Evaluation of mixing zones in a Latvian–Lithuanian transboundary river basin

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ABSTRACT

The neighbouring countries of Latvia and Lithuania should use common water assessment methodologies and measures for water management in the transboundary rivers according to EU Water Framework Directive, establishing a framework for community action in the field of water policy. However, there are no national and local legislative acts describing how to harmonise water policy and activities for good water status at the cross-border level. This study intends to propose practical measures for management of chemical pollution risk in the cross-border region by mixing zones. The transboundary basin of the Venta River was used as a case study. After initial assessment of water quality status on both sides (Latvian and Lithuanian) in Venta River Basin District, 12 hot spots of pollution were selected for evaluation of mixing zones. Chemical analysis of cadmium, lead, nickel, chromium, copper, zinc, arsenic, phenols, formaldehyde, mercury, benzene as well as total nitrogen and total phosphorus in the water samples from the selected sites was performed. The modelling, using the selected Discharge Test, ensured evaluation of mixing zone dimensions. Such joint investigations might benefit the evaluation of possibilities to integrate mixing zones to the overall transboundary water body for harmonisation of water quality management.

Key words | mixing zones, transboundary river, Venta River Basin District (RBD), water pollution

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INTRODUCTION

Many countries throughout the world share water resources that cross their political boundaries and have to be properly managed together by more than one owner (Barrett 1994; Wolf et al. 1999). Despite the best efforts of the existing legislation, e.g., in the European Union the Water Framework Directive (WFD) (2000/60/EC) and its Daughter Directive as Environmental Quality Standards (EQS) Directive and its update 2013/39/EU Directive, Urban Waste Water Treatment Directive (91/271/EEC), neither of the single EU Member States Latvia or Lithuania is able to deal with pollution threats alone. There is an obvious need to bring together the existing know-how of key environmental protection activities in Europe cross-border regions and beyond.

The Venta River is such a transboundary water body that belongs to the two neighbouring Baltic countries, Latvia and Lithuania. Healthy water (good rivers' water quality in the meaning of the WFD) at cross-border regions is essential for life in both countries. For that purpose, many water policies, e.g., related to European WFD (2000/60/EC), Directive on EQS (Directive 2008/105/EC), aim to protect or improve the quality of water courses. Both neighbouring countries should use common water assessment methodologies and further establishment of measures for water management at cross-borders. However, to date, there are neither national nor local legislative acts describing how to harmonise water policy and measures for good

water chemical status achievement or maintaining good status at cross-border level in compliance with WFD and EQS Directives. Exchange and sharing of all available data would be the first step in the process for protection of their common waters. In this paper, an expressed need is described for a coordinated and integrated approach to the collection, management and assessment of the existing water quality data on priority substances and other pollutants of concern. This new coordination and integration challenge is based on applying adequate modelling and monitoring based approaches. The paper presents some policy frameworks by the result-based integrated permit system analysis for the feasible integration of emissions from waste water discharges in the implementation of the WFD. In the paper, this is done by offering the overall methodological approach on how to assess the significance of discharges of priority and other hazardous substances and establishing a methodology for assessment of significant nutrient quantities or concentrations in effluents from waste water treatment plants (WWTP).

Directive 2008/105/EC of the European Parliament and of the Council on EQS in the field of water policy sets the EQS for 33 priority substances and eight other pollutants (Annex I Part A). Its Article 4 states that Member States may designate mixing zones adjacent to points of discharge. Concentrations of one or more substances listed in Annex I Part A may exceed the relevant EQS within such mixing zones if they do not affect the standard compliance of the rest of the body of surface water. The same article declares that technical guidelines for the identification of mixing zones shall be adopted in accordance with the regulatory procedure referred to in Article 9 (2) of this Directive. Such European guidelines were created in 2010 (Technical Guidelines 2010), and this study was performed following them. As the Guidelines affirm, mixing zones have been widely used since the 1980s. This concept is recognised in European countries as well as in the USA, Canada, Australia, etc. (Jirka *et al.* 2004; Environment et Parcs Quebec 2007; Cooke *et al.* 2010; EPA Victoria 2010). According to EPA's Technical Support Document for Water Quality-based Toxics Control (USEPA 1991), 'a mixing zone is an area where an effluent discharge undergoes initial dilution and is extended to cover the secondary mixing in the ambient water body. A mixing zone is an allocated impact zone

where water quality criteria can be exceeded as long as acutely toxic conditions are prevented.' Water quality criteria must be met at the edge of a mixing zone. Therefore, mixing zone design should meet some defined criteria. Mixing zones are a tool for responsible management of the water environment (EPA Victoria 2010).

The currently available models may help to predict the physical mixing behaviour of any waste water discharge into various receiving water bodies (Bonnomet 2004). Different models and modelling strategies have been reported (Kachiashvili *et al.* 2007; Ani *et al.* 2009; Šajer 2013). In most European countries, water pollution control has been based on discharge permits. Emission limit values were predominantly established according to technological considerations. Approaches based on EQS or objectives were not usually applied (Jirka & Weitbrecht 2005).

What is the situation concerning the implementation of a mixing zone concept in Latvia and Lithuania? In 2000, the 'Manual of surface water quality monitoring' was prepared by the Latvian Environmental Agency (2002). Regarding a selection of sampling points for surface water monitoring, it states that if the aim of the research is a study of waste water or tributary impact on a river, then there is a need to establish two sampling points, one of which is an upstream discharge source or tributary, while the second one is a downstream discharge. The distance between these points should ensure complete mixing between discharged waters and receiving river waters. These manual reports are based solely on the hydrological approach. Concentrations of substances neither in discharge sources nor in receiving or mixing waters were taken into account. Thus far, the mixing zone concept has not been used in Lithuania.

In the EU countries, it is currently proposed to apply mixing zones based on the annual average criteria (AA-EQS) and/or maximum allowable concentration (MAC-EQS) of the dissolved priority substances (Bleninger & Jirka 2011). AA-EQS criteria are related to the chronic effects of hazardous substances on human health and organisms living in aquatic environments, while MAC-EQS criteria are concerned with the acute effects. It may be necessary to implement transitional mixing areas for point source discharges where EQS cannot be met at the vicinity of the outfall. This is defined as a regulatory administrative zone,

in which the concentration of substances may be allowed to exceed the EQS. However, the concentrations of substances should be at or below the EQS at the border of this zone.

Nowadays, mixing zone design is based on the use of different models, and more than one model may be necessary to adequately describe the behaviour of discharges from WWTP. A number of models for mixing zone assessment have been developed in European and non-European countries. CORMIX and PLUME are the most common models used for mixing zone development in the USA. Hydraulic models developed in Europe include DHI Software models (Denmark), Delft Hydraulic Software (The Netherlands) and TELEMAC-2D (Germany) (Ceka 2011).

The main task of this article is the implementation of the mixing zone concept in Latvia and Lithuania using the transboundary basin of the Venta River as a case study. The task was performed using the tool selected from the Technical Guidelines (2010) for the identification of mixing zones (for modelling according to Tier 2, i.e., simple approximation of mixing zones).

METHODS

Under Article 4 of Directive 2008/105/EC, Member States may designate mixing zones in surface waters adjacent to the point of discharge of effluents that contain priority or priority hazardous substances. Under these provisions, Technical Guidelines (2010) have been developed to set out the approach for the identification of such polluted zones. These guidelines offer a tiered approach for the assessment of EQS exceedance zone acceptability. Risk assessment is well-suited for a tiered approach, which is commonly used in risk assessment practice, both in human health risk assessment and in ecological risk assessment (Comber *et al.* 2008; Medema 2012). The tiered approach allows an effective interaction between risk assessment and risk management: it starts from a crude risk assessment, usually based on limited information to determine the urgency of the perceived problem, then prioritises the risk of different water supply sites or scenarios, and finally determines the need of a more detailed study for a particular situation. This approach may be summarised as follows (Figure 1).
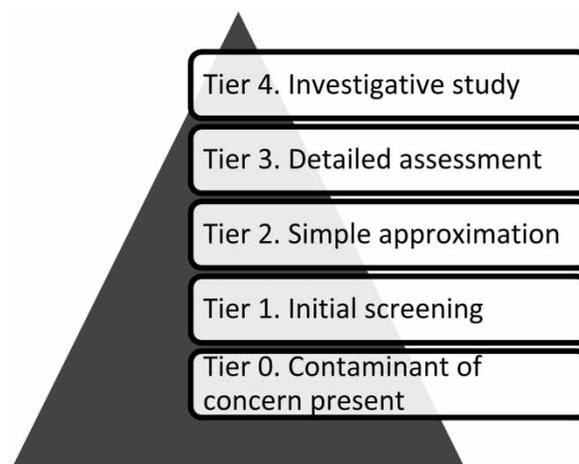
Figure 1 │ The tiered approach scheme (prepared according to Technical Guidelines (2010) for the identification of mixing zones).

The assessment of mixing zone acceptability using the tiered approach can be accomplished by applying different techniques and models. Many models can be complicated for inexperienced users; many input data may be necessary (and not available) for modelling tasks; some of these models or tools are not free of charge (commercial licenses are needed). Usually, such models are used for calculation of mixing zones according to Tier 3 (detailed assessment of mixing zones) or Tier 4 (investigative study), whereas in this study, a simple assessment of the mixing zone size at Tier 2 level was performed using Excel-based Discharge Test software (Figure 2). Originally, the software was developed in the Netherlands in 2000 by Steenkamp and Luttikhuize from Rijkswaterstaat. In 2010, the software was extended and adapted to the starting points of the technical working group on mixing zones by Dju Bijstra (Rijkswaterstaat). As well, Rijkswaterstaat together with Deltares has developed a web-based application, which enables the calculation of mixing zones in tidal waters and (tidal) harbours as well as fresh waters. Both applications are available for Member States.

The Discharge Test is provided as a MS Excel Workbook. It is based upon the widely used Fischer equations and provides a mechanism for simple approximation of the mixing zone dimensions based on the input of discharge data (effluent flow and total concentration of the pollutant in the effluent) and water body data (flow, dimensions, bed-roughness and upstream-concentration of the pollutant in a water body).
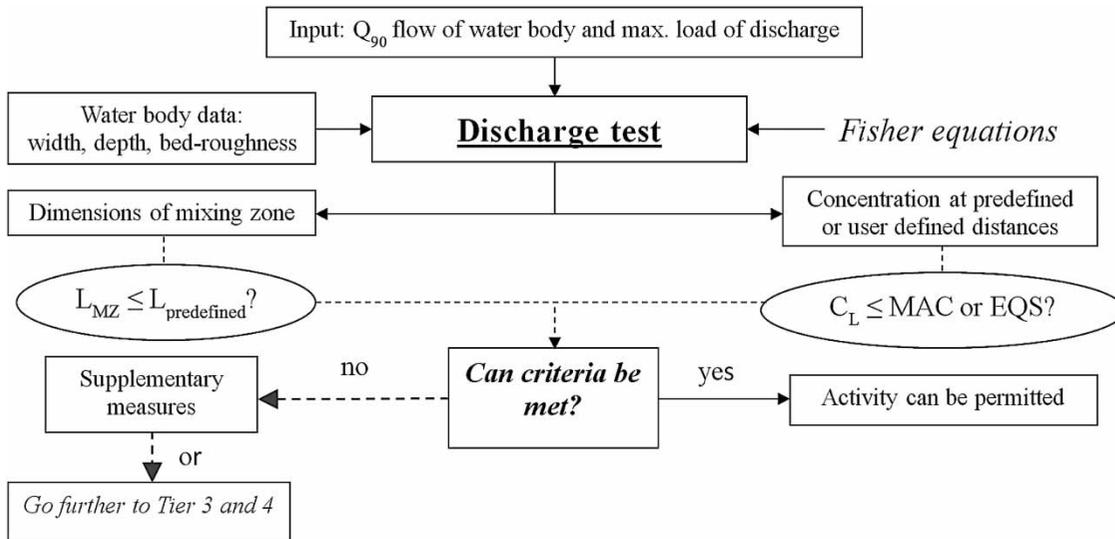
Figure 2 │ An overview scheme of the Discharge Test software (according to CIS-WFD (2010) and Ministry of Infrastructure and the Environment (2011)). Max. load of discharge refers to the maximum flow of discharge and effluent concentration.

A simple approach for dilution as a function of the distance from the point of discharge can be derived from the mentioned Fischer equations, the most important of which is provided below (Equation (1)). An important limiting condition is that the flow of the effluent is negligible to the flow of the water body.

$$\phi(x, y) = \frac{W}{a \cdot u \cdot \sqrt{\pi \cdot K_y \cdot \frac{x}{u}}} \cdot \sum_{n=-\infty}^{n=\infty} \exp\left[-\frac{(y - 2 \cdot n \cdot B)^2}{4 \cdot K_y \cdot \frac{x}{u}}\right]$$

(1)

where: W = emitted load of a substance (g/s); a = depth of the receiving surface water (m); u = river flow velocity (m/s); B = width of the receiving surface water (m); K_y = transversal dispersion coefficient in y direction; x = distance to the point of discharge (maximum L) (m); k = bottom roughness; $\varphi(x, y)$ = concentration at a distance x from the point of discharge and distance y from the bank of the receiving surface water. With:

$$K_y = \max(0.6.u.a.\sqrt{10}/C_{chezy}; 0.001)$$

(2)

$$C_{chezy} = 18.\log((12.B.a)/(B + 2.a)/k)$$

(3)

The model proposes the assessment of mixing zones using a worst-case approach, i.e., 90-percentile low flow (flow which exceeds 90% of the cases during a year), thus the river depth and width have to be recalculated according to the estimated low flow value in each river and used as model input parameters. Using the listed criteria, three options are available: calculation of the real dimensions of the mixing zone bounded by AA-EQS or MAC-EQS; the consequences for a discharge when the predefined default distances of the Discharge Test are L-EQS = min (10 × width of water body; 1,000 m) and L-MAC = min (0.25 × width of water body; 25 m); and freely chosen dimensions of the mixing zones.

In cases of huge pollution (if concentrations of the discharged pollutant are very high, or the entire river-receiver has already been polluted prior to the pollution discharge place), a river length is not sufficient for the pollutant to be diluted and reach AA-EQS; then the test indicates that the zone necessary for mixing is 'unlimited'.

Two approaches in the Discharge Test can be identified: existing discharges (used in normal situations) and reduced mixing zones (an optional approach, which can be used in situations where the approach for existing discharges applied for all significant discharges present at a water body results in exceedance of EQS at water body level or river basin level).

The Biotic Ligand Model was used to calculate bio-available nickel concentrations. This model states that bioavailable nickel concentration depends on the concentration of measured dissolved nickel as well as the concentrations of pH, dissolved organic carbon and calcium. Different EQS are applied for different Ni states: dissolved nickel EQS (20 µg/L) comes from Directive 2008/105/EC (Directive on EQS), while a new EQS for bioavailable nickel (4 µg/L) comes from Directive 2013/39/EU (Directive 2013/39/EU of the European Parliament and of the Council of 12 August 2013 amending Directives 2000/60/EC and 2008/105/EC as regards priority substances in the field of water policy), i.e., more time is necessary to dilute to concentration less than EQS.

STUDY OBJECT AND DATA

The Venta River Basin District (RBD) comprises the Lithuanian parts of the Venta, Bartuva and Šventoji river basins and Latvian parts of the Venta River, catchments of the Baltic Sea and the Gulf of Riga (Barta, Sventaja, Irbe, Saka, Uzava, Riva), and other small river basins (Figure 3). The Lithuanian part of the district covers an area of 6,280 km² (9.6% of the total country area), while the Latvian part covers 15,625 km², which makes up 24.2% of Latvia's territory (Venta River Basin District Management Plan (LV) 2010a, 2010b). The drainage basin of the Venta River stretches from Lake Medainis in Lithuania to the Baltic Sea near Ventspils city; therefore, the lower section of the Venta and part of its basin is located in the territory of

Figure 3 │ Geographical position of the studied areas: 1 – LV side and 2 – LT side of Venta RBD (left) and the analysed hot spots (waste water treatment plants) (right).

Latvia. The total length of the Venta River is 346 km: a stretch of 159.1 km of the Venta flows from springs in Lithuania, another 1.7 km coincides with the Lithuanian–Latvian border, while a 178 km long stretch flows into the Baltic Sea in Latvian territory (Gailiusis *et al.* 2001).

The rivers in the studied area mostly belong to marine type rivers (according to their hydrological regime). The main source of feeding for this type of river is precipitation. Runoff distribution (hydrographs) in different gauging stations of the Venta RBD is presented in Figure 4. This shows that the highest discharge values, i.e., spring floods, in these rivers are observed in March and April due to the snowmelt and heavy spring rains, then summer low flow season follows, and after that discharges become higher again because of larger precipitation amounts and lower air temperatures.

Description of hot spot selection

The largest polluters (hot spots) in the Venta RBD Latvian and Lithuanian territories were chosen based on a similar methodology.

WWTP of the largest agglomerations or the largest enterprises that release pollutants into the rivers were screened. Data from the operators' environmental monitoring databases about all waste water discharges in the Venta RBD were summarised. The operators that may discharge priority substances and their compounds (according to their integrated permits) were selected. State monitoring results of surface water quality were analysed. A number of operators who (according to their integrated permits) may discharge and monitor N_{tot} and P_{tot} (the limiting parameters of physico-chemical quality) were chosen as well. Using the operators' statistical reports, concentrations of these substances from emission data (tons/year) and waste water amount (thousands m^3/year) were calculated; the calculated concentration was compared with the reported one. Final concentrations in discharged effluents were compared with the annual average EQS (or limiting values between good and moderate physico-chemical quality class). Potential sites of hot spots were those with the documented exceedances. The geographical location of the polluter (distance to the LV–LT border), the amount of available hydrological information about the rivers, into which the waste water was released, size of the river-receiver (the river runoff; river basin sub-catchment area $A > 50$ km^2), and representation of different river sub-catchment basins in the Venta RBD were all considered.

After this primary assessment, expeditions (field surveys) were organised to visit the largest polluters ('hot spots') in the area. During the onsite survey, 14 hot spots from the primary list were eliminated from further analysis because of a complicated scheme of waste water discharge or other reasons that prevented using the polluter data for mixing zone modelling using the Discharge Test. At the end of the primary assessment, 12 hot spots in the shared river basin district were selected and investigated.
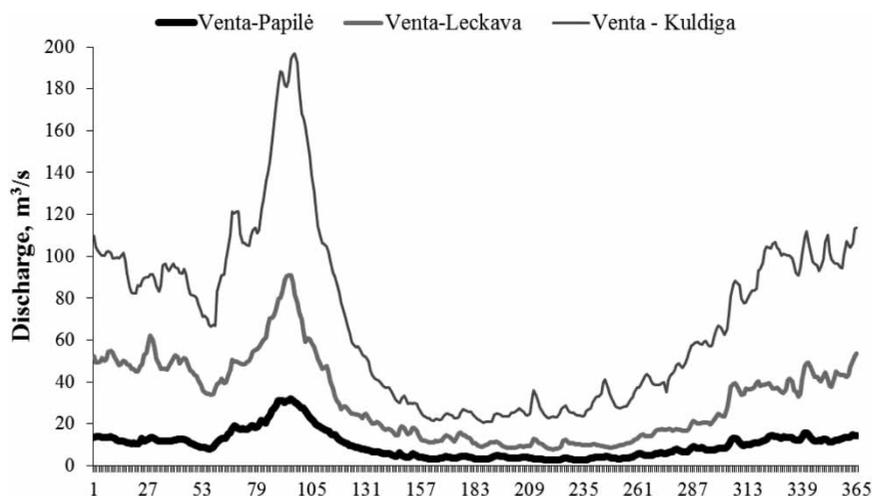

Figure 4 │ Runoff distribution (hydrographs) in different gauging stations of the Venta RBD.

Hot spot data

In each of the 12 hot spots, information necessary for mixing zone analysis and the Discharge Test calibration was gathered during two field surveys carried out in the summer of 2014 (June and August). Water samples for pollution analysis were taken from the waste water discharge pipes and rivers upstream and downstream (at the predefined default distance of 10 widths of water body) of the waste water discharge pipes. Discharge of the waste water was determined using the capacity/volume method. The essence of the method is very simple: to evaluate the discharge, it is necessary to know container volume and the time required to fill it. Capacity/volume method can be described by the formula $Q = W/t$, where Q is discharge, W is water volume in container and t is time needed for water to get into the container.

The water body (river) data such as river cross-section data (velocities at different verticals, riverbed width) were measured in order to use them for the average stream velocity and depth calculation. The area-velocity method was used for calculating the discharge of the rivers-receivers. The main parameters for this calculation are the cross-sectional area (A, m^2) and the water flow velocity (u, m/s). The product of these two measurements gives discharge in volume per unit time: $Q = u \cdot A$ (in m^3/s).

Laboratory chemical analysis of cadmium (Cd), lead (Pb), nickel (Ni), chromium (Cr), copper (Cu), zinc (Zn), arsenic (As), as well as total nitrogen (N_{tot}) and total phosphorus (P_{tot}) in the water samples was performed.

RESULTS

The Discharge Test calibration

For model calibration, it is necessary to select the proper roughness coefficient value. It was performed using the proposed scheme of river channels and their description by selecting the most appropriate river channel and bottom conditions. The determined most correct Manning roughness constant for selected rivers was 0.048. This value was used to calculate polluting substances in the rivers, specifically concentrations of these substances at the end of the mixing zones.

The information gathered during the expeditions to the Venta RBD was used for calibration. The calculated concentrations of the selected pollutants (including priority substances) at the end of the predefined distance downstream from the discharge (default mixing zone of 10 river widths according to the Discharge Test) in the rivers were compared to the results of the chemical analysis from the laboratory. The correlation coefficients between these two data series were very high (above 0.9), indicating that this Discharge Test model can be successfully applied for the mixing zone modelling in the selected rivers of the Venta RBD. For example, Figure 5 presents the comparison of the measured and calculated values of chrome concentrations (μg/L) at the end of the predefined mixing zones.

Calculation of mixing zones in the Venta RBD

According to the tiered approach, at the first step (i.e., Tier 1), all discharges where a contaminant of concern is present in a concentration above the EQS values have to be checked for potential significant impact on the receiving water body. At Tier 2, the dimensions of the mixing zone must be estimated to judge whether a discharge is acceptable. This requires an assessment using simple computation of the size of the mixing zone. The calculations were carried out for the selected polluting substances in four sites (rivers) in Lithuania and eight sites in Latvia. The aim of the modelling was to evaluate whether or not discharges of different magnitude are acceptable and compliant with standards (of Directives 2008/105/EC and 2013/39/EU, Latvian Cabinet Regulation No 118 'Regulations Regarding the Quality of Surface Waters and Groundwater' (12 March 2002), limiting parameter values of ecological quality (in the case of N_{tot} and P_{tot})), and how the length of the mixing zones depends on the effluent discharge and the river (receiving water body) data.

The results of the Discharge Test showed pollution by only some analysed substances, and for them, a certain river zone needed to reach AA-EQS. However, in many cases, pollution was not detected. It should be pointed out that when the modelling is performed in the worst-case conditions, not only is the river discharge significantly smaller, but also the predefined length of the mixing zone is smaller, since the river width during the low flow conditions is smaller as well.
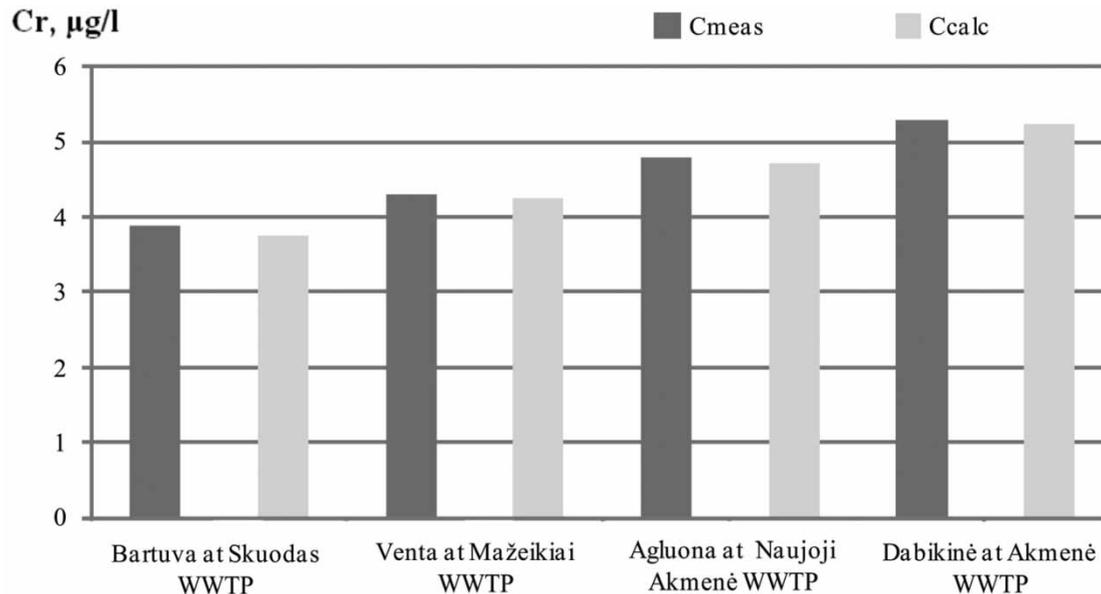
Figure 5 | The measured (Cmeas) and calculated (Ccalc) values of chrome concentrations (μg/L) at the end of the predefined mixing zones in four hot spots on the Lithuanian side.

Modelling revealed that in the selected rivers, the mixing zones formed mainly for nutrients (limiting parameters of physico-chemical quality) (Figure 6); the worse the flow conditions (i.e., smaller river discharge value), the longer the river stretches needed for pollutant concentration to meet AA-EQS values.

The results show that a certain river zone for mixing of the discharged total nitrogen was necessary for eight pollution sites (Figure 6(a)). Modelled mixing zones for N_{tot} ranged from 0.34 m long for 'Ezeres pagasta pārvalde' at the Vadakste to 45 m for Akmenė WWTP at the Dabikinė. In the Dabikinė River (at Akmenė WWTP), the calculated and the default mixing zones were of the same length, indicating that N_{tot} in this river is of concern. Upper limits of the size for modelled mixing zones were exceeded near 'Aizputes komunālais uzņēmums' in the Tebra and N. Akmenė WWTP in the Agluona; their lengths were unlimited according to the test. In low flow conditions in these two rivers, good physico-chemical quality (in respect to N_{tot}) cannot be reached downstream from the discharges because of the magnitude of the discharge point sources. In the Dīcmaņu stream below 'Saldus komunālserviss' as well as above it, concentrations of N_{tot} were higher than the EQS used (the threshold value between good and moderate physico-chemical quality class), i.e., they did not correspond to good physico-chemical quality of water body.

Pollution by total phosphorus in the selected rivers was even higher, while the calculated mixing zones were much longer (Figure 6(b)). The mixing zones for P_{tot} were identified in 10 rivers. Only in four rivers, mixing zones were acceptable, i.e., they did not exceed the default lengths and met the Discharge Test (as well as Tier 2) criteria; therefore, there was no need to analyse them further. In three rivers (the Tebra, Agluona and Dabikinė), unlimited mixing zones for total nitrogen were determined, meaning these polluters significantly affect the water bodies of the investigated rivers. In the Venta downstream from Mažeikiai WWTP, EQS standards for P_{tot} were exceeded in a 777 m long river stretch, whereas pollution was permitted only at 292 m distance downstream. In the Dīcmaņu stream below 'Saldus komunālserviss' and in the Slocene at 'Tukuma ūdens' as well as above them, concentrations of N_{tot} were higher than the used EQS (the threshold value between good and moderate ecological quality class), i.e., they did not correspond to a good physico-chemical quality of water body.

It should be mentioned that this calculation does not take into account the influence of tributaries and the fate of chemicals in waters.

Nickel was the only priority substance with concerning concentrations in a single investigated site (Figure 7).

(a)

(b)
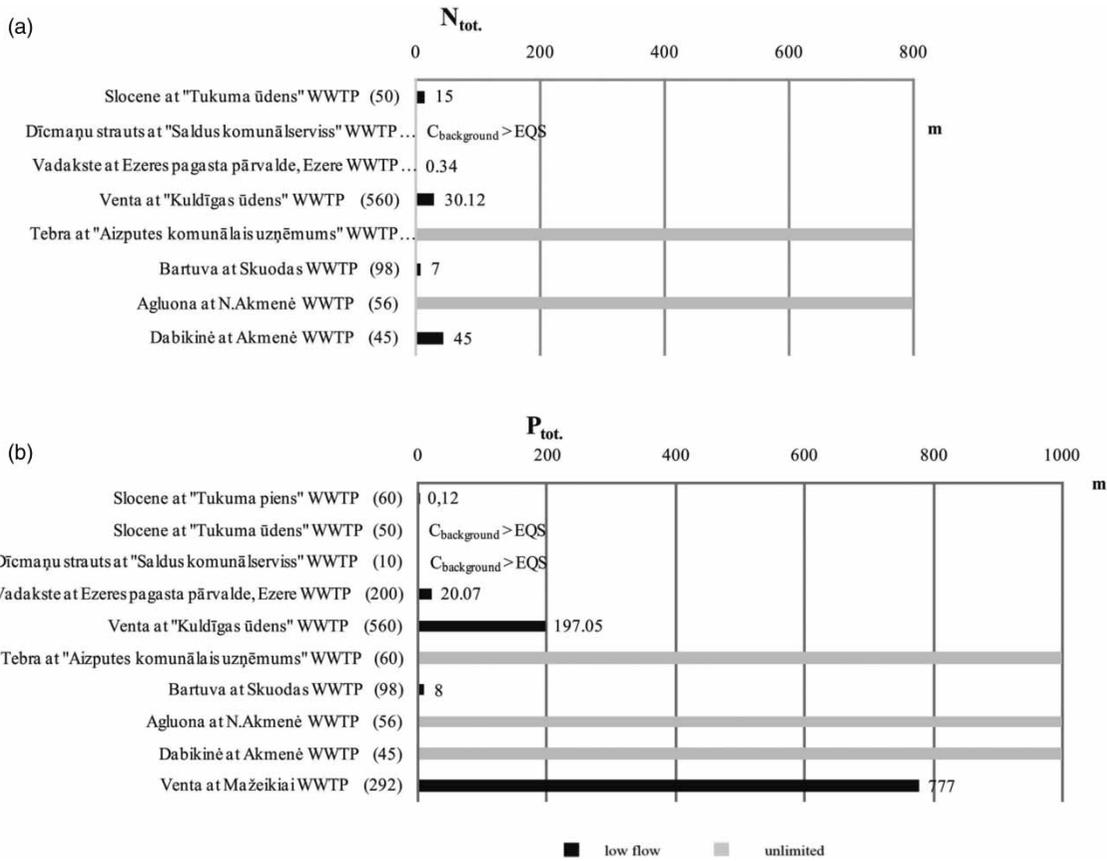
Figure 6 │ Comparison of the lengths of calculated mixing zones for nutrients: (a) total nitrogen (N_{tot}) and (b) total phosphorus (P_{tot}) (in brackets – length of the default mixing zone (value equal to 10 water body widths), another number – length of the calculated real mixing zone bounded by AA-EQS).
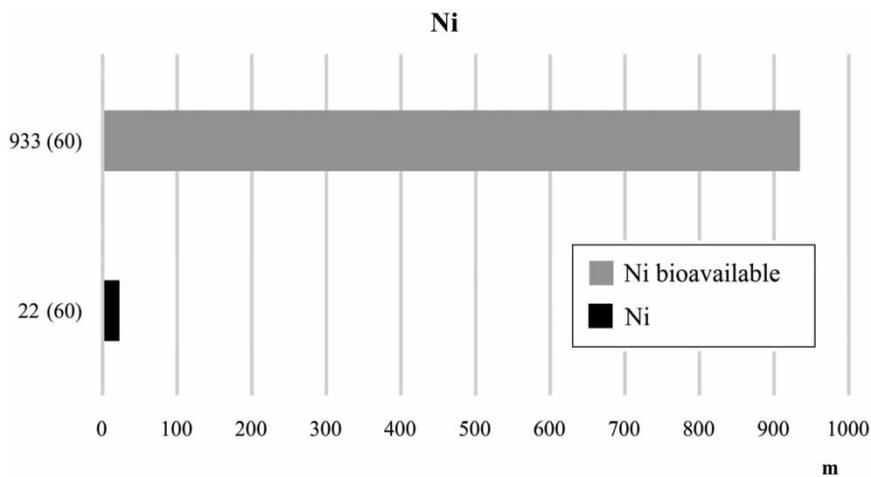
Figure 7 │ The lengths of calculated mixing zones for dissolved and bioavailable nickel at 'Aizputes komunālais uzņēmums' in the Tebra: Ni, applied EQS from the 2008/105/EC; Ni bioavailable, applied EQS from the 2013/39/EU.

Downstream from the 'Aizputes komunālais uzņēmums' in the Tebra, there is a need for a mixing zone (22 m long). For bioavailable nickel, a river length of 933 m is needed to complete the mixing process and to reach the EQS (the default length is only 60 m).

Such comparison of the lengths of the calculated and default mixing zones in low flow conditions was not possible for other analysed polluting substances, since their measured concentrations in effluents were very low (less than EQS) or under the method detection limit.

Further modelling was performed in order to find out the concentration limit of polluting substances in the effluent discharge for a particular river mixing zone in worst-case conditions, i.e., for 90-percentile low flow. This approach would be valuable for competent authorities and operators in order to establish the emission limits in permits for polluting activities if they were going to establish mixing zones as is proposed in Directive 2008/105/EC.

The concentrations were increased as much as the Discharge Test criteria allowed. In cases when the measured concentrations in effluents had already caused an exceedance of the allowable/default mixing zone, the concentration was decreased in order to meet the model criteria (a length of the mixing zone cannot exceed a river width more than 10 times; at the end of the mixing zone, concentrations of the pollutant substances cannot be higher than AA-EQS).

The compared concentrations of analysed priority substances in waste water from Skuodas and Akmenė showed that should there be a need, concentration of such substances could be higher according to the test (Figure 8). It

has to be stressed that in order to meet the stricter EQS values of Directive 2013/39/EU for certain priority substances, the increase in their concentrations should be much smaller than it could be according to the earlier directive.

CONCLUSIONS AND RECOMMENDATIONS

The analysis of databases of the state environmental monitoring of rivers, operators' environmental monitoring and other scientific studies/projects as well as the results of chemical analysis of water samples gathered during the expeditions revealed that there is no pollution by priority/hazardous substances in the rivers of Venta RBD on the Lithuanian side. The problem of river water pollution by nutrients (total nitrogen and total phosphorus) was identified both in the Lithuanian and Latvian Venta RBD.

The Discharge Test was calibrated and applied for calculation of the mixing zones in the rivers of the Venta RBD. The modelling of the mixing zones was performed using a worst-case approach (low flow conditions). Further modelling was performed in order to find out the concentration limit of a polluting substance in the effluent discharge for a particular river mixing zone (in worst-case conditions).

Excel-based Discharge Test is an appropriate tool to calculate mixing zones for a Tier 1–Tier 2 assessment. Advantages of the tool are: simplicity (it can be used not only by scientists, but also by students and stakeholders), open accessibility, and the ability to provide a length of mixing zone for each input substance. The main disadvantage is that the test has not been designed to replace more complex modelling tools which may be employed at Tier 3 level, so it cannot offer, for example, graphical visualisation of the pollutant concentration distribution; however, the intention is that most routine assessments will be resolved without the need to be considered at this level of detail.

It is recommended to adopt the national criteria for mixing zones: conformity assessment of incorporating default criteria ($10 \times$ river width with a maximum of 1,000 m for AA-EQS and $0.25 \times$ width for MAC with a maximum of 25 m) and for limiting values to model mixing zones for nutrients is in line with the aims of the EU Water Framework Directive.
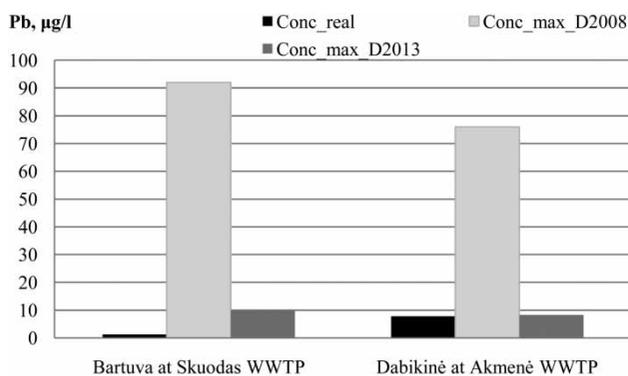
Figure 8 | Real measured (Conc-real), estimated maximum concentrations according to Directive 2008/105/EC (Conc_max_D2008) and Directive 2013/39/EU (Conc_max_D2013) of lead using the mixing zone approach.

The Discharge Test application and mixing zone designation are more important in cases of discharged effluents to the smaller rivers (the Agluona and Dabikinė rivers) and medium rivers with small width and depth (the Tebra and Slocene rivers). In the larger rivers (the Venta and Bartuva), the pollutant mixing process is more rapid and needs a smaller mixing zone (according to EQS criteria) for dilution with receiving river water.

This approach could be useful for competent authorities and operators: it might help to establish the emission limits of substances that could initially be allowed to be released into rivers (in permits for polluting activities), if mixing zones were settled for those substance concentrations.

The mixing zone approach using the Discharge Test could be successfully applied in the Lithuanian and Latvian RBD, where more significant pollution by priority and other hazardous substances was observed in previous state monitoring programmes, operator-performed monitoring, scientific projects, or any other funded projects. Concentration limit values for nutrients between the good/moderate quality classes in rivers may be applied as a decision tool for mixing zone calculation.

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REFERENCES

Ani, E. C., Wallis, S. G., Kraslawski, A. & Agachi, P. S. 2009 Development, calibration and evaluation of two mathematical models for pollutant transport in a small river. *Environ. Modell. Softw.* **24** (10), 1139–1152.

Barrett, S. 1994 *Conflict and Cooperation in Managing International Water Resources*, Policy Research Working Paper 1303. The World Bank, Washington, DC, USA.

Bleninger, T. & Jirka, G. H. 2011 Mixing zone regulation for effluent discharges into EU waters. *Proc. ICE Water Manage.* **164** (8), 387–396.

Bonnomet, V. 2004 *Implementation of Requirements on Priority Substances within the Context of the Water Framework Directive*. Transitional area of exceedance guidance document. International Office for Water & INERIS, Limoges, France.

Ceka, A. 2011 *Water Framework Directive and Mixing Zone Guidelines. Applied on a Smelter and Mine Scenario at two Boliden Sites*. Swedish University of Agricultural Sciences, Department of Aquatic Sciences and Assessment. http://stud.epsilon.slu.se/3639/1/MIXING_ZONE_PROJECT%20AC.pdf (accessed 20 November 2015).

CIS-WID 2010 *Technical Background Document on Identification of Mixing Zones*. http://apps.helpdeskwater.nl/prog/extra/emissieimmissie/documents/Technical_Background_Document_on_the_Identification_of_Mix.pdf (accessed 20 November 2015).

Comber, S. D. W., Merrington, G., Sturdy, L., Delbeke, K. & van Assche, F. 2008 Copper and zinc water quality standards under the EU Water Framework Directive: the use of a tiered approach to estimate levels of failure. *Sci. Total Environ.* **403**, 12–22.

Cooke, J., Milne, P. & Rutherford, K. 2010 A review of definitions of 'mixing zones' and 'reasonable mixing' in receiving waters. Prepared for Auckland Regional Council. Auckland Regional Council Technical Report 2010/045.

Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy, OJ L 327, 22.12.2000, p. 72.

Directive 2008/105/EC of European Parliament and of the Council on environmental quality standards in the field of water policy, amending and subsequently repealing Council Directives 82/176/EEC, 83/513/EEC, 84/156/EEC, 84/491/EEC, 86/280/EEC and amending Directive 2000/60/EC of the European Parliament and of the Council, OJ L 348, 24.12.2008, p. 84.

Directive 2013/39/EU of the European Parliament and of the Council amending Directives 2000/60/EC and 2008/105/EC as regards priority substances in the field of water policy, OJ L 226, 24.8.2013, p. 1.

Environment et Parcs Quebec 2007 *Evaluation and recommendation result from the water quality defined for 300 contaminants* (in French). http://www.mddep.gouv.qc.ca/eau/criteres_eau/index.htm (accessed 27 March 2015).

EPA Victoria 2010 *Guidance for the determination and assessment of mixing zones*, Publication 1344. http://www.epa.vic.gov.au/~/media/Publications/1344.pdft (accessed 20 November 2015).

Gailiusis, B., Jablonskis, J. & Kovalenkoviene, M. 2001 Lietuvos upės. Hidrografija ir nuotėkis [*The Lithuanian Rivers. Hydrography and Runoff*], LEI, Kaunas, Lithuania, p. 792.

Jirka, G. H. & Weitbrecht, V. 2005 Mixing models for water quality management in rivers: continuous and instantaneous pollutant releases. In: *Water Quality Hazards and Dispersion*

of Pollutants (W. Czernuszenko & P. M. Rowinski, eds), Springer, New York, USA, pp. 1–34.

Jirka, G. H., Bleninger, T., Burrows, R. & Larsen, T. 2004 Environmental Quality Standards in the EC-Water Framework Directive: Consequences for Water Pollution Control for Point Sources. European Water Management Online (EWMO). http://www.ewpca.de/journal/on-line.htm (accessed 27 March 2015).

Kachiashvili, K., Gordeziani, D., Lazarov, R. & Melikdzhanian, D. 2007 Modelling and simulation of pollutants transport in rivers. *Appl. Math. Modell.* **31**, 1371–1396.

Latvian Environmental Agency 2002 *Virszemes ūdeņu kvalitātes monitoring rokasgrāmata* [Manual of surface water quality monitoring], Latvijas Vides agentūra, p. 79. http://www.meteo.lv/fs/CKFinderJava/userfiles/files/Noverojumi/Monitorings/VUKMR.zip (accessed 20 November 2015).

Medema, G. 2012 Microbial risk assessment of pathogens in water. In: *Encyclopedia of Sustainability Science and Technology* (R. A. Meyers, ed.), Springer, New York, pp. 6605–6633.

Ministry of Infrastructure and the Environment 2011 *Toetsing van lozingen op effecten voor het oppervlaktewater*. Handboek Immissietoets, p. 101.

Šajer, J. 2013 Some Details of Mathematical Modelling of Effluents in Rivers Downstream of a WWTP, Water Treatment (Dr W. Elshorbagy, ed.), InTech, doi:10.5772/50423. Available from: http://www.intechopen.com/books/water-treatment/some-details-of-mathematical-modelling-of-effluents-in-rivers-downstream-of-a-wwtp.

Technical Guidelines for the identification of mixing zones pursuant to Art. 4 (4) of the Directive 2008/105/EC 2010 p. 60. http://ec.europa.eu/transparency/regcomitology/index.cfm?do=Search.getPDF&4AHhole8A3EtZ9tP6GMVj6Dbby3gYP7DoFPCzj0pZY65SVAw47eF02NzJJLXFBE77kGvLzo2Pu5uyjPyPE0HGhn1Yyu8a5hceFqN5ixnqYI (accessed 27 March 2015).

USEPA 1991 Technical Support Document for Water Quality-Based Toxics Control. http://www.epa.gov/npdes/pubs/owm0264.pdf (accessed 20 November 2015).

Venta River Basin District Management Plan (LT) 2010a http://vanduo.gamta.lt/files/Venta%20river%20management%20plan.pdf (accessed 20 November 2015).

Venta River Basin District Management Plan (LV) 2010b http://www.meteo.lv/lapas/vide/udens/udens-apsaimniekosana-/upju-baseinu-apsaimniekosanas-plani-/upju-baseinu-apsaimniekosanas-plani?id=1107&nid=424 (accessed 20 November 2015).

Wolf, A. T., Natharius, J. A., Danielson, J. J., Ward, B. S. & Pender, J. K. 1999 International river basins of the world. *Int. J. Water Resour. Dev.* **15** (4), 387–427.

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