An Approach to Delineate Groundwater Bodies at Risk: Seawater Intrusion in Liepāja (Latvia)

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ABSTRACT

Groundwater quality in coastal areas is frequently affected by seawater intrusion as a consequence of intensive water consumption. To achieve "good chemical status" of a groundwater body according to Water Framework Directive the effects of saline or other intrusions should not be observed. Groundwater pumping in former decades has caused a significant seawater intrusion into confined aquifer in Liepāja and has led to deterioration of relatively wide coastal area of the third largest city in Latvia. However, the area affected by seawater intrusion is a small part of groundwater body F1 which overall chemical status is good. Thus, no specific management measures have been applied to explore and control seawater intrusion. A political decision was made to delineate the area affected by seawater intrusion as new groundwater body at risk- F5. This study demonstrates simple approach for delineation of groundwater bodies at risk in coastal areas. Delineation process was based on chloride concentration gradient along the well profile and gradient based buffers. Finally, the worst-case scenario was selected for delineation of boundaries.

INTRODUCTION

The key purpose of the Water Framework Directive (WFD) is to protect and improve the quality of all European waters, including groundwater. Another purpose of maintaining good groundwater status is to eliminate any significant damage to ecosystems which directly depend on groundwater body. Member States already had to reach good groundwater status (both chemical and quantitative) by 2015 but no later than 2027 (WFD 2000).

Groundwater body is a reporting unit set to estimate its quantitative and chemical status, and to which environmental objectives under Article 4 of the directive should apply. Groundwater body should be delineated in such a way to ensure proper status assessment and monitoring, effective management and future treatment (Kovács et al. 2012). According to WFD (2000) groundwater body is in bad chemical status if the chemical composition of the body is such that the concentration of pollutants exhibits the effects of saline or other intrusions. Groundwater Directive (GWD 2006) goes on to state that the chemical status assessment shall be carried out for all groundwater bodies at risk of not meeting WFD Article 4 objectives in relation to each of the pollutants which contribute to the groundwater body being so characterized.

Currently the area affected by seawater intrusion in Liepāja is relatively small part of groundwater body F1 (total area of F1 is 2974 km^2) which is in good chemical status. Latvia used proposed procedure for general assessment of the chemical status of the whole groundwater body and applied 20% criterion. It follows that the proportion of the total area or volume of the groundwater body affected by seawater intrusion (in this case) was compared to the total area or volume of the groundwater body. An exceedance of less than

20% of the area does not lead to a poor status of the groundwater body (European Commission 2009).

The boundaries of 22 groundwater bodies in Latvia were mainly delineated by watersheds using modelled groundwater levels as input data. On the one hand, it is impossible to exceed 20% criterion considering the size of F1 groundwater body. One the other hand, it would be inappropriate to set whole groundwater body in bad status considering the size of the area affected by seawater intrusion. Thus, a political decision was made to delineate the area affected by seawater intrusion in Liepāja as a separate groundwater body at risk- F5. This study demonstrates developed simple approach for delineation of groundwater bodies at risk in coastal areas using long term chloride data.

Hydrogeological setting

Seawater intrusion takes place in freshwater aquifer at city Liepāja - Upper Devonian Mūru-Žagares (D_3*mr-žg*) partly confined aquifer which is formed of weakly cemented sandstones, siltstones and dolomites in total thickness of 44 - 47 m and at depth of 38 - 43 m. D_3*mr-žg* is covered by Upper Devonian clayey formations and Quaternary till and sand around Liepaja city. Deposits of D_3*mr-žg* aquifer are exposed at the bottom of the Baltic Sea - approximately 5 km from the coast. Cause is the dipping of Devonian deposits towards S-SE (and outcropping at N-NW) and the lack of Quaternary sediments at some areas at the sea.

Underlying formations consist of dolomitic marls, clays, dolomite and sandstones forming several aquitards and minor aquifers. At the depth of 230 - 241 m lies Upper Devonian Gaujas and Middle Devonian Burtnieku formation (D_2br+D_3gj) - significant hydraulically connected aquifer with total thickness of more than 100 m consisting of sandstones and clays. The D_2br+D_3gj aquifer has no direct connection to uppermost aquifers and the Baltic Sea, however, D_2br+D_3gj aquifer is mainly used for industrial water supply due to elevated mineralization and high sulphate content from gypsum dissolution.

Thus, the most important aquifer for water supply needs in Liepāja surroundings is shallow D_3*mr-žg* freshwater aquifer. It contains good quality drinking water and has been extensively used for decades.

Historical evolution of seawater intrusion

In the beginning of the 20^{th} century and intensive groundwater abstraction from Upper Devonian Mūru-Žagares (D_3*mr-žg*) aquifer took place in Liepāja surroundings. First evidence of water level decrease and quality change (high chloride concentrations) in water supply wells were reported in early 1930's. However, regular groundwater monitoring started only in 1961 and already formed depression cone was identified. A decision was made to switch to centralized water supply and the new well field "Otaņķi" was created in 1961. Still, it abstracted groundwater from the same aquifer - D_3*mr-žg*. As a result, depression cone expanded southeast and in 1976 reached "Otaņķi". In 1986 the center of depression cone was located in "Otaņķi" area and groundwater levels were reported as 14 m below sea level in D_3*mr-žg* aquifer. In ten years the seawater intrusion has moved 1 km southeast and reached the northern part of the lake "Liepāja". A specific measure was established to prevent further movement of saltwater - an abstraction of the affected water for technical needs (Janikins et al. 1993).

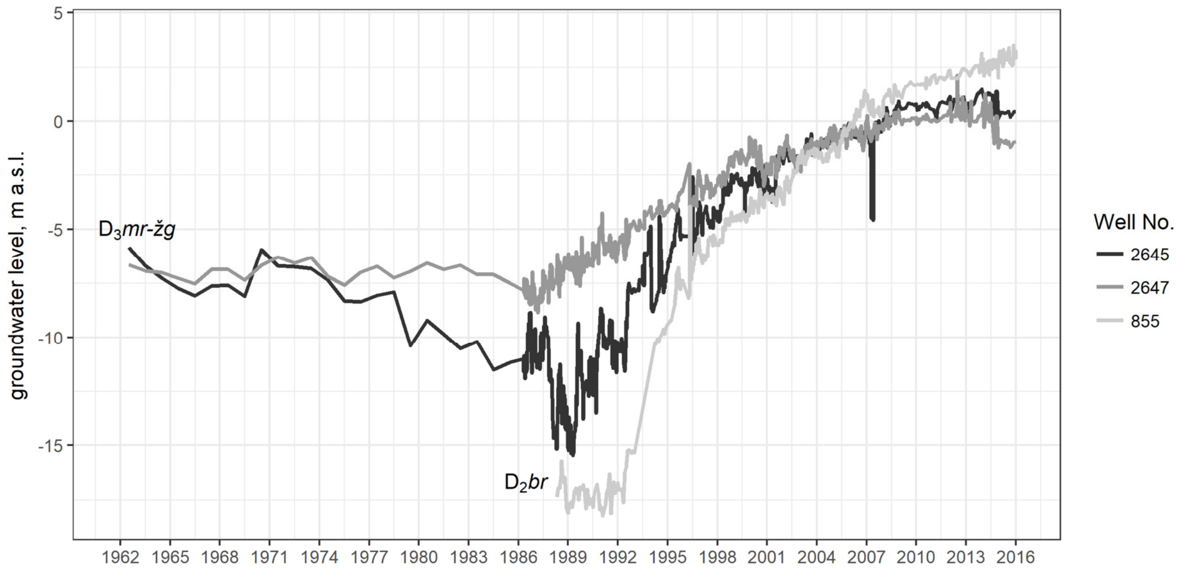

Figure 1. Historical groundwater levels in D_3*mr-žg* and D_2*br* aquifers.

It was decided to exploit Middle Devonian Burtnieku and Upper Devonian Gaujas (D_2*br+*D_3*gj*) aquifer to reduce the pressure on Upper Devonian Mūru-Žagares (D_3*mr-žg*) aquifer. New wells in "Otaņķi" in D_2*br+*D_3*gj* aquifer were installed in 1967. Other aquifers in the area contain high sulphate content and mineralization, and therefore are unsuitable for water supply.

Depression cone started to decline in the beginning of 1990's when consumption rate dramatically decreased because of the collapse of USSR. In about 15 years groundwater level in D_3*mr-žg* aquifer restored and exceeded the Baltic Sea level (Figure 1). Chloride concentrations decreased in marginal zone of the area affected by seawater intrusion, still in central part of the zone chloride values remain high.

METHODS

Information about monitoring and abstraction wells was gathered from the largest Latvian hydrogeological database "Wells" (limited access) (Urbumi 2017). Records about chloride concentrations are dated from 2017 back to 1960's.

Delineation of groundwater body at risk was made based on chloride concentrations from all wells with available data. The profile consisting of four groundwater wells located at the edge of the intrusion was used to determine chloride concentration gradient in D_3*mr-žg* aquifer (Figure 2). Six groundwater sampling campaigns from 2003 to 2017 have been made in these wells thus, permitting calculation of chloride concentration gradient along the profile for several time frames. Linear gradients along the well No.2647 and rest of the wells on the profile was calculated. Natural background level for chloride (13.2 mg/l) was subtracted from saltwater impacted samples to obtain gradient that represents only seawater impact (Bikse et al. 2016).

Chloride ion gradient was used to calculate buffer around each groundwater well based on chloride concentration. If time series from a single well were available, then sample with

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highest chloride concentration was used as it accounts for worst case scenario. As a result, gradient based buffer shows the maximum distance around each groundwater well where seawater intrusion could take an effect. Thus, the boundary of the groundwater body at risk was delineated as a combination of outermost buffers (Figure 3).

RESULTS

Calculation of chloride concentration gradient along the profile (Figure 2) yielded results ranging from 0.65 mg/l/m to 1.01 mg/l/m with median value of 0.83 mg/l/m. To account for worst case scenario, the value of 0.65 mg/l/m was selected for calculation of gradients buffers.

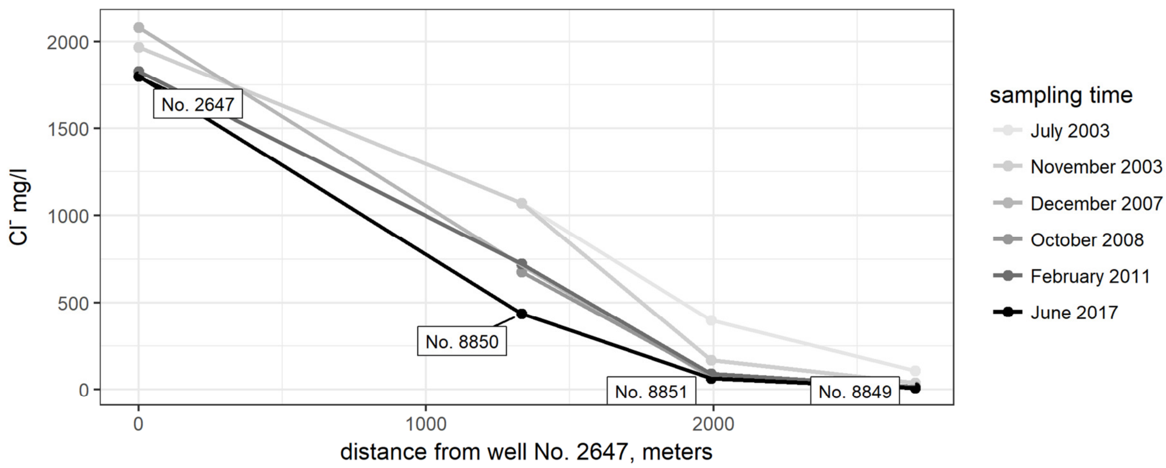

Figure 2. Chloride concentration variations in groundwater well samples along the profile.

Constructed buffers cover large part of the city Liepāja, especially at the central and northern part of the city (Figure 3). The largest buffer has a radius of 3385 m that corresponds to chloride concentration of 2200 mg/l.

The boundary of the groundwater body was delineated along the outermost buffers and along the Baltic Sea shoreline, however, minor corrections were made to smoothen the boundary and to include closest wells from groundwater well field "Otaņķi" which is the main water supply in study area and must be protected from seawater intrusion. Total area of the new groundwater body at risk (F5) is 46.42 km^2 and it includes most of the city Liepāja, western part of lake "Liepāja" and southern part of lake "Tosmare".

DISCUSSION AND CONCLUSIONS

The methodology described in this paper permit simple approach to delineate groundwater bodies at risk in coastal areas, however, two preconditions must be met: (1) large number of groundwater samples from seawater affected area with acceptable spatial coverage must be available and (2) profile of groundwater wells covering central and marginal part of seawater intrusion must be sampled simultaneously for several times to account for temporal variability of chloride concentration gradient. A simplification was made - that seawater intrusion has equal impact on all directions from each groundwater well, therefore an approach that would include seawater intrusion dynamics would yield boundary with different extension and therefore may improve this approach.

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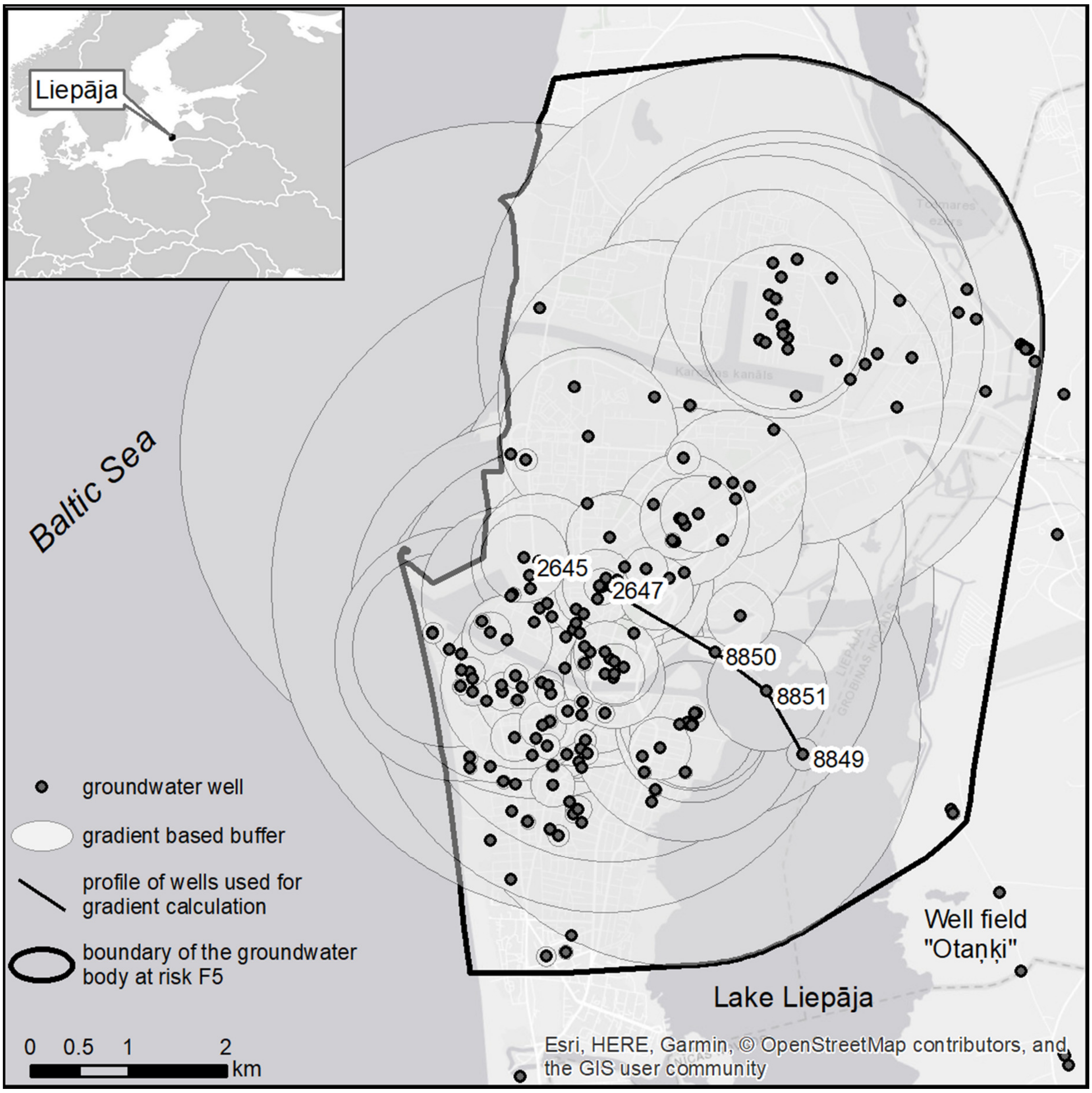

Figure 3. The boundaries of delineated groundwater body at risk - F5.

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