Pollution Impacts on Norwegian Groundwater Bodies

Panagiotis Dimakis
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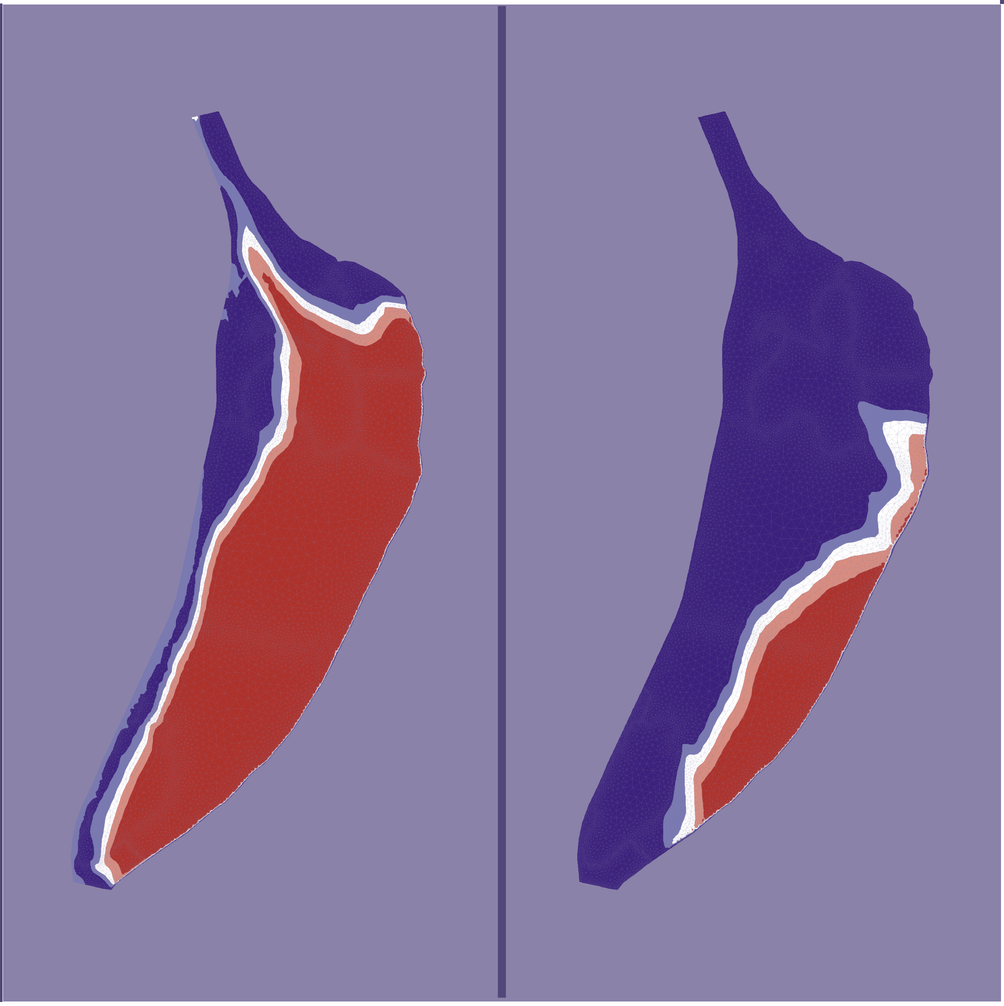

REPORT

Pollution Impacts on Norwegian Groundwater Bodies

Norwegian Water Resources and Energy Directorate
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Pollution Impacts on Norwegian Groundwater Bodies

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Summary: To assess the pollution impact of agriculture on groundwater bodies in the context of the EU Water Framework Directive (WFD), it has been suggested by some member states that the percentage of agricultural area in relation to the total surface area of the groundwater body can be used for a quick yet reliable risk assessment.

An analysis of a typical Norwegian groundwater body shows that in Norway catchment areas and recharge have to be included in the assessment of pollution impacts. Any analysis based exclusively on groundwater body vs. agricultural area will greatly overestimate the risk and is not recommended.

Keywords: Groundwater, Pollution, WFD

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April 2005

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Preface

Established in 1921, the Norwegian Water Resources and Energy Directorate (NVE) is a directorate under the Ministry of Petroleum and Energy and is responsible for the management of Norway's water and energy resources.

Our mandate is to ensure an integrated and environmentally sound management of the country's water resources, to promote efficient energy markets and cost-effective energy systems and to work to achieve a more efficient use of energy.

We are Norway's national centre of expertise for hydrology, and we have a central role in the national flood contingency planning. NVE also has the overall responsibility for maintaining national power supplies.

Since 2001 the Norwegian Water Resources and Energy Directorate is actively engaged in the implementation of EUs Water Framework Directive. This report has been requested by NVEs Water Resources Department and produced by the Hydrology Department to facilitate the risk assessment of groundwater bodies in Norway.

In this report we make use of a groundwater model which was developed with funds from the Norwegian Research Program for Environmental Flows (Miljøbasertvannføring) which we gratefully acknowledge.

Oslo, April 2005

Morten Johnsrud
Department Director

Sverre Husebye
Section Manager

Summary

The Norwegian landscape was formed by the erosive effects of the last ice age and in addition created a very large number of small groundwater bodies with similar characteristics. These groundwater bodies are located in typical “U” shaped valleys, have oblong shapes with the width being typically much smaller than the length and receive considerable amounts of water from the mountain sides of the valley they reside in.

The fact that the majority of Norwegian groundwater bodies have remained free of pollution problems in spite of modern agricultural practices is associated in this report with the above-mentioned characteristics. A case study involving a groundwater body from central Norway was carried out showing the effects these characteristics have on the ability of the groundwater body to dilute and transport away pollution concentrations.

The results show that for a typical Norwegian groundwater body the combination of small size, oblong shape and mountainside replenishment will reduce the time required to wash away any pollution contamination by a factor of 2 or higher.

We conclude that the majority of Norwegian groundwater bodies have characteristics that render them the ability to “clean” themselves in a very effective and natural way. The results demonstrate that assessment of pollution impact on Norwegian groundwater bodies can not be based only on the use of the surface areas of the groundwater bodies. In Norway catchment areas and recharge have to be included in the assessment of pollution impacts. Any analysis based exclusively on groundwater body vs. agricultural area will greatly overestimate the risk and is not recommended.

1 Introduction

To assess the pollution impact of agriculture on groundwater bodies in the context of the EU Water Framework Directive (WFD), it has been suggested by some member states that the percentage of agricultural area in relation to the total surface area of the groundwater body can be used for a quick yet reliable risk assessment.

At first sight such an assessment does not seem feasible for Norwegian groundwater bodies. In Norway one finds numerous examples of groundwater bodies with agricultural area coverage of up to 100% of the groundwater body, which however never show signs of being at risk by the agricultural practices. Partly this may be due to an agriculture without excessive fertilizing and intensive use of pesticides. In Norway preading of manure is regulated by legislation, and fertilizing plans are required to get agricultural grants. In addition due to the cold climate the need and use of pesticides are small compared to other areas.

Our assumption is that the majority of Norwegian groundwater bodies have particular recharge-discharge properties due to the unique Norwegian mountainous landscape that makes them capable of diluting and transporting away pollution concentrations relatively fast. The Norwegian climate contributes in strengthening the importance of these properties.

It is a schoolbook example to talk about the formation of valleys under the influence of glacier erosion with their typical “U” shapes. The majority of Norwegian valleys could be used as schoolbook examples, but for hydrogeological purposes one has to look somewhat beyond the typical “U” shape.

Figure 1. A typical Norwegian valley from West Norway (Jølster)

Figure 1 shows a typical Norwegian “U” shaped valley. The sediments at the floor of the valley comprising the groundwater body are on an average around 40m in thickness in the centre of the valley and wedge out at the valley sides and are usually highly inhomogeneous, typical of the dynamic environment that created them. If we now observe the landscape beyond the valley confinement area, we see that it broadens out at higher altitudes.

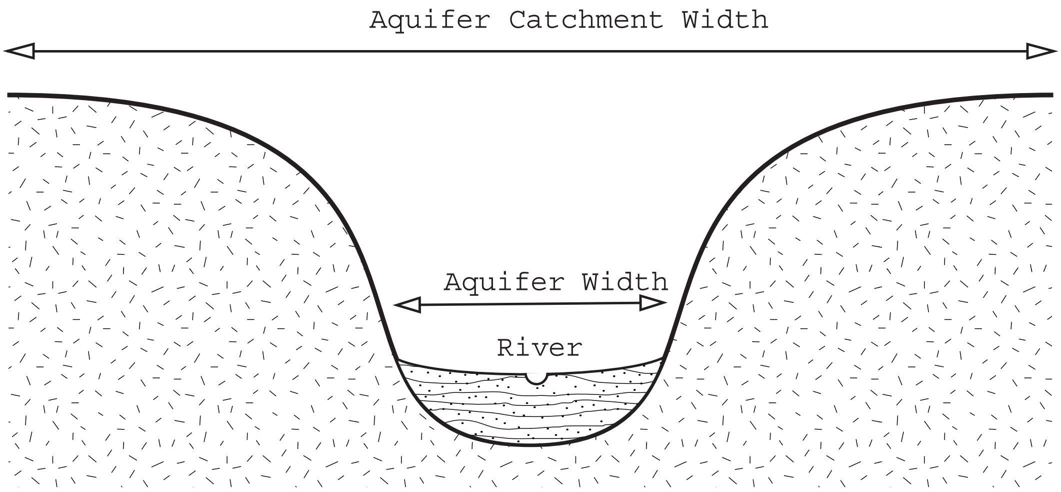


Figure 2. Idealized hydrogeological cross section of a typical Norwegian valley

In the idealized cross section of figure 2 we see that the valley does not so much resemble a “U” shape but rather an upside-down bell shape or normal distribution curve (Gaussian curve). From a hydrogeological point of view this is important because it indicates that the catchment area of the groundwater body can be much larger than the groundwater body area. As a result large amounts of water are usually replenishing the groundwater body from the mountainside boundary. This and the fact that the shapes of the groundwater bodies are such that groundwater needs only to flow across short distances before it outlets into a river or lake, lead us to assume that Norwegian groundwater bodies are capable of renewing their groundwater resources in a matter of years and thus are capable of diluting and transporting away pollution concentrations relatively fast.

2 Problem Analysis

In order to validate our assumption we decided to start off with a case study using the Rena groundwater body. Colleuille et al.(2004) have developed a groundwater model using the Visual Modflow groundwater simulation system for the Rena groundwater body. We implement as closely as possible the same geological, hydrogeological, and hydraulic boundary conditions using the Feflow simulation tool.

2.1 Brief description of the Rena Groundwater Body

The Norwegian Water Resources and Energy Directorate (NVE), initiated a research project with focus on interactions between groundwater and surface water. The purpose of the project was to provide the licensing authorities with tools for quantitative assessment of the effects of regulation on groundwater resources and at the same time the effect of groundwater abstraction on river flows.

A small, urbanized alluvial plain (1.5 km^2) by the river Glomma in Southern-East Norway is used as a case study (figure 3). The local aquifer consists of heterogeneous glaciofluvial and fluvial deposits, mainly sand and gravel. Aquifer and river sediment (figure 4) have been examined by use of Ground Penetrating Radar (GPR) and soil samples collection, preferential flow has been examined by tracer tests and hydro-climatic regime analyzed by statistical tools.

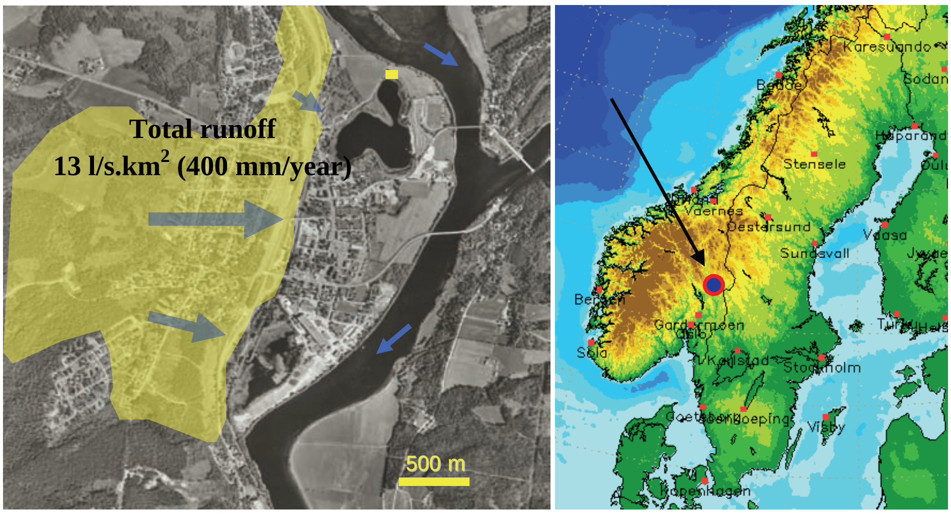


Figure 3. Location of the alluvial plain and its catchment by the river Glomma.

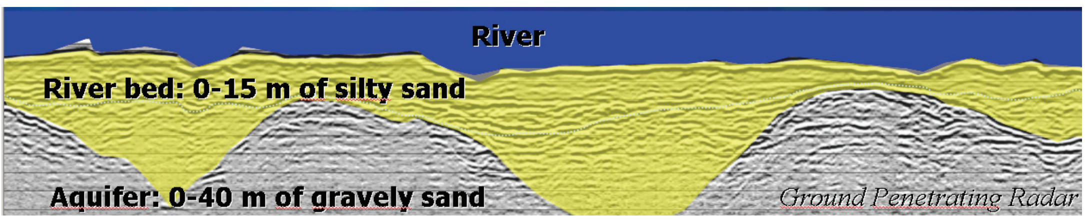


Figure 4. Example of aquifer profile obtained by use of Ground Penetrating Radar.

A three-dimensional numerical model was developed for this study (figure 5). MODFLOW (Visual Modflow 3.0) was used to numerically simulate the river-aquifer system. The model consists of 3 layers: The first one is a virtual layer where the river is simulated by Constant Head Boundary Conditions. The second layer is the river bed and the upper sediment in the alluvial plain consisting of fluvial deposits (silty sand). The third layer is the major aquifer consisting of heterogeneous glaciofluvial deposits (gravely sand). The model is delimited at the bottom by an impervious layer of till.

The model was calibrated with 2 independent kinds of observations: groundwater levels and daily measures of water temperature and electrical conductivity recorded in both aquifer and river. Figure 6 shows the results of the automated calibration using PEST with transient simulation on daily data from 01.02.2002 to 07.09.2002 (R^2=0.99, RMS[1]=3.2 %, n= 316). The values of the 6 adjustable parameters are given in Table 1.

Effective precipitation (groundwater recharge from the hill) has been manually adjusted in order to have a water balance in agreement with the observation of water temperature and conductivity in the river bed (figure 7).

Sensitivity analyses have been performed in order to evaluate the effect of parameter uncertainty on model results (river level, hydraulic conductivity of the riverbed, groundwater recharge quantity from the hill, time steps and time units). The model has also been validated with data from 1999.

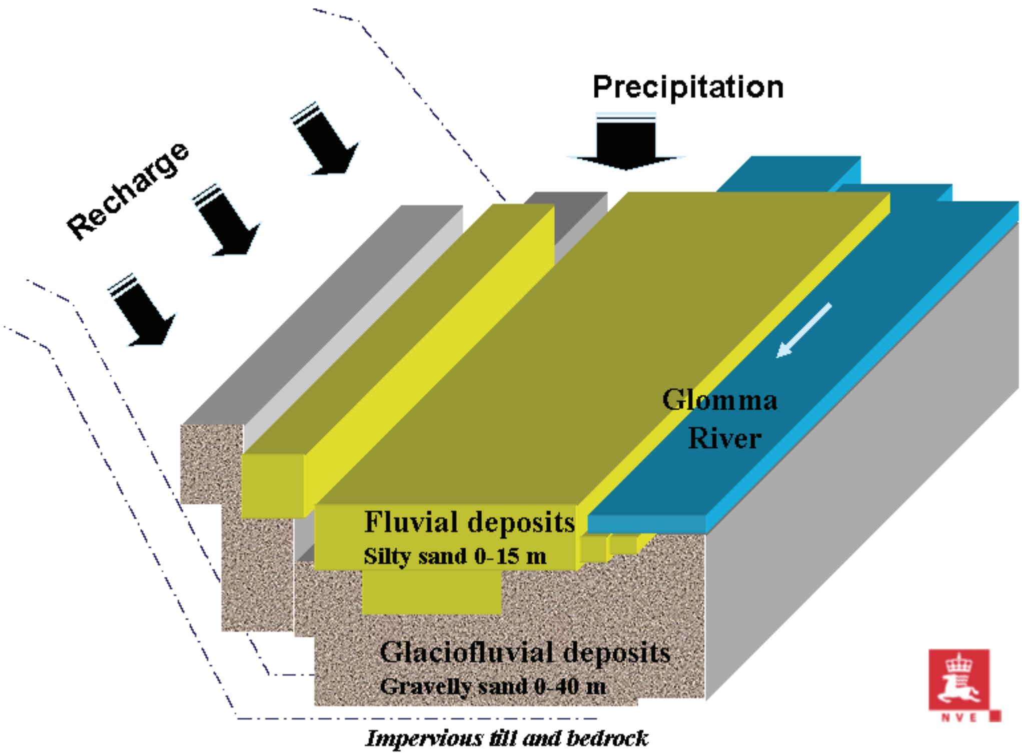


Figure 5. Implementation of the conceptual model in MODFLOW.

[1] Sum of squared weighted residuals between calculated and observed head values

	Calibrated values
Kx_2	$5.7\ 10^{-5}$ m/s
Kx_3	$9.8\ 10^{-3}$ m/s
Ss_2	$5.6\ 10^{-5}$ 1/m
Ss_3	$4.7\ 10^{-4}$ 1/m
Sy_2	$3.9\ 10^{-4}$ m/m
Sy_3	$8.7\ 10^{-2}$ m/m

Table 1. Hydraulic conductivity (K), Specific storage (Ss) and Specific yield (Sy) for layer 2 (x_2) and layer 3 (x_3).

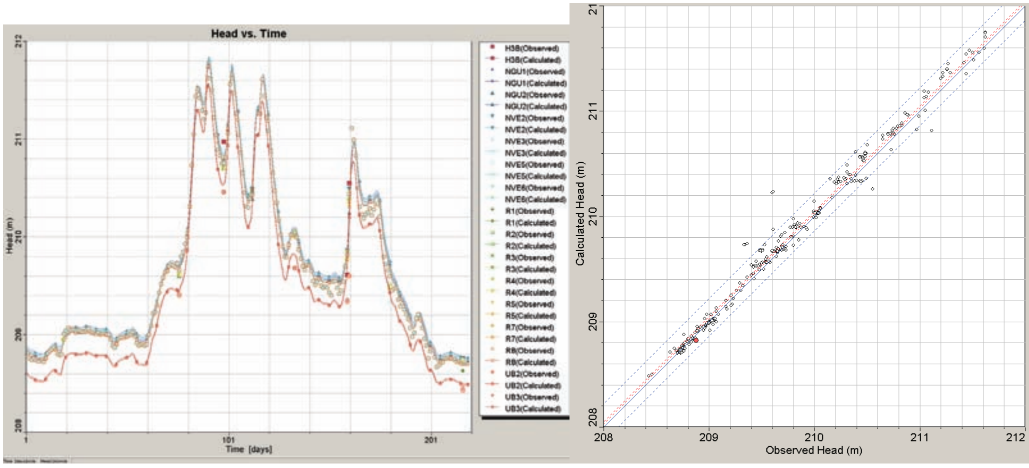


Figure 6. Calibration results: Head data versus time (left) and observed head versus calculated head (right).

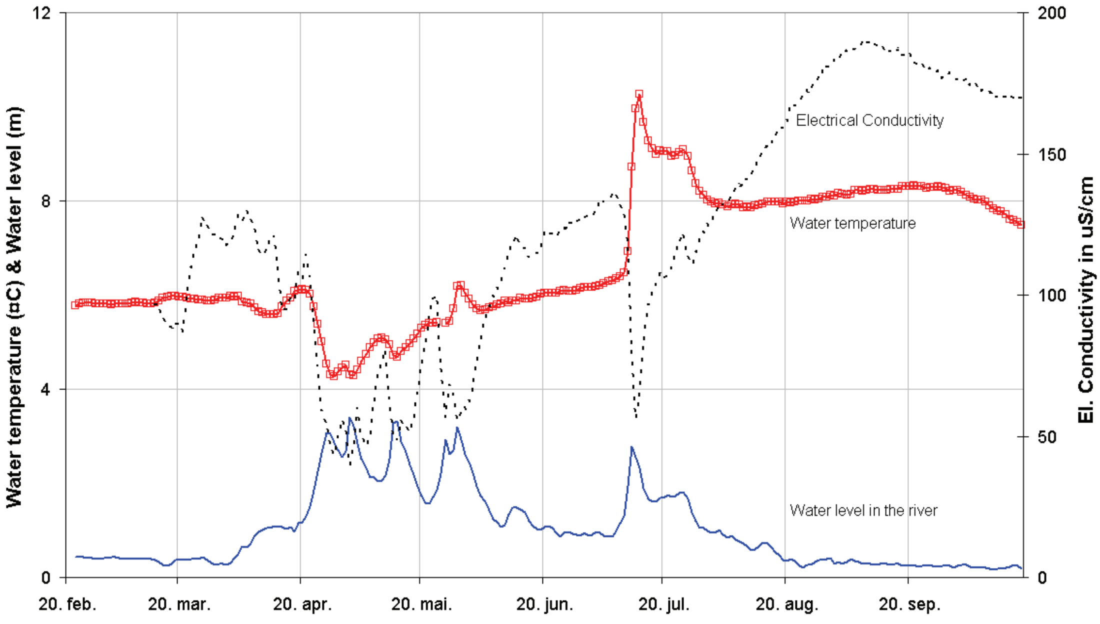


Figure 7. Water level, water temperature and electrical conductivity measured in the river bed.

The first task of the project was to carry out water balance studies in order to estimate the change in rate of groundwater recharge from and to the river in a normal hydrologic year with snow melting, flood, and base flow.

The model shows that discharge of groundwater is almost constant (about 5300 m^3/day in 2002) except on periods with rapid rise in river level (only few days a year: see figure 6). Generally the Glomma River gains water from groundwater discharge through the river bed (figure 8). The absolute river level is not crucial; it is rather the rapid rise of water level that controls the recharge from the river. The loss of river water to bank storage and return of this water to the river in a period of few days tend to reduce flood peaks. The bank storage contributes in the small alluvial plain of Rena in July 2002 to a reduction of river flow with 40 000 m^3/day, representing 0.15 % of the flow of the river at this period.

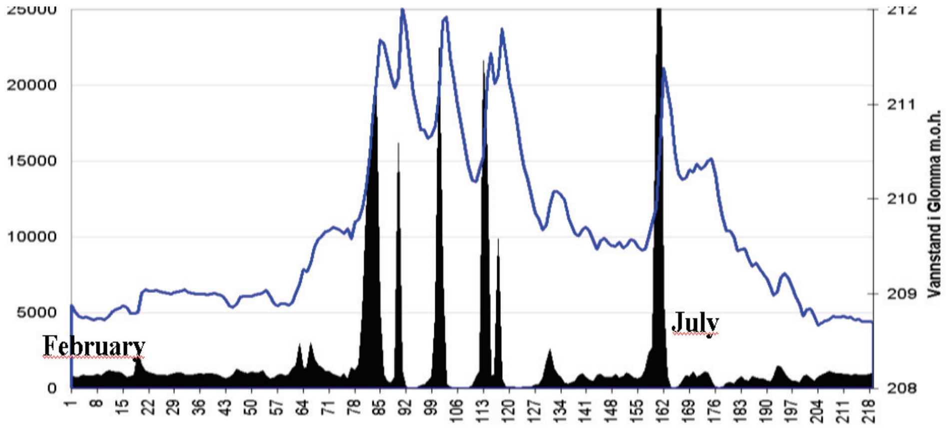


Figure 8. Modelled recharge flux from the river (given in m^3/day) and water level in the Glomma River (m.a.s.l.) versus time (01.02 to 07.09.2002).

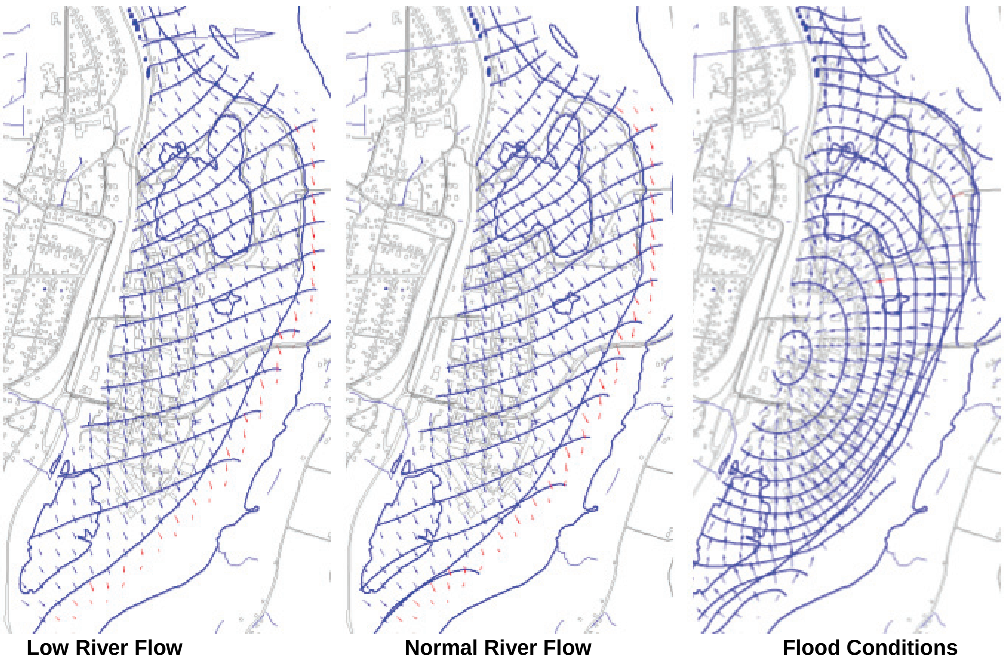


Figure 9. Flow pattern of the groundwater in the major aquifer (layer 3) at different periods of the year. The arrows indicate the flow direction, and the size of the arrows is proportional to the flow velocity. The lines indicate the groundwater piezometric level (2 cm equidistance).

The second task was to analyze the potential effect of change in the river water regime (due to regulation or climatic change and consecutive possible clogging/erosion) on groundwater resources and their interaction with river water.

A 10 times thinner river bed, or a 10 times higher hydraulic conductivity of the riverbed in the northern part of the alluvial plain leads to: an increase in groundwater discharge from 200 to 400 % of the base case and a lower residence time in the aquifer (higher water velocity). Pumping of groundwater from the aquifer reverses the natural hydrologic condition on a local scale: an abstraction of 30 l/s consists of 90 % groundwater and 10 % river water, and an abstraction of 113 l/s consists of 66 % groundwater and 34 % river water. Pumping of groundwater contributes to river depletion through 2 components: base flow reduction (lower groundwater discharge), and induced river infiltration.

The effect of groundwater recharge from the hinterland catchment (5.5 km^2) is also very important (figure 10). An increase in groundwater recharge of 200 % results in an increase of groundwater discharge of 800 % of the base case in the northern area. An increase in groundwater recharge results in lower groundwater residence time in the aquifer (water velocity increases from 1 to 3 m/day).

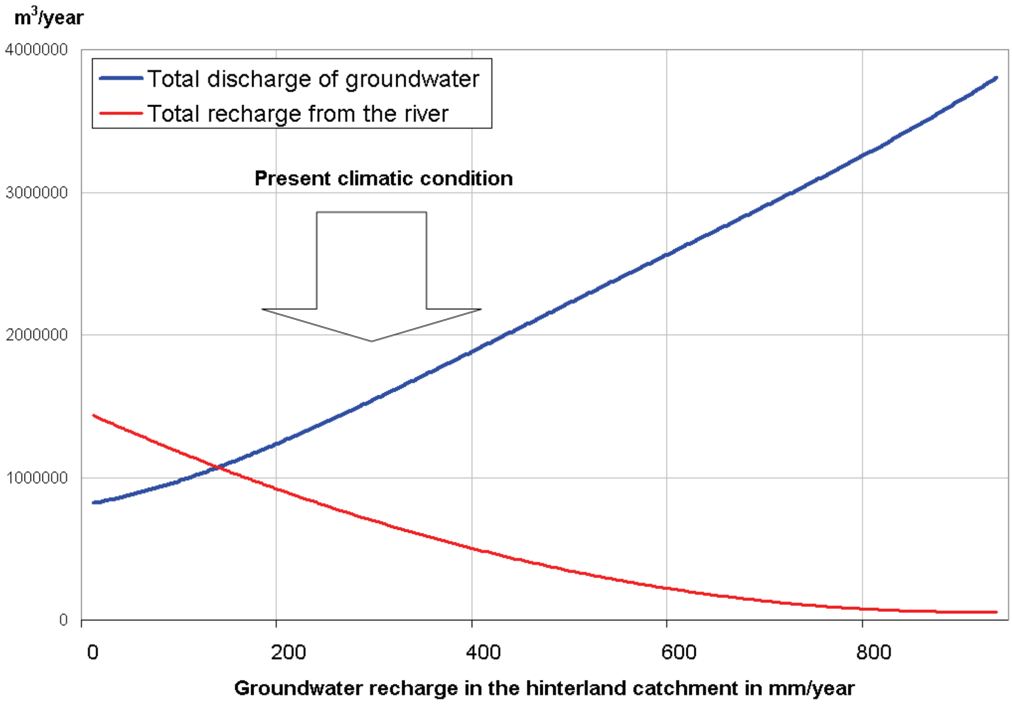


Figure 10. Effect of change in change in the groundwater recharge from the hinterland on the total water exchange quantity between aquifer and river.

Changes in sedimentation/erosion, groundwater abstraction and groundwater recharge from the hinterland catchment have significant local effects on the exchange quantities between the river and the aquifer, in addition to change in the groundwater residence time. These results suggest that climatic change and human activities may affect the groundwater chemistry in the alluvial plain (O_2 content, pH, temperature) and thereby possibly the habitat of fish and other organisms in the riverbed. Preliminary scenarios for climatic changes in South-East Norway (www.regclim.met.no) suggest a small increase in total runoff and thereby higher groundwater discharge and several floods events with bank storage, which in most cases will be positive for the faunal diversity in the river.

3 Pollution Scenarios and FEFLOW Simulations

Using Feflow[2] we decided to simulate two scenarios. In the first one we implement full mountainside replenishing, while in the second one we assume only normal precipitation. Every valley has its main river that plays a significant role in controlling the groundwater levels in the groundwater body. The Rena groundwater body is influenced by the Glomma river which is the largest river in Norway and one which exhibits large water level variations (>5m) during the year. All these things have been taken into account in the Feflow model, so we only need to define the specifics of each simulation.

One could try to implement actual pollution scenarios or vary the magnitude of the agricultural area and analyze the effect on water quality over time. Instead we decided to investigate a scenario that is extreme and simple. We assume that the whole groundwater body is polluted with 100 mg/l and are interested in finding out how long it will take to remove the polluted water and re-establish fresh non-polluted water in the groundwater body. To avoid getting into a discussion about effective porosity versus total porosity and the effects the porosity has on pollution transport, we run 3 simulations for each scenario where we change the porosity from 0.3, to 0.2, to 0.1, respectively.

Figure 11 shows the basic results for the scenarios with mountain-side replenishment. These results have been obtained by integrating the total amount of pollutant in the groundwater body. We notice that for higher porosity we have a larger amount of groundwater stored in the groundwater body and thus a larger amount of pollution mass is present. More water will be needed to replace the polluted water for a higher porosity scenario than for a lower porosity scenario. Since the process we are interested in is advective transport we do not consider the effects of dispersion important for our simulation and use commonplace values of 10m and 2m for the longitudinal and transverse dispersivities respectively. The three curves presented in figure 11 seem to have the same general characteristics. They show the same rate of pollution removal with time which seems to be independent of porosity value, until approximately ½ to ⅔ of the total pollution mass has been removed. Thereafter the rate is decreased asymptotically towards obtaining a zero value that of course is never really achieved since some pollution will always remain in the groundwater body. Even with a scenario of 0.3 porosity we find that a 99% pollution removal will be achieved within approximately 2700 days (i.e. 7.4 years). For a scenario of 0.2 porosity, which is the porosity close to the median value of porosity for Norwegian groundwater bodies, a 99% removal will take place within 1500 days (i.e. 4.1 years). Tracer tests performed by Colleuille et al.(2004) in Rena indicate an effective porosity of 10% appropriate for this area. If this is the case a 99% removal is achieved within 800 days (i.e 2.2 years).

If we compare these results with those for the scenarios without mountain-side replenishment shown in figure 12 we observe a significantly different behavior.

[2] Although the original model was developed using the Visual Modflow simulation tool we decided to use Feflow in this project mainly because we find it more flexible in implementing boundary conditions and faster since a much smaller number of numerical nodes is required.

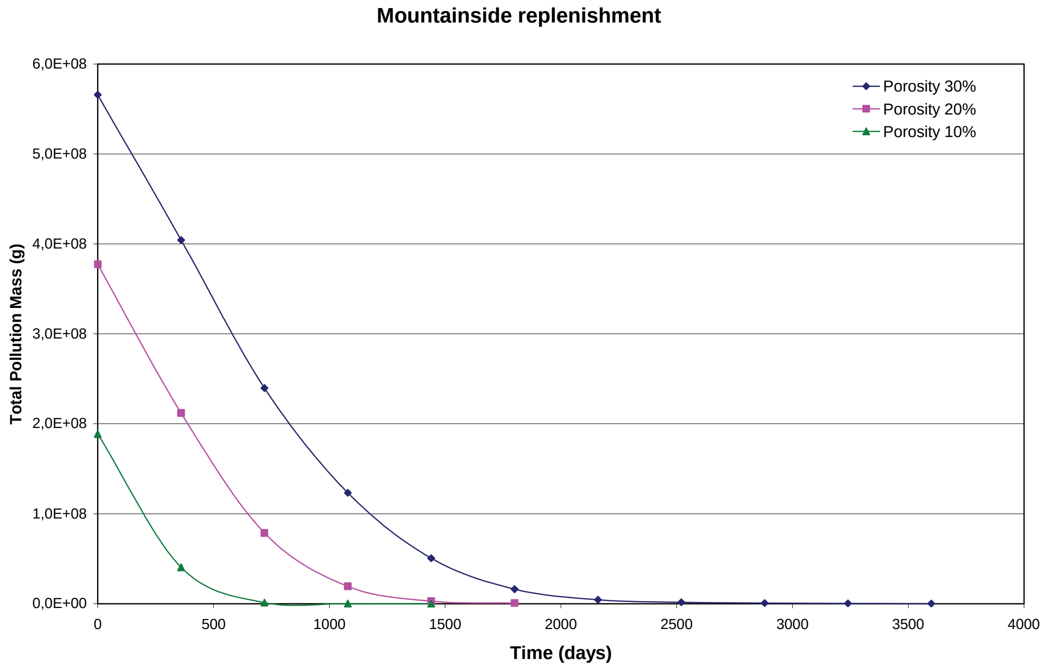


Figure 11. Analysis results with mountain side replenishment for three different porosity scenarios

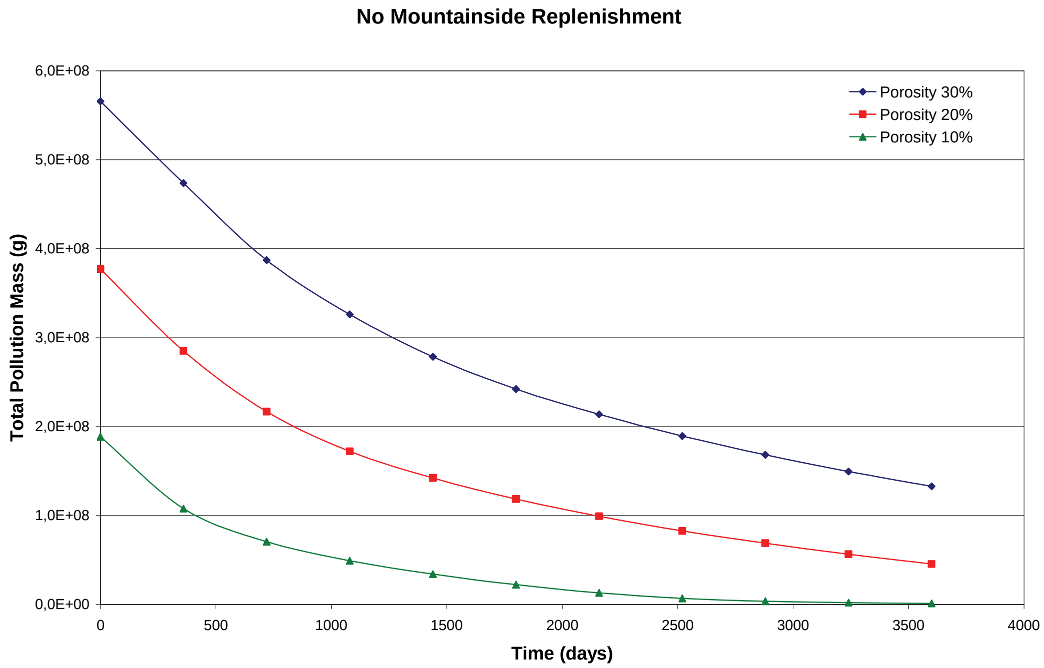
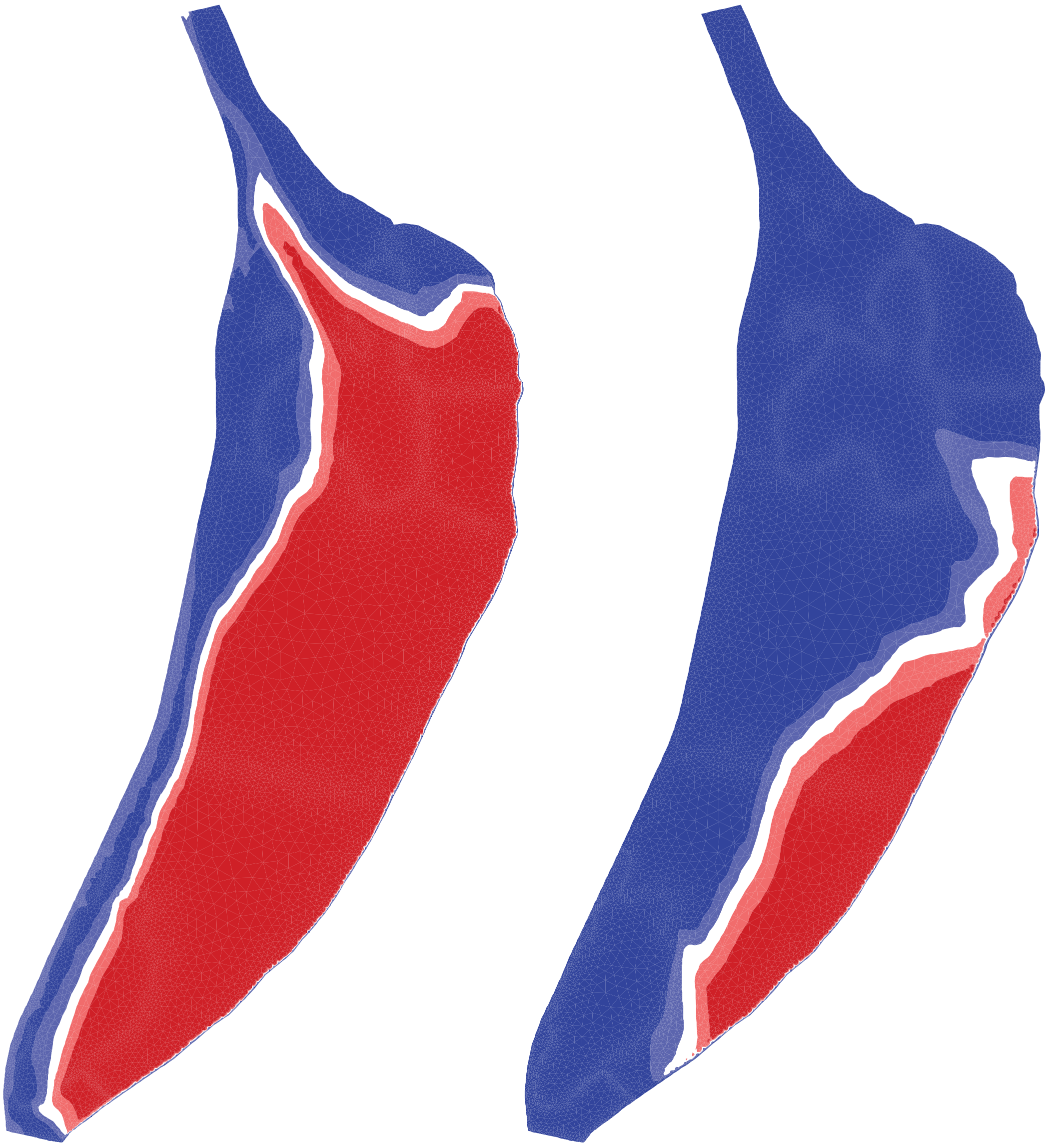
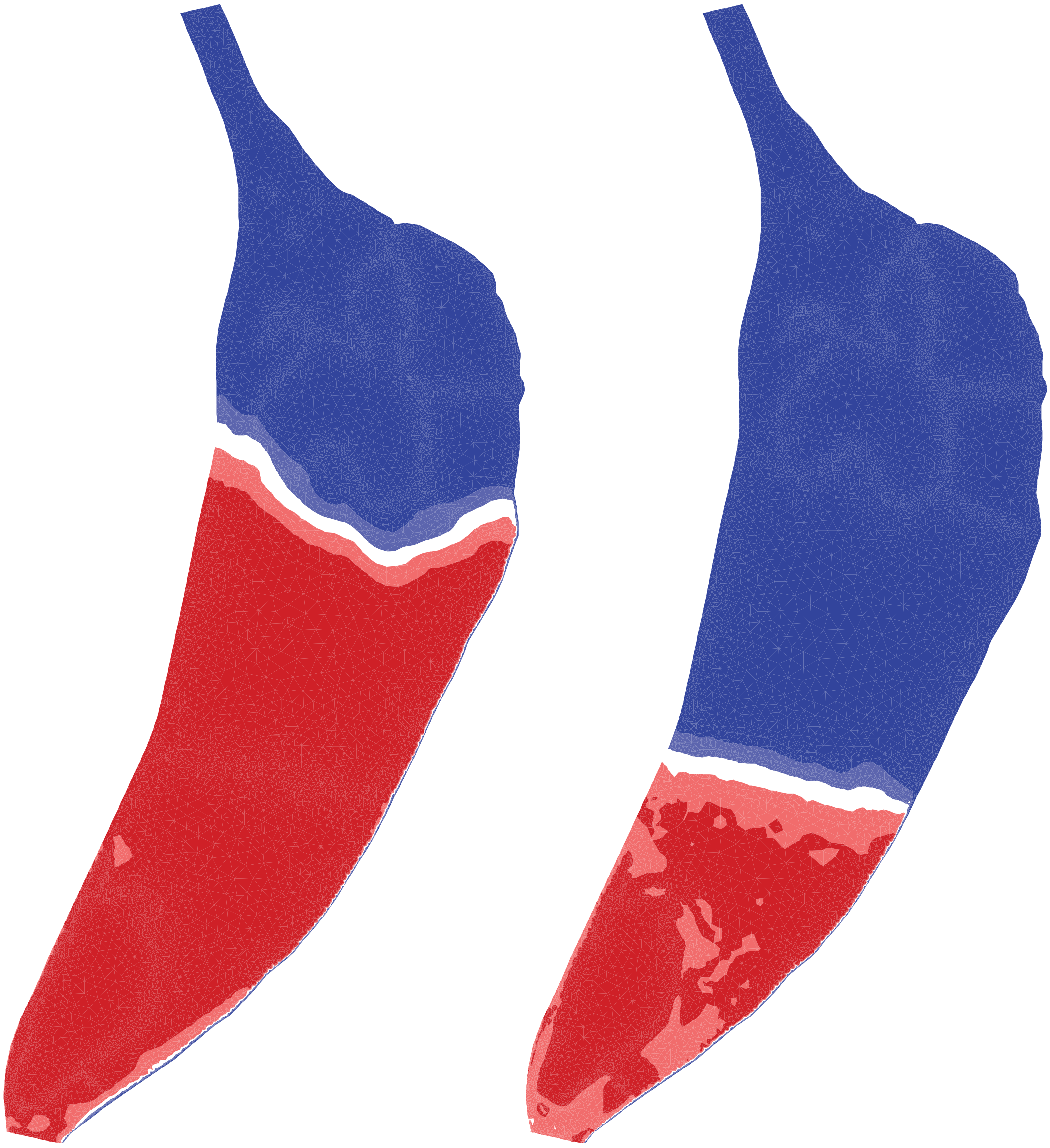


Figure 12. Analysis results with no mountain side replenishment for three different porosity scenarios.



A. **B.**

Figure 13. Simulation results with mountain side recharge. A. Shows the distribution of pollution after 360 (1 year) days, while B the distribution after 1100 days (3 years). Red (80-100%), Light Red (60-80%),White (40-60%) Light Blue(20-40%) Dark Blue(0-20%). Percentage of initial pollution.



A. **B.**

Figure 14. Simulation results without mountain replenishment. A. shows the pollution distribution after 1000 days (2.7 years) while B shows the distribution after 3000 days (8.2 years). Red (80-100%), Light Red (60-80%),White (40-60%) Light Blue(20-40%) Dark Blue(0-20%). Percentage of initial pollution

The rate of pollution removal is smaller. After 10 years of simulation the groundwater body has still significant amounts of pollutant residing in the body for porosities of 0.3 and 0.2. 99% removal has only been achieved for the 0.1 porosity scenario, which took just under 10 years, compared to approximately 2 years for the mountain replenishment scenario for the same porosity.

By comparing the results shown in figures 13 and 14 one can see the effects that mountain replenishment has on the pollution of the aquifer. It is clear that the amounts of water infiltrating the aquifer from the mountain side will not only help in diluting the pollution content of the aquifer but will also change the direction of flow in the aquifer. In the simulated case of the Rena aquifer a change of flow direction is favorable for pollution removal since the new flowpaths are considerably shorter and the polluted water is removed along the right side of the aquifer at a faster rate. Without mountainside replenishment the flowpaths will be sub-parallel to the valley axis (or river direction) and become 2 to 3 times longer which results in a much slower pollution removal process.

The Rena aquifer was chosen because of its oblong shape with the long axis being sub-parallel to the river direction, which is typical for the majority of Norwegian aquifers. Variations of course occur with respect to the shape of the aquifer and the amount of water infiltrating for the mountain side. One can always find atypical aquifers with very little mountain side replenishment which can and should be neglected in a simulation context or semicircular aquifers where a change in flow direction is not favorable for pollution removal. Based on existing information from quaternary maps we estimate that less than 10% of all aquifers in Norway are atypical. When it comes to important aquifers which are used for water production or are assessed to be a potential water production aquifer, 95% are typical and exhibit the same characteristics as the Rena aquifer in varying degrees.

Another important characteristic of Norwegian aquifers is that the groundwater table is found typically within a couple of meters from the surface (2-5 m) with annual variations being typically between 1-2.5 m. This means that Norwegian aquifers have very small unsaturated zones. In general this is considered to be a problem for Norwegian aquifers because the unsaturated zone is too thin to function as a pollution barrier. Such conditions are not ideal for establishing drinking water production wells. However in the context of this report we consider these effects as positive. Pollutants which reside in the unsaturated zone are in most cases easily washed away on an annual basis reducing the possibility of accumulating concentrations to reach or exceed safety limits.

Obviously some aquifers in Norway will not have a significant mountain side replenishment and/or a relatively thin unsaturated zone and thus be vulnerable to contamination or at least much more than the majority of Norwegian aquifers. These aquifers have already been identified and are considered to be at “risk” according to definitions supplied by EUs Water Framework Directive. As such these aquifers will be monitored closely.

4 Conclusions

There is little doubt that mountainside replenishment plays an important role in keeping Norwegian groundwater bodies “healthy”. It certainly helps in diluting pollutant concentrations and in most cases will change the flow patterns in the aquifer resulting in faster contaminant removal.

These observations have been confirmed by our analysis of the Rena aquifer. We basically assumed that the Rena aquifer was initially 100% polluted and preformed a simulation analysis of the aquifer to observe the processes of natural remediation. Without mountainside replenishment the Rena aquifer required a substantial amount of time to re-establish near normal/natural conditions. Mountainside replenishment reduced the amount of time needed to achieve near normal conditions by more than half.

Different agricultural practices will obviously cause different types of pollution pressures for the groundwater body and some agricultural practices will be potentially more harmful than others. The properties and supply of pollutants are important parameters in pollution transport analysis and we have not taken them into consideration in this report. Our analysis assumes a pollution agent which is basically non-reactive and mobile and thus easily transported through advection processes.

Norway has not experienced the severe pollution problems observed in other European countries. Some incidents have occurred but these were moderate compared to similar incidents in other European countries and were treated easily. Historically, the majority of Norwegian groundwater bodies have not shown any signs of pollution and therefore we have no reasons to assume that this will change in the future.

The majority of Norwegian groundwater bodies receives a considerable amount of water from their mountainside boundaries and behaves much like the Rena aquifer. Their ability to dilute and remove pollutants is thus considerably enhanced. Even in extreme cases Norwegian groundwater are capable of removing pollution mobile agents quickly and maintain pollution concentration below threatening thresholds.

The results demonstrate that the percentage of agricultural area in relation to the total surface area of the groundwater body can not be used for a quick assessment of risk for Norwegian groundwater bodies.

5 References

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