# WATER RESOURCES MANAGEMENT: A CASE OF CONTAMINATION BY CHLORIDES IN BELGIUM

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## ABSTRACT

*In the context of European Water Framework Directive (2000/60/CE), EU member countries are recently putting their efforts in improving the quality of water resources in order to enhance its durable consumption, the environmental protection and to improve water ecosystem state. This case regards a historical chloride contamination which affects drinkable groundwater, in a Belgian hydrogeological context. A hydraulic system consisting of pumping wells was implemented to contain the contaminant source; the water collected by this system is discharged into a river nearby, which constitutes an important water way for commerce and tourism for the entire region. The discharge is submitted to some regulatory conditions by regional Authorities: water ecosystem state should not be altered in the respect of some quality parameters. In order to attain quality parameters, in agreement with regional Authorities, a management plan was developed, involving model implementations and several field experiences. The whole studied area is extended to about 200 km². This study constitutes a complex case of water resource management, regarding groundwater and surface water, two environmental contexts that are closely related. Solutions given could be extended to other different cases of responsible and sustainable water resource management projects.*

Keywords: chlorides contamination; hydrogeological modelling; water resources management; environmental monitoring.

## RESUMEN

*En el contexto del Cuadro Europeo Directivo de las Aguas (2000/60/CE), los miembros de la EU, recientemente han dirigido sus esfuerzos en la mejora de la calidad de los recursos de agua, así aumentar y incrementar su consumo, proteger el medio ambiente y mejorar el ecosistema de las mismas aguas. Este caso reguarda la histórica contaminación de cloruros que afecta el agua potable en un contexto hidrogeológico en Bélgica. Un sistema hidráulico que consiste en pozos de bombeo ha sido utilizado para contener las aguas contaminadas; El agua recogida por este sistema ha sido vaciada en un rio en el alrededor, que constituye una importante vía acuática comercial y turística para toda la región. La descarga esta sometida a unas condiciones reglamentarias por las autoridades regionales: el estado del ecosistema acuático no debería ser alterado en el respeto de algunos parámetros de calidad. Para poder lograr estos parámetros de calidad, de acuerdo con las Autoridades Regionales, un plan de gestión ha sido desarrollado que implica un modelo de implementación y varios campos de experiencia. Toda la área estudiada se extiende alrededor de 200 km$^2$. Este estudio constituye un caso complejo de la gestión del agua, subterránea y superficiales, dos contestos ambiéntales que son estrechamente relacionados. Las soluciones dadas podrían ser utilizadas en otros casos de responsabilidad y sostenibilidad en la gestión de proyectos de los recursos de aguas.*

Palabras clave: contaminación de cloruros; modelización hidrogeológica; gestión de los recursos hídricos; monitoreo del medio ambiente.

# INTRODUCTION

The present document relates to an integrated approach operated in an important Belgian hydrogeological basin within the European Water Framework 2000/60/CE (EUWF). This type of methodological approach could be extended to other projects of responsible and sustainable management of water resources. For reasons of confidentiality, fictitious names are used, precise locations are not given and some quantities are not displayed in graphics.

This study case relates to an historical groundwater contamination by chlorides as a consequence of an intense historical chemical production. This contamination affects some drinking groundwater wells positioned down gradient of the contaminant source. A hydraulic system of pumping wells was implemented to contain the contaminant source; the water collected by the system was discharged into a river nearby, which constitutes an important water-way for commerce and tourism of the entire region.

Groundwater bodies are subjected to a rehabilitation plan following directions defined by EUWF, which defines an action plan for the European Union countries regarding the protection of surface and groundwater, also defining the concept of “Body of groundwater”. Every identified Water Body (surface or groundwater) must reach the environmental objectives assigned.

The groundwater body studied is part of an important river basin district and it consists of a series of aquifers, acquitards and aquicludes disposed according to a complex geometrical structure, which develops from west to east and extends for a length of about 70 km, over an area of 484 $km^2$.

The river is defined as a heavily modified water body, which according to the definition provided by the EUWF, is represented by a body of surface water which is substantially changed in character as a result of physical alterations by human activity.

For each river basin district identified by the member countries, a management plan to achieve the goals by 2027 is provided and for chloride the objective is to achieve concentrations below 150 mg/l by the same date.

## Background of the study and logical organization

A process of sodium carbonate (soda) production was active since the XIX$^{th}$ century: not too far from the production site a quarry was exploited to feed the plant with primary materials used in the production process. Residual production sludge, mainly charged in $CaCl_2$ and secondly in NaCl, was stocked in some settling basins since the twenties and up to half of the nineties; the settling basins, located next to the quarry, were build-up one next to the other, the extension of basins surface increased progressively to allow new sludge to be stocked; when production was stopped, the whole basins surface measured almost 60 hectares.

Due to chloride solute sludge migration from basin to groundwater, allowed by a weakness in basin bottom sealing, a chloride plume was historically detected in groundwater next to the basins and towards drinking water catchments. These catchments, supplying different municipalities in the surroundings with several millions of cubic meter of water per year, are located some kilometres down gradient the basins.

The contamination driving forces are mainly two: the piezometric gradient between basin and water catchments and chloride settling dynamics, due to density difference between salted and fresh water, which allows chloride to migrate towards the bottom of the aquifer.

To avoid chloride plume to extend, contamination containment actions started just after production was stopped. These actions were the realization of a capping in the basins to reduce meteoric infiltration, the realization of a leachate collection system to help to reduce chloride percolation out of the basins, the implementation of a pumping device in the bottom of the quarry to remediate and contain the basins chloride source.

Water pumped from the quarry is rejected, at an average rate of 250 m³/h to the river, 1.5 km far away from the settling basins of the site. The discharge (upstream discharge) was allowed by Authorities with a maximum chloride load.

After the pumping was implemented, the trend of observed concentration in chloride in the two drinking wells showed a progressive rise up. This evidence indicated that the implemented hydraulic containment was not sufficient during low water table regimes.

A first solution aimed to intercept deep chloride plume, pumping by three new deep wells, called PR1, PR2 and PR3, pumped water was rejected to the river. This solution was designed to replace the quarry pumping device. A flow-rate of 220 m³/h was estimated to be sufficient to assure both the containment both the site remediation.

Once PR1, PR2 and PR3 realization was complete, in 2012, chloride concentrations for each well were measured and the total estimated charge (upstream discharge) resulted to slightly exceed authorized charge.

As a consequence, an impact assessment of the upstream discharge on the river was required by regional Authorities to avoid degradation of stream quality state (this is in line with EUWF asking to reach specific chemical and biological quality goals within 2027: the present case study address chemical state evaluation, biological state was also evaluated but it is not object of the present); the assessment takes into account another significant chloride discharge to the river (downstream discharge) which issues from another industry process, located 25 km downstream.

The second solution was selected among different technical solutions as explained below. This solution involves the following actions: capping finalization, hydraulic containment and regulated discharge into the river. While the capping was finalized during 2012, the last two actions are subjected to a study, object of this paper. In particular, exploiting an analytical model, a regulation logic (the regulation plan) of the upstream discharge is defined to achieve the following objectives:

- To reach water quality target fixed by European Union: a reference limit of 150 mg/l of chloride has not to be exceeded in term of average of analytical results sampled during a year basis.
- To ensure containment of chloride plume into the site.
- To optimize site remediation with PR1, PR2, PR3 wells.

## Available relevant Literature

Due to study complexity, scientific researches about the different techniques [1-2-3-7-8-9-10-11-12-13-14-15-16] on reduction of chloride in surface and groundwater were undertaken to restore qualitatively the aquifer.

The following techniques were identified as the most appropriate on the treatment of saltwater: nano-filtration, reverse osmosis and distillation.

It was found that all investigated technologies require high energy consumption and residues recovery is not economically advantageous, that is why another solution has to be identified.

This solution was identified in capping finalization, hydraulic containment and regulated discharge into the river.

## STUDY SITE

Site is oriented approximately W-E north of the Paleozoic fault system called "Faille du Midi" [4-5]. This structure includes geological formations ranging in age from Carboniferous to Middle and Upper Devonian, allocated in stratigraphic unconformity on the Ordovician-Silurian continental basement. The river's valley lies on a large Cenozoic alluvial plain, overlying geological formations of Carboniferous age and is composed mainly of calcareous formations. More locally, the limestone of quarry and old settling basin are located on the southern side of a secondary structure of the Midi Fault, above strongly folded and faulted geological formations (Figure 1).

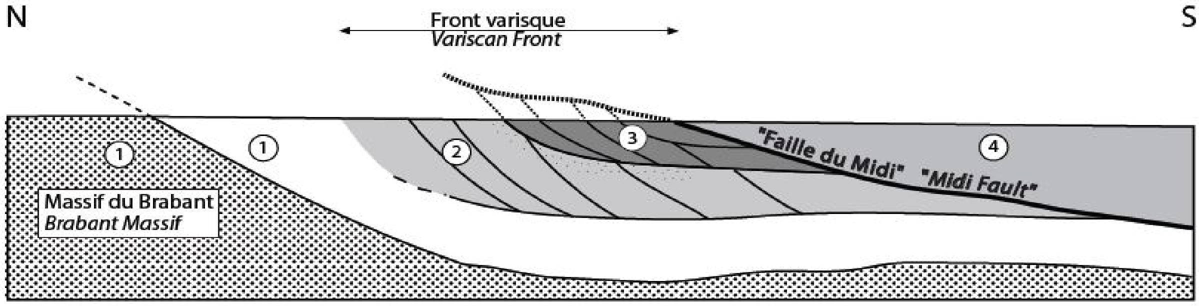


Figure 1: Schematic N-S profile across the Variscan Front. Starting from the autochthonous Brabant Massif several deformed zones are recognized which constitute the basis for the recognition of structural units. (Belanger et Al., 2012).

In hydrogeological terms, the area is characterized by the presence of numerous aquifers at different depths, mainly located in the Carboniferous limestone [6]. The aquifers are double-permeability, porosity and faults permeability, with larger volumes of water trapped in typical karst fissures of limestone formations. Most of the groundwater resources that belong to the groundwater body are caught in aquifers of Carboniferous limestone, fed by rainwater infiltration processes. The piezometric surface gradually decreases from S-W to N-E.

The river is slow scrolling, having an average gradient of 0.05%. The total area of the river basin is about 2800 km $^2$ and is fully ducted for the exploitation of transport activity [6]. In the reach of the river interested by this study, 6 locks are present, from upstream to downstream. they are: A, B, C, D, E and F. The upstream discharge is positioned about 400 m upstream of lock B, the downstream discharge is positioned 4000 m upstream of lock E. 4 tributary to the river exist, from upstream to downstream, they are called Alpha, Beta, Gamma and Delta, their positions are reported in the Figure 2.

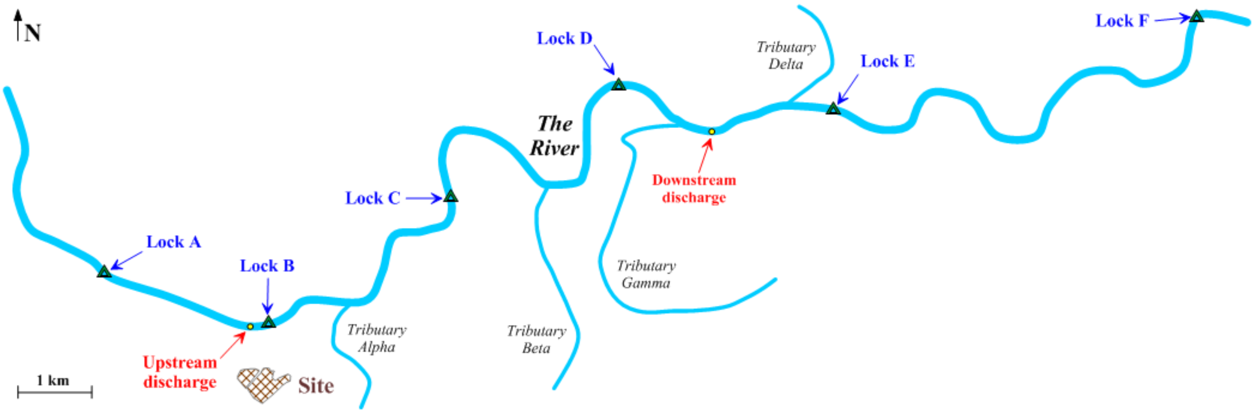


Figure 2: Conceptual site plan: locks, tributaries and points of discharge are indicated. (Aquale, 2013).

## MATERIALS & METHODS

In the studied area a consistent program of activities was executed. The main objectives were: a) to enrich the database used to develop the analytical model and to define the regulation plan; b) to implement the state of knowledge of the site.

The quarry pumping device was replaced by the deep wells during a period, in order to test the new solution and to define a chloride mass balance, on which the analytical model is based.

A pumping test by deep wells was performed in the period 8 November till now (March 2013). The deep wells were started-up the 8 November at the designed flow-rate of 220 $m^3/h$ and they were stopped in the period 10 -14 December; they were started-up again the 14 December and they are still running.

During the test the following activities were executed:

- Monitoring of chemical-physical water quality carried out through programmed water sampling with auto-samplers and dataloggers probes (November 8, 2012 – March 2013).
- Longitudinal profiles of electrical conductivity (December 6, 2012).
- Transversal profiles of electrical conductivity (December 6 and 13, 2012).
- Transversal velocity-profiles for flow rates estimation (December 6 and 13, 2012).

Each activity is explained below.

### Monitoring with auto-samplers and data-loggers

A monitoring of chemical-physical water quality was realized using four auto-samplers positioned at stations A, B, D, and E, in association with data-loggers. The auto-samplers were programmed to collect water samples at regular time intervals (every 24 hours) and they are designed to store up to 24 samples. Samples were periodically sent to analysis to evaluate variations in chloride concentration and conductivity values when pumping was started or stopped. The data-loggers measure conductivity, temperature and depth of water at programmed time intervals (one measure per minute). Concentration and conductivity acquired data are then correlated to build a concentration - conductivity curve. As chloride tent to settle on the bottom of the river for gravitational effect auto-samplers and data-loggers sampling depth was properly adjusted to intercept the plume of chlorides.

### Longitudinal and transversal profiles of electrical conductivity

Longitudinal and transversal profiles of electrical conductivity were acquired to evaluate how chlorides plume dilutes in the immediate downstream of upstream discharge.

Longitudinal profiles of electrical conductivity with data-loggers were performed in the segment of the river between the point of upstream discharge and the lock B (first lock downstream of the upstream discharge). The investigated segment measured about 400 m of length. 6 data-loggers, connected to a steel cable, were plunged from a boat (3 on the right side and 3 on the left side) at different depths (1, 2.5, 3.5 m). The boat was conducted along different lines, arranged parallel to the river flux to survey the entire stream section.

Transversal profiles of electrical conductivity with data-loggers were performed at lock A, B, C, D and F. This technique allowed to analyse the spatial evolution of the chloride plume and its dilution dynamics.

### Transversal velocity-profiles ADCP

Velocity profiles at locks A, B, D and E were measured to estimate river flow-rate. The objective of the investigation was to set-up a hydraulic flow budget. The measurements were performed using Rio Grande ADCP method (Acoustic Doppler Current Profiler). This technique exploit the Doppler effect of sound waves scattered back from particles within the water column, to measure water velocities.

## RESULTS

Results obtained for each single activity are described below.

### Monitoring continuous with auto-samplers and data-loggers

Auto-samplers and data-loggers installed at the locks allowed monitoring respectively chloride concentrations and electrical conductivity trends into the river. Overall, after PR1, PR2 and PR3 started-up, an increase in conductivity and chloride was observed. Analytical results for each lock indicate that a wave of higher concentration transits towards downstream, with a time of transition that is proportional to advective velocity (as shown in Figure 3).

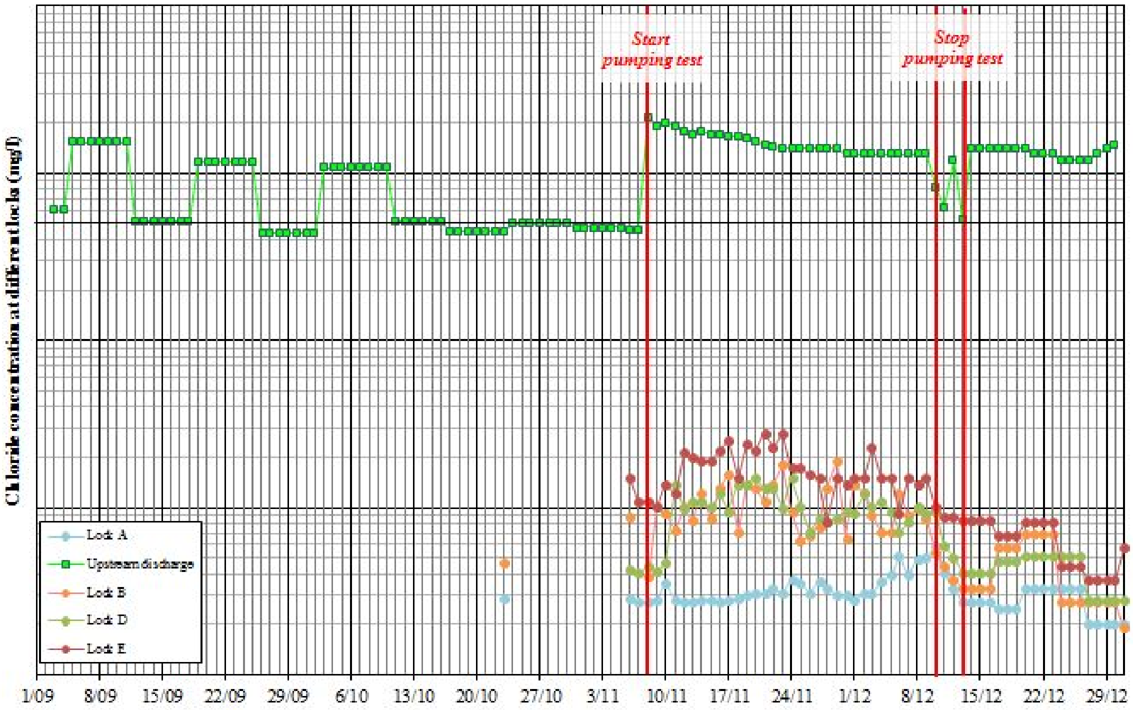


Figure 3: Evolution of chloride concentrations measured during the pumping test (monitoring period: September-December 2012), (Aquale, 2013).

## Longitudinal and transversal profiles of electrical conductivity

Longitudinal profiles provided conductivity distribution at 1, 2.5 and 3.5 meters of depth; acquired values were interpolated to realize three planar conductivity maps and one vertical section (Figure 4). The planar maps show that , within 50 m downstream of the discharge, values of conductivity vary: between 500 and 900 µS/cm at 1 m of depth; between 900 and 1000 µS/cm at 2.5 m of depth; between 900 and 1000 µS/cm at 3.5 m of depth. The vertical section shows that higher conductivity values (beyond 800 µS/cm) occur within 3 m of depth and river bottom and up to 250 m downstream of the discharge.

For all the elaborations, conductivity values decrease progressively moving downstream, in general till to 600 – 800 µS/cm.

According to the correlation chloride concentrations-electrical conductivity obtained by historical data series collected at lock C, a conductivity value of 800 µS/cm as a lower limit was defined: below this limit, chlorides concentrations are always below 150 mg/l[1]. As a consequence, during this experience, the limit of 150 mg/l is exceeded up to 250 m downstream of the discharge point.

Overall, elaborations reveal chlorides tendencies to position on the bottom of the river and to homogenize with the mass of water within 200 m from the point of upstream discharge, stabilizing at values between 600 and 800 µS/cm.

Two campaigns of transversal profiles of electrical conductivity were carried out December 6 and 13. A significant increase of conductivity values in the section between lock D and lock E was

[1] Values between 800 and 1100 µS/cm represent the "safety zone" and values above 1100 µS/cm correspond to a chloride concentrations always greater than 150 mg/l.

observed, due to the presence of the downstream discharge. In each section no significant lateral or vertical variations in conductivity were measured, as measurement points are sufficiently downstream to allow discharge (upstream or downstream) complete mixing.

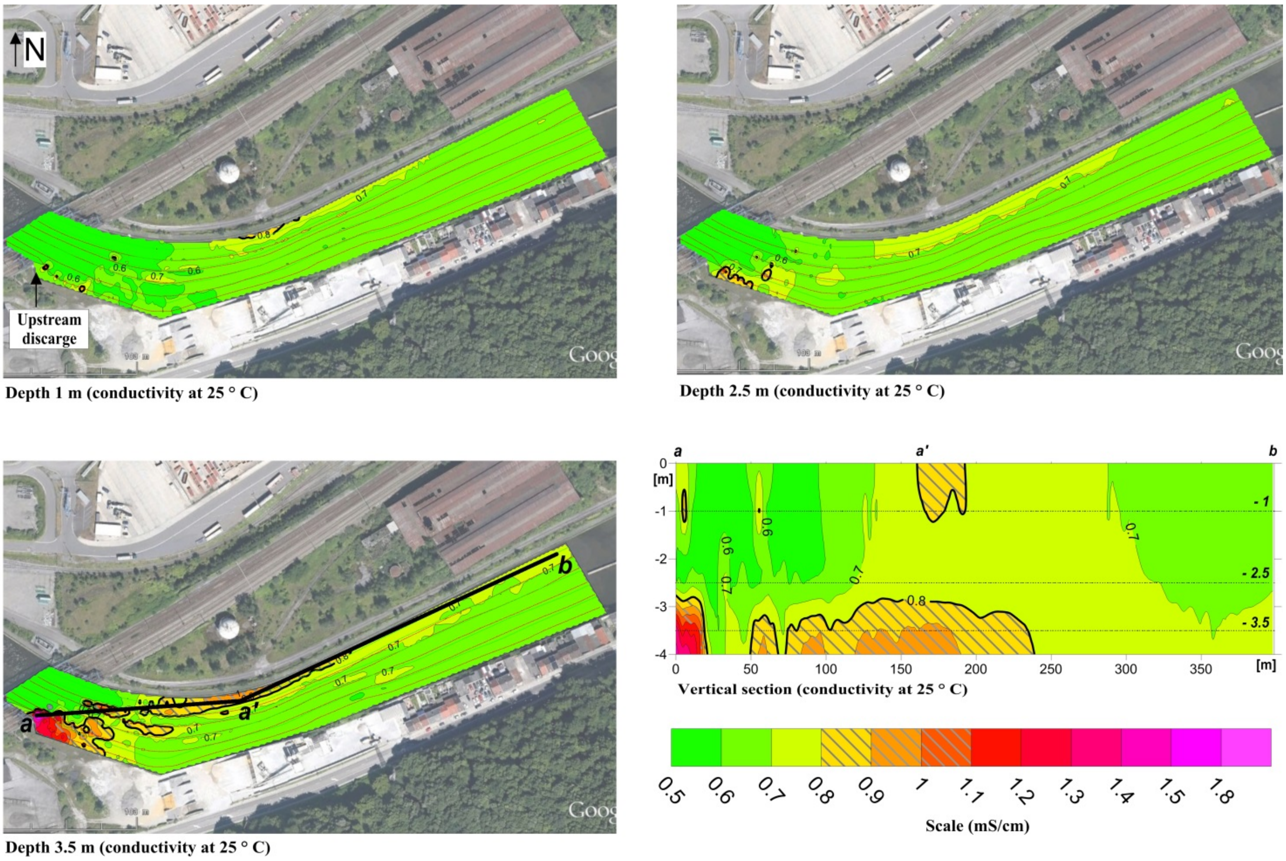


Figure 4: Planar interpolation at depths 1, 2.5 and 3.5 meters and vertical interpolation of electrical conductivity, (Aquale, 2012).

### Transversal velocity-profiles ADCP

As it was done for the transversal profiles of electrical conductivity, two campaigns of transversal velocity profiles were carried out on December 6 and 13 at lock A, B, D and E. Several transversal profiles were made for each lock and an average was calculated. The results were used to assess the conservation of water mass between lock A and lock E, in order to define analytical model described below.

## DISCUSSION

In this case study, a regulation logic of upstream discharge is defined to achieve the following objectives:

- To reach water quality target fixed by European Union: a reference limit of 150 mg/l in chloride should not be exceeded in term of average of analytical results obtained on a year basis.
- To ensure containment of chloride plume into the site.
- To optimize site remediation with PR1, PR2, PR3 wells.

Regulation plan is a methodological approach based on an analytical model. Before analyzing regulation plan structure, the analytical model is described.

The model is based on a chloride mass balance between A and E locks to evaluate annual average concentrations.

Once model is developed, it is used to define a Threshold Flow-rate (TFR), which is the fundamental parameter to regulate the discharge, as it will be explained in the following chapters.

It is important to be noticed that E lock is chosen as conformity point, therefore from now on concentration are always referred to E lock.

## Model development

Model development follows these steps:

- Conceptual model definition.
- Development of analytical model.
- Model calibration.

Conceptual model definition

The domain is defined between A lock, located upstream of upstream discharge and E lock, located downstream of downstream discharge; the river is fully ducted along the reach interested by the present.

The basic hypotheses of the conceptual model are:

- The river is independent from groundwater table.
- There are no outlet fluxes (derivations).
- Inlet fluxes are upstream and downstream discharge and tributaries Alpha, Beta, Gamma and Delta (other contributions like minor discharges are considered as negligible).

River independence from water table is an acceptable approximation, in agreement with results issued by a FEM hydrogeological model recently developed, whose mesh is reported in Figure 5. The mesh consists of 524594 elements and 304832 nodes arranged on 7 layers, the modeled domain is extended to almost 100 km². Hydraulic conductivity field presents values in the range $1.10^{-7}$ – $2.4 .10^{-4}$ m/s.

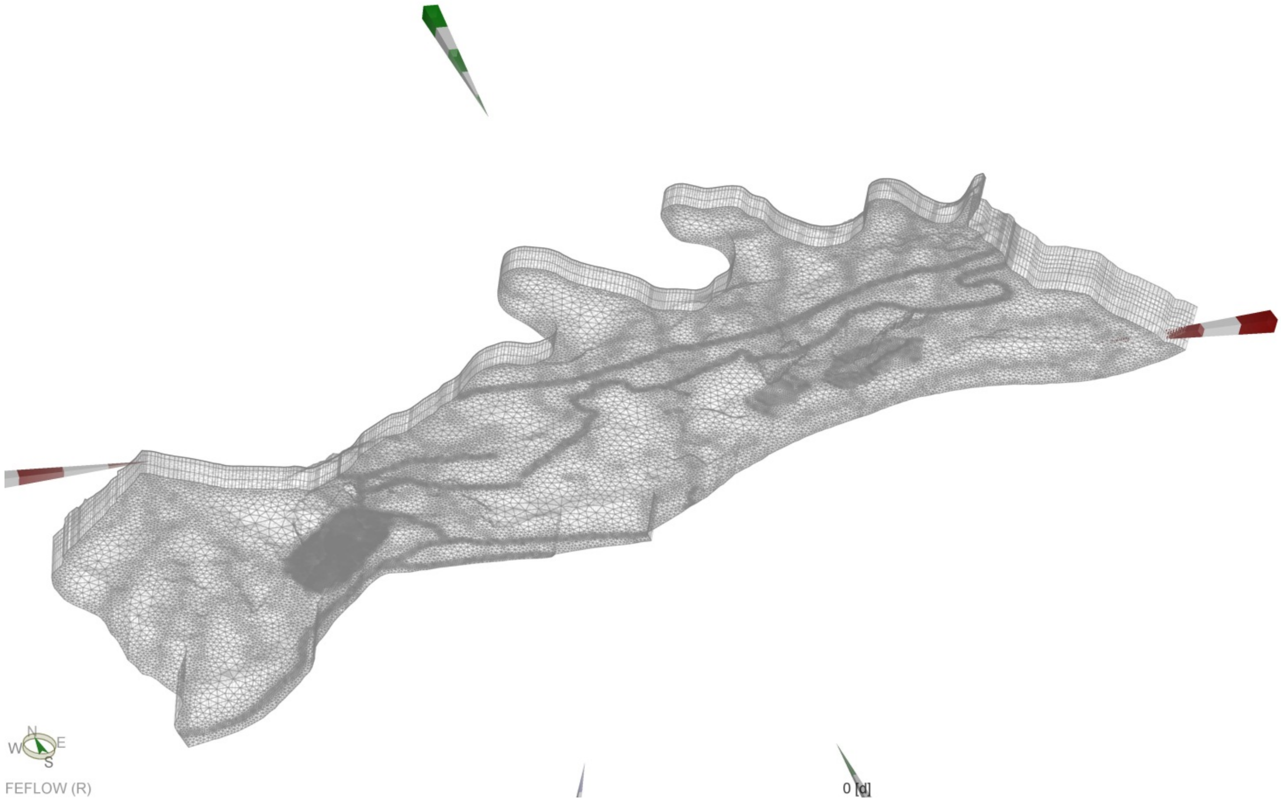


Figure 5: Three-dimensional FEM mesh of the hydrogeological model, (Aquale, 2012).

A hydraulic flux balance was done to evaluate water budget using flow-rates measured with ACDP method (described before). The water budget indicate a balance closure, with an acceptable degree of approximation, therefore basic hypothesis can be validated.

Development of the analytical model

Conceptual model is the base to develop the analytical model, whose equation is shown below:

$$M_A + M_{UP\ DISCH} + M_{ALPHA} + M_{BETA} + M_{GAMMA} + M_{DOWN\ DISCH} + M_{DELTA} = M_E \quad (1)$$

Where $M_x$ represents chloride charge at location “x” expressed in tons per day and is equal to:

$$M_x = 0.0864 \times C_x \times Q_x \quad (2)$$

Where:

- $M_x$ *[tons/day]* represents chloride load at location *x*;
- $C_x$ *[mg/l]* represents chloride concentration in location *x;*
- $Q_x$ *[m³/s]* represents flow rate at location *x.*

As the objective of the model is to evaluate annual average concentrations, the advective process is not considered. For this reason model is valid if exploited on a minimum 10 day time-step basis.

Model calibration

In the aim to test model capability to correctly reproduce chloride concentration in E lock, two calibrations are realized:

- Calibration on one-day time basis: model is run on the period 8/11/2012 – 31/12/2012, simulated and observed daily chloride concentration are compared.
- Calibration on one-year time basis: model is run on the period 2007 – 2012, simulated daily chloride concentration values are averaged on one-year basis and compared to average annual observed values.

Input parameters imposed are concentration in A lock, upstream and downstream discharge charges and tributary charges.

Observed data for the first calibration are based on data collected during the pumping test conducted in November 2012. Calculated concentration values are reasonably comparable with measured values if a 2.5 time lag is considered, which is due to the advective process approximation explained in the previous chapter.

Observed data for the second calibration are based on historical series available for the period 2007 – 2011. Calculated concentration values are compared with observed values for the period 2007 – 2011: error between measured and calculated values is inferior to 8%.

## The Regulation plan

The model is now used to simulate annual average concentration for 2013, depending on future chloride charge evolution of upstream and downstream discharge and the river flow rate.

Future chloride charge evolution for upstream discharge is estimated by historical trends analysis and expected remediation effects; future chloride charge evolution for downstream discharge is estimated by industrial production expected evolution, which is related to economical market variables and technological development.

It is important to remember that the object of the present project is to propose a flow-rate regulation logic of the upstream discharge; downstream discharge is managed independently by the regulation plan.

In order to compare the influence of river flow-rate variations to upstream discharge flow-rate variations on Chloride concentration, before to simulate the 2013 scenario, some preliminary simulations are firstly run.

Chloride concentration is calculated in function of upstream discharge variation for different river flow-rate values: results are plotted in an abacus form, as shown in Figure 6.

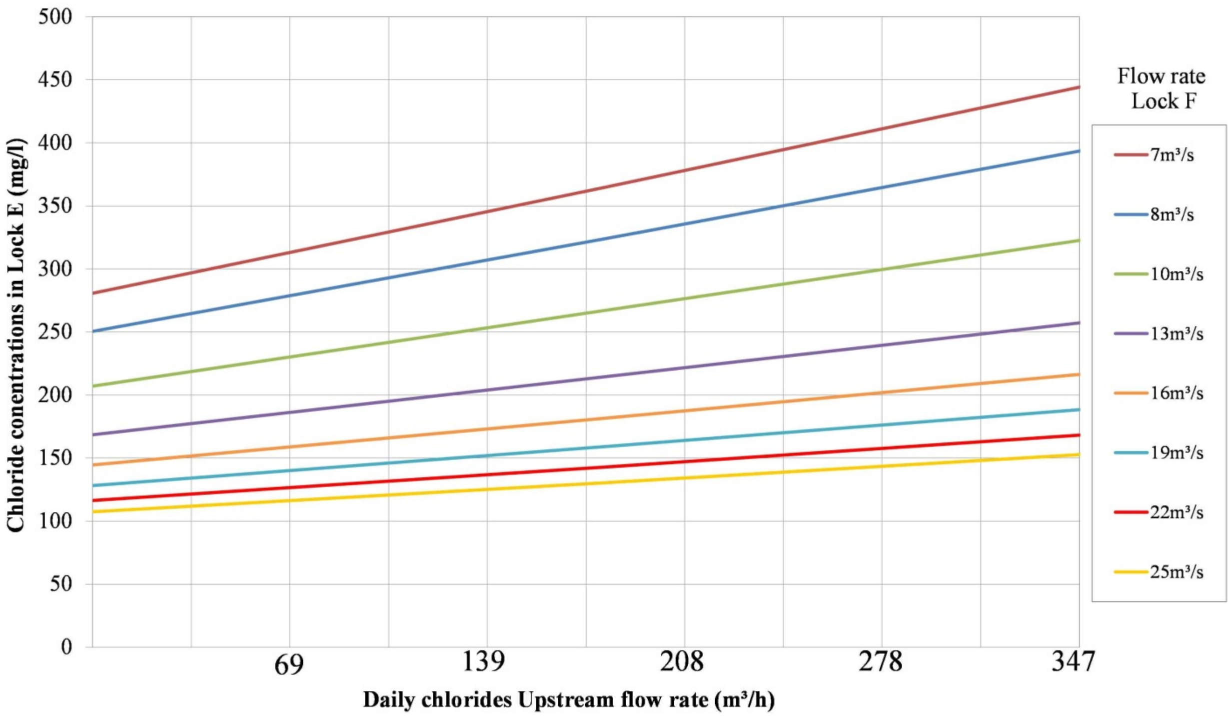


Figure 6: Abacus for the calculus of the instantaneous chloride concentrations in E lock, depending on the chloride charge in upstream discharge and flow rate of the river (Aquale, 2013).

From this abacus it can be observed that, for an upstream discharge of 227 m³/h, the respect of 150 mg/l limit upstream discharge is obtained when the river flow-rate is greater than or equal to 22 m³/h. Otherwise the limit is exceeded.

Besides it can be observed that a significant reduction in upstream discharge from 227 to 0 m³/h gives a slight decrease in concentration. This suggests that concentration is significantly more influenced by river flow-rate variations than upstream discharge variations, in particular the more river flow-rate is high and the more concentration decreases.

River historical flow-rate series analysis was conducted to study dilution effect in regulation plan: cumulated evolution of average daily flow-rate in lock F for each year in the available period (1992 - 2012) is calculated, results are plotted in Figure 7. It is important to notice the following curves:

- Red curve: it represents typical low-flow year.
- Green curve: it represents typical high-flow year.
- Blue curve: it represents average-flow year.
- Black curve: it represents cumulated evolution of the whole considered period.

In each scenario red, green and blue curves respectively correspond to low, high and medium dilution effect.

Regulation plan is based on upstream discharge modulation depending on overcoming of a threshold flow-rate (TFR) value. When flow-rate is higher than TFR, river dilution effect is high: in these conditions the regulation plan assumes that a higher charge is discharged to river (configuration A); on the other hand, when flow-rate is lower than TFR, river dilution effect is low:

in these condition regulation plan assumes that a lower charge is discharged to the river (configuration B).

In configuration A, a discharge flow-rate of 227 m³/h is proposed, with three active wells; in configuration B, a discharge flow-rate of 75 m³/h is proposed, with one out of three active wells.

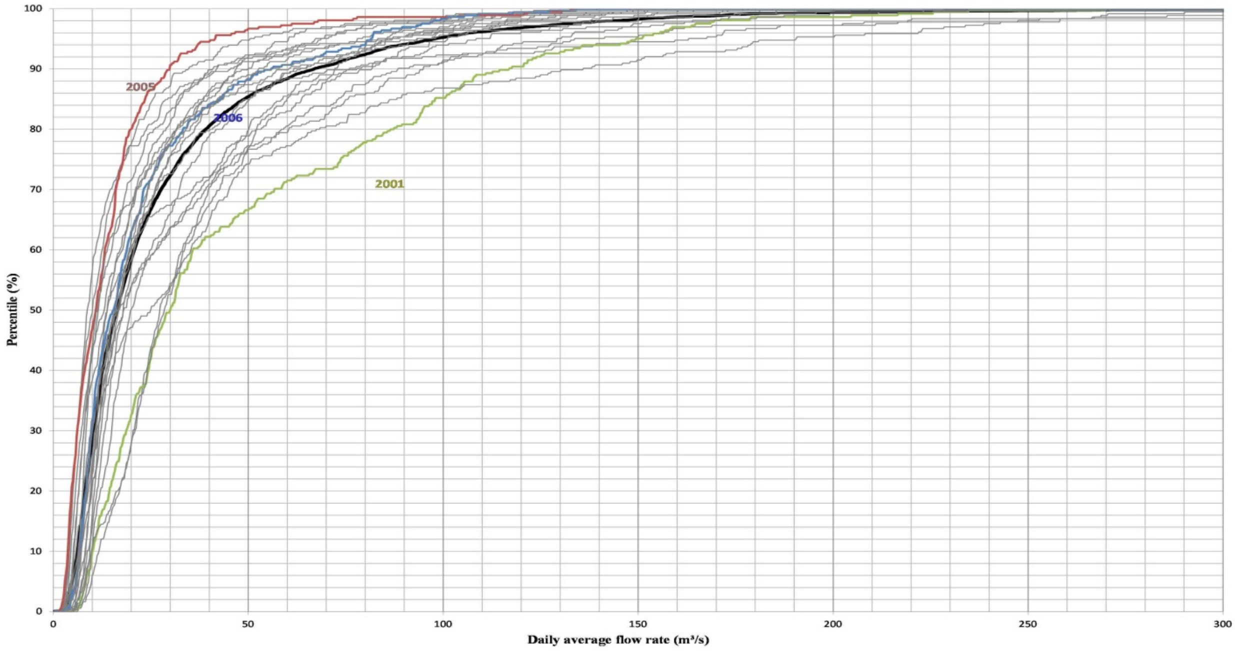


Figure 7: Daily flow-rate cumulated evolution expressed like percentiles, for each year in the available period (1992 - 2012), lock F (Aquale, 2013).

The FEM hydrogeological model introduced before and results of previous pumping tests indicates that the configuration B ensures a sufficient plume containment, but it has to be confirmed with some new monitoring well implantation in the down gradient zone of the site.

If containment efficiency is tested for the two configurations, TFR optimum value remains to be determined. In following chapters TFR variations is evaluated for the three scenarios to identify which one is the best in order to respect river water quality limit and remediation objective for 2013 scenario. Average chloride mass extracted in the period 2007 – 2012 is a reference value, since remediation target for the future is to extract more than this value.

2013 scenario: simulation results

Scenario simulation assumes to impose upstream discharge concentration and downstream discharge charge.

Average yearly concentrations are calculated in function of:

- Three different river regimes (2001 – 2005 – 2006).
- Different TFR values.
- Extracted chloride mass.

Results are plotted in an abacus form, as shown in Figure 8.

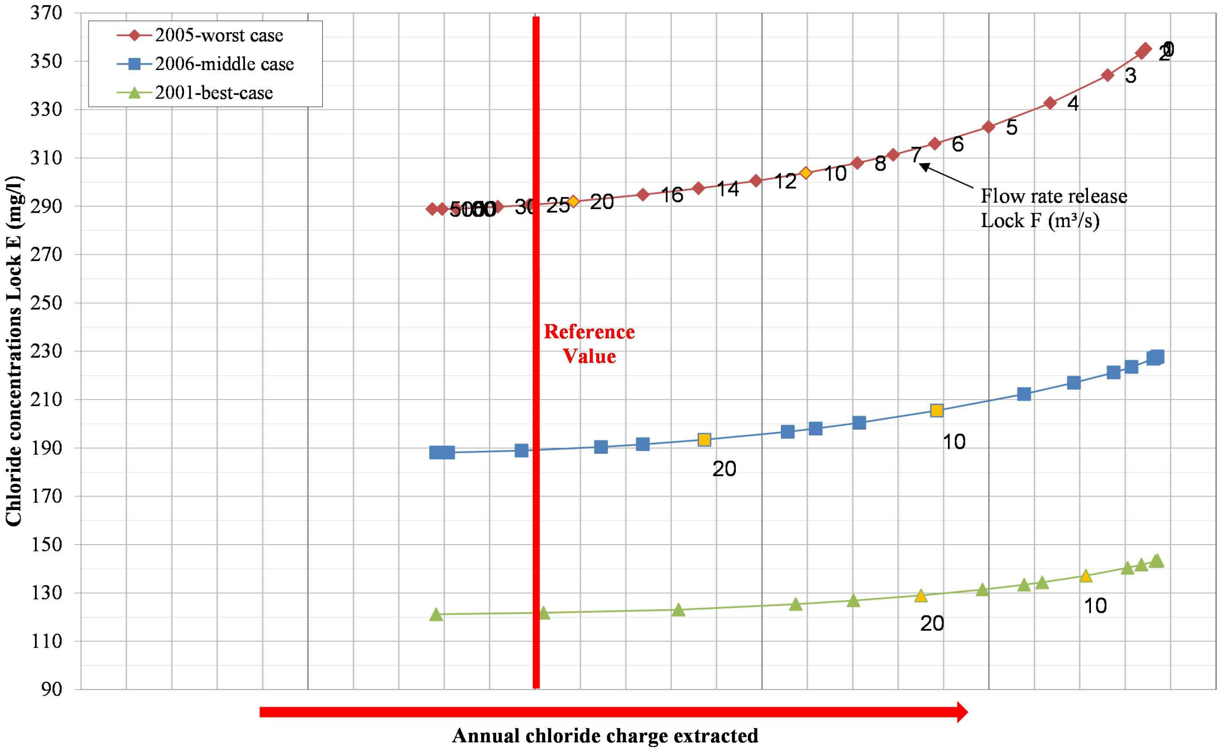


Figure 8: Annual average chloride concentrations calculated in E lock in function of threshold flow-rate (TFR) – Scenario 2013 (Aquale, 2013).

For each of the three year, a curve was calculated applying a TFR from 0 (right limit of the curve) to 500 m³/s (left limit of the curve).

A TFR of 10 m³/s seems to be a good compromise as it ensure for the middle case (2006):

- An average concentration of 205 mg/l.
- A chloride mass extracted almost double than the reference value mg/l (meeting remediation target).

## CONCLUSIONS

This study case relates to an historical groundwater chloride contamination as a consequence of an intense historical chemical production in a Belgian hydrological context (Carboniferous limestone). This contamination affects some drinking groundwater wells positioned down gradient of the contaminant source. A hydraulic system of pumping wells was implemented to contain and remediate the chloride plume; water collected by the system was discharged into the river nearby, which constitutes an important water-way for commerce and tourism for the entire region.

In order to respect the quality of the river in term of average annual chloride concentration, as required by regional authorities and in line with the European Water Framework 2000/60/CE (EUWF), an action was required to moderate discharge chloride charge into the river.

Different applicable solutions were compared to accomplish this goal, in particular water treatment technologies like nano-filtration, reverse osmosis and distillation.

If we consider that all investigated technologies require high energy consumption and the recovery of residues is not economically advantageous, another solution had to be found.

This solution was identified in a regulated discharge; the regulation has to be managed by a regulation plan, whose specific objectives are:

- To reach water quality target fixed by European Union: a reference limit of 150 mg/l of chloride should not be exceeded in term of average of analytical results sampled during a year basis.
- To ensure containment of chloride plume into the site.
- To optimize site remediation with PR1, PR2, PR3 wells.

The regulation plan is based on an analytical model exploiting a chloride mass balance. The regulation logic is based on the discharge flow variation in function of river flow. At higher flow-rates, dilution effect is higher, then a higher flow can be discharged and three wells out of three are active (configuration A); on the opposite, at lower flow-rates, dilution effect is lower, then a lower discharge flow can be discharged and one well out of three is active (configuration B).

The methodological approach described in the present paper was recently accepted by regional Authorities. The study contributed to a modification of a Ministerial Decree of the rehabilitation plan of the old settling basins, encompassing authorizations for pumping and discharge. This Ministerial Decree aims at the good qualitative and quantitative management of the water bodies.

The recommendations made are presently implemented, based on a performance monitoring that is taking place in the coming semesters.

The regulation plan constitutes a multi-criteria decision-making tool and it provides users with sufficient elements to achieve coupled ground/surface water quality objectives, often in opposition to each other. In particular it can be useful when dealing with multiple stakeholders.

In this case study, the regulation plan demonstrates to be a flexible tool which could be applied to other cases of responsible and sustainable management of water resources, if all the application assumptions are met (in particular the followings can be listed: the respect of a minimum simulation time-step, river independence from groundwater table and no outlet fluxes). Analytical model used by this methodology approach is user-friendly and it allows to verify each implementation phases (it is a transparent tool).

It is important to consider that the Regulation plan is still in progress and further development could be supplied. The actual criterion provides an estimation of the average annual concentration for representative river flow regimes. A further approach could involve to regulate discharge flow-rate depending on the specific flow regime occurring a given year. This method implies to forecast, with a statistical analysis, the flow regime of the incoming year.

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