to the remaining city subcatchments.

In this facility an automatic sampler and a continuous turbidity probe was also placed in order to characterize the CSO spills pollutographs. During the sampling period, six valid rainy events were characterized (Jan-July 2010). The recorded events were used to validate the hydraulic model of the Casás sewer network. The relative volume error ranges between 8% - 22%.

3.3 River system modelling

The 2D depth averaged velocities and water depth of the river reach under study were computed with an hydrodynamic model based on the 2D shallow water equations. The only input parameters of the model are the bed elevation, which was obtained from a bathymetric survery of the river reach made specifically for this study, and the Manning coefficient, which was fixed to a value of 0.025 based on the characteristics of the river bed. The eddy viscosity is computed with the k-e turbulence model. Unfortunately, no field data was available for model calibration. However, given that the only non-measured parameter of the model is the bed friction coefficient, which can be properly identified from visual observation, the water depht and velocity results are expected to be adequate for the water quality model.

Once the CSO spills events were calculated with the sewer system model, they were introduced as input data in the receiving water quality model (in the locations marked in Figure 3). As mentioned previously, no sewer quality model was performed due to the SWMM limitations. Therefore, 6 CSO spill events were characterized at the Casás CSO tank (Piñeiro et al., 2011) in order to determine the input pollutographs for the river model. The EMC concentration values of BOD, total ammonia and organic nitrogen were fitted to a log-normal distribution. The median values (50% probability) were used as constant values to define the spill concentration.

As the tank size can affect the pollutant removal performance, two different kinds of tanks were defined in this study. In the large tanks of the Miño system, the values obtained for the Casás structure were kept constant in all the storage units: BOD=70 mg/L, NH_4^+=1.5 mg/L, Org-N=5.0 mg/L, DO=4.0 mg/L. In the smaller tanks of the Rato-Chanca-Fervedoira river reach, a conservative approach of no-pollutant reduction was assumed. In these units, the EMC median values are obtained from the log-normal distributions determined by the GEAMA research team in several field campaigns developed in the Galicia Region: BOD=220 mg/L, NH_4^+=8.0 mg/L, Org-N=18 mg/L, DO=4.0 mg/L (see Piñeiro et al. 2011).

On the other hand, the base-flow discharge and pollution concentration values in the river Miño have to be introduced in the model. The daily flow records of 2008 and monthly averaged values of BOD, DO, organic nitrogen, total ammonia and water temperature were obtained from the national SAICA environmental quality net. Accordingly, a daily flow variation and a monthly variation of the rest of the parameters was imposed at the upstream boundary of the model (DO varied from 8.1 to 11 mg/L, temperature from 7.6 to 20.8°C and total ammonia from 0.001 to 0.031 mg/l throughout the year). Nevertheless, the parameters with little annual variation were fixed as constant (BOD=3 mg/L, Org-N=0 mg/L).

As noted above, the transport due to advection and turbulent dispersion, as well as the kinetics of the different constituents, were considered in the model. The kinetic constants controlling the DO and nitrogen cycle transformations were evaluated using the following values: k_1=0.35 d^{-1} (BOD decay rate), β_3=0.2 d^{-1} (organic nitrogen hydrolysis rate) and β_1=1.0 d^{-1} (ammonia nitrification rate).

Lastly, compliance with the water quality standards was studied by means of both the time series in control points and the 2D concentration fields. By way of illustration, the dissolved oxygen time series at control point C9 and 2D concentration fields are shown in Figure 3. Since the model is a 2D depth-averaged model, it is able to reproduce the progressive mixing that occurs downstream of the confluence of the two rivers. It assumes a complete vertical homogeneous concentration of the constituents, but calculates its variation in cross section. As can be seen in Figure 3, the mouth of the tributary river creates, to some extent, a spill plume in the Miño river. Its subsequent evolution is governed by advection and dispersion processes.

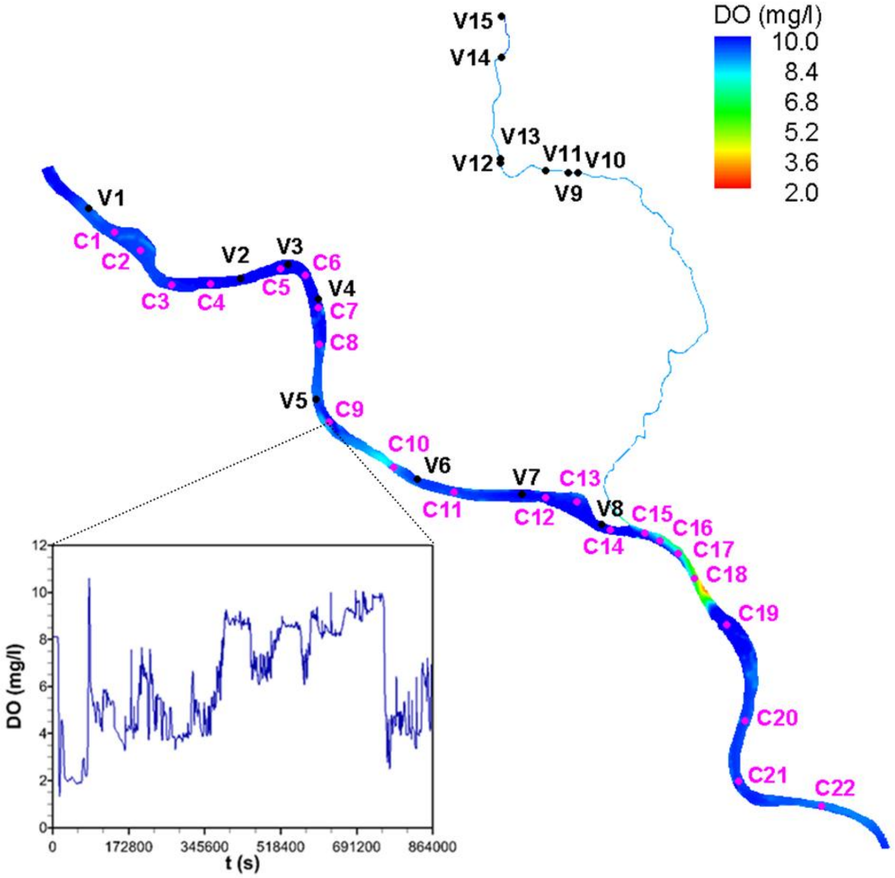

Figure 3. Dissolved oxygen levels in an instant of the simulation and time series in control point C9 for the first 10 days of the simulation. Note: location of spill points (V1-V15) and control points (C1-C22) in the river model.

4 WATER QUALITY IMPACT ASSESSMENT IN THE RIVER MIÑO

Firstly, the hydraulic long-term behaviour of the CSO tanks of the Lugo sewer system was assessed in terms of the CSO spill frequency/volume emission standards during the year 2008. These indicators were obtained using the SWMM statistical module. Figure 4 shows the effect of the tank volume on the number of CSO spills and the volume of intercepted runoff in the tanks.

A large dispersion with a no clear relationship between the storage volume and emission values can be observed. This is especially true for the CSO units of Rato-Chanca-Fervediora trunk, where specific storage volumes of 5-10 m^3/net ha can produce from 10 to 140 spills per year. In the Miño trunk, the annual spill frequency is about 10-30 except for O Valiño and San Fiz, with 61 and 43 spills, respectively.

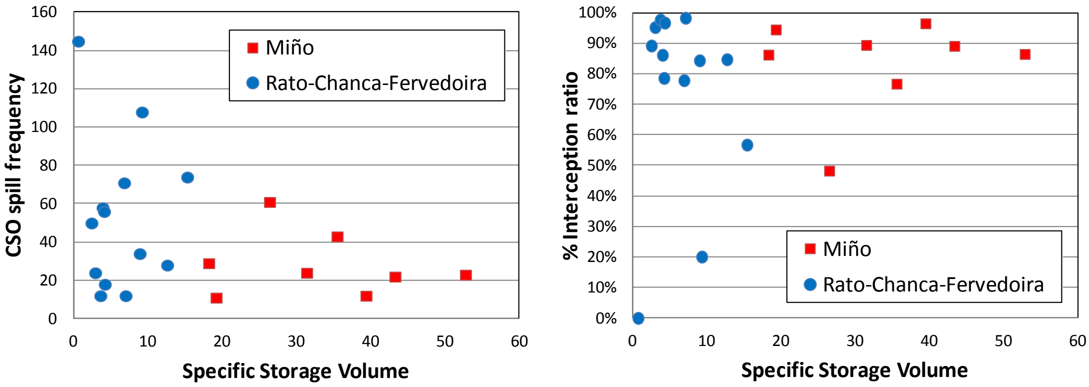

Figure 4. CSO spill frequency and % of intercepted runoff vs CSO tank specific storage volume.

The annual intercepted runoff in the tanks also presents a high scattering. This is due to the fact that the emission discharges depend not only on the specific storage volume, but also on factors such as catchment and tank topology (slope, imperviousness, flow regulator). In addition, a large variability would be expected when analyzing pollution parameters (Gamerith et al. 2011).

Following the UPM methodology, the exceedance frequency of the concentration-duration limits is evaluated at the different control points (Table 3). The dissolved oxygen criteria for salmonids are violated in almost all control points, except for the ones located at the ends of the domain. The more restrictive concentration-duration-frequency thresholds correspond to the 1 hour duration limits. On the contrary, the total ammonia thresholds were verified throughout the spatial domain. The exceedance frequency increases slightly downstream the confluence of the two rivers (control point C15 vs C13 in Table 3), but it is still far below the limits specified by UPM methodology for salmonids. As in the case of dissolved oxygen, the 1 hour duration limits are the most frequently exceeded.

Table 3. UPM salmonid fishery Fundamental Intermittent Standards adopted in the present study and the number of times in which they are exceed at control points 9, 13 and 15. Violations of FIS EQS standards are marked with an asterisk. Total ammonia values are translated from un-ionised ammonia standards assuming safety values of 14ºC and pH 8.

		Dissolved Oxygen			Total Ammonia		
	Return period / Duration	1 h	6 h	24 h	1 h	6 h	24 h
FIS standards (mg/L)	1 month	5.0	5.5	6.0	2.6	1.0	0.7
	3 months	4.5	5.0	5.5	3.9	1.4	1.0
	1 year	4.0	4.5	5.0	4.3	1.6	1.2
Control point C9 (Nº exceedances)	1 month	43*	12	3	2	0	0
	3 months	36*	8*	1	1	0	0
	1 year	24*	5*	1	1	0	0
Control point C13 (Nº exceedances)	1 month	37*	11	3	2	0	0
	3 months	18*	5*	2	1	0	0
	1 year	8*	4*	2*	1	0	0
Control Point C15 (Nº exceedances)	1 month	38*	17*	4	3	0	0
	3 months	19*	10*	2	1	0	0
	1 year	10*	4*	1	1	0	0

5 CONCLUSIONS

This paper describes the methodology to develop an integrated detailed model of the CSO impacts of a sewer system on a river reach. The main goal of the paper is to analyze the reliability of a 2D shallow water quality model in evaluating the receiving waters by means of the FIS Environmental Quality Standards from the UPM procedure (FWR, 1998). Additionally, the traditional emission water quality indicators such as the CSO spill frequency/volume were quantified.

The methodology was applied to the Lugo sewer system and its receiving waters, in which a 1-year long water quality simulation was performed. The results show that the reach is not suitable for salmonids according to the FIS EQS standards for dissolved oxygen concentrations. On the contrary, total ammonia limitations are verified throughout the reach.

The application of an integrated EQS modeling approach permits a better understanding of the CSO impacts exerted on the Miño river reach. This allows implementing catchment specific strategies to reduce the outfall loads (e.g. using advanced treatment units for the CSO spill) or even changing the layout of the CSO units by, for instance, analyzing different locations. In comparison, the evaluation of ES is less time and cost consuming. Nevertheless, site- specific ES standards are not broadly extended in the drainage regulations. In Spain the common spill frequency is 20 spills per year with no consideration of the aquatic media. A rationale approach to CSO tank design may consist in sequential application of ES and EQS standards. ES standards can be useful as the first step in a screening design procedure meanwhile EQS can be used for a detailed analysis of the most sensitive receiving waters.

Further research is needed to complete the developed analysis. In particular, it is important to include in the analysis the behavior of the WWTP in terms of continuous pollutant discharge to the receiving waters, extending the model downstream. Moreover, simultaneous measurements of the CSO spill and river flow quality will provide more insights into the system behavior and would permit a validation of the river quality model.

6 ACKNOWLWEDGEMENTS

This work was performed with the support of Confederación Hidrográfica Miño-Sil and PROYFE. The second author acknowledges support by the Spanish Ministry of Education (FPU grant reference AP2009-2070). Pablo Ures and Daniel Torres performed the field campaign for CSO spill characterization in Casás catchment. Thanks to Jose Piñeiro, Fran Aguirre and Juan Vidal for his fruitful comments and discussions.

7 REFERENCES

Blumensaat, F., Staufer P., Heusch S., Reubner F., Schütze M., Steiffert S., Grauber G., Zawilski M. and Rieckermann J. (2011). Water quality based assesment of urban drainage impacts in Europe – where do we stand today. *12nd International Conference on Urban Drainage*, Porto Alegre.

Cea L., Bermúdez M. and Puertas, J. (2009). Modelo de calidad de aguas bidimensional para flujos poco profundos en lámina libre. Aplicación a la desembocadura del río Ulla. (2D water quality model for shallow free-surface flows. Application to the river Ulla.) *I Jornadas de Ingeniería del Agua*, Madrid.

Cea L., Bermúdez M. and Puertas, J. (2011). Uncertainty and sensitivity analysis of a depth-averaged water quality model for evaluation of Escherichia Coli concentration in shallow estuaries. *Environmental Modelling & Software*, 26(12), 1526-1539

Cea L., French J. and Vázquez-Cendón, M.E. (2006). Numerical modelling of tidal flows in complex estuaries including turbulence: an unstructured finite volume solver and experimental validation. *International Journal for Numerical Methods in Engineering*, 67 (13), 1909-1932.

Chapra S. C. (1997). *Surface Water-Quality Modeling* WCB McGraw-Hill: Boston, MA, USA.

CHN (1995). *Especifiaciones técnicas básicas para proyectos de conducciones generales de saneamiento (Technical guidelines for sewer trunk design)*. Confederación Hidrográfica del Norte, Oviedo.

De Toffol S. (2007). *Sewer system performance assesment – an indicators based methodology.* PhD thesis, Unit of Environmental Engineering, Insbruck University, Austria.

EUREAU (2010). *EUREAU position on Combined Sewer Overflows (CSO).* Position Letter, European Federation of National Associations of Water and Waste Water Services. eureau.org/documents/PositiononCombinedSewerOverflows.pdf (accesed 15 March 2012)

Fisher H.B., List E.J., Koh R.C.Y., Imberger J. and Brooks N.H. (1979). *Mixing in inland and coastal waters* Academic Press: New York, USA.

Freni G., Mannina G. and Viviani G. (2010). Emission standards versus inmission standards for assesing the impact of urban drainage in ephemeral receiving water bodies. *Water Science and Technology*, 61(6), 1617-1629.

FWR (1998). *Urban Pollution Management manual: a planing guide for the management of urban wastewater discharges during wet weather.* Foundation of Water Research, Buckinghamshire.

Gamerith V., Bertrand-Krajewski J.-L., Mourad M. and Rauch W. (2011). Implications of long-term stormwater quality modelling for design of combined sewer infraestructure. *Urban Water Journal*, 8(3), 155-166.

Hernáez D., Blanco J.P., Arias R., Sánchez E.M., Suárez J., Puertas J., Anta J. and Jácome A. (2011). ITOHG: CSO regulations in NW Spain. *12nd International Conference on Urban Drainage*, Porto Alegre.

Lau J., Butler D. and Schütze M. (2002). Is combined sewer overflow spill frequency/volume a good indicator of receiving water quality impact?. *Urban Water*, 4(2), 181-189.

Piñeiro J., Maestro I., Aguirre F., Ures P., Torres D., Anta J., Puerta J. and Suárez J. (2011). Análisis del funcionamiento de un depósito-aliviadero en el sistema de saneamiento unitario en la aglomeración de Lugo (Behavior analysis of a CSO tank in Lugo combined sewer system). *Jornadas de Ingeniería del Agua,* Barcelona.

Puertas J., Suárez J. and Anta j. (2008). *Gestion de las aguas pluviales. Implicaciones en el diseño de los sistemas de saneamiento y drenaje urbano (Stormwater management. Design consideration for sewer and drainage systems).* CEDEX, Madrid.

US-EPA. (2011) Storm Water Management Model. www.epa.gov/nrmrl/wswrd/wq/models/swmm/ (accessed 15 March 2012).

WFD (2000).Directive 2000/60/EC of the European Parliament and of the Council. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32000L0060:EN:NOT (accesed 11 May 2012).