IMPACT OF PRIVATE SEPTIC INSTALLATION ON THE FRACTURED ROCK AQUIFER AT THE MONT-CERVIN HOUSING DEVELOPMENT, LAC-BEAUPORT, QUÉBEC

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ABSTRACT
The presence of nitrate and pathogenic micro-organisms in private wells of the Mont-Cervin housing development, Lac-Beauport, Québec, was identified in the area in 1995. Most of the residents use individual septic installations for their waste water treatment and disposal and private wells in the fractured roc aquifer as potable water supply. This development was built in the 1970's on small lots resulting in a high density of septic installations and a high volume of waste water discharge to the aquifer. The area is vulnerable to contamination due to discontinuous and relatively permeable sandy till overlying the fractured bedrock. This paper presents the hydrogeological context and the groundwater flow mechanisms affecting the contamination in private wells based on a characterization done in 2002 and 2003. Mass balance and numerical simulations of nitrate transport were used to better understand the presence of contaminants in the groundwater in order to propose aquifer management guidelines.

RÉSUMÉ
La présence de nitrates et de micro-organismes pathogènes provenant des installations septiques dans les puits du Mont-Cervin a été observée en 1995. Les résidents de ce secteur utilisent des installations septiques et possèdent des puits individuels au roc pour leurs besoins en eau potable. Le développement résidentiel date des années 1970 et est caractérisé par des lots de petites dimensions, ce qui résulte en une grande densité d'installations septiques et génèrent d'importants volumes d'eaux usées dans l'aquifère. Cet article présente les facteurs hydrogéologiques ainsi que les mécanismes d'écoulement qui affectent la présence de contaminants dans l'eau souterraine et les puits sur la base d'une caractérisation effectuée en 2002 et 2003. Un bilan de masse et un modèle numérique de transport des nitrates à l'échelle du Mont-Cervin ont été utilisés pour élaborer un modèle conceptuel de la dynamique d'écoulement de l'aquifère. Les résultats pourront aider à définir des règles pour la gestion du territoire et de la ressource en eau souterraine.

1. INTRODUCTION

The Mont-Cervin housing development is a case of human impact on groundwater quality by the use of septic installations. Mont-Cervin is part of the municipality of Lac-Beauport located 20 km north of Quebec City on the Laurentian (Figure 1). Residents use mostly septic tank soil-absorption systems for their wastewater disposal and private wells for their water needs. In Mont-Cervin, most of the houses were built in the 1970's on lot sizes often less than 1000 m^2 resulting in a very high density of septic installations (460 in 1.3 km^2). In addition, the fractured rock aquifer of the area is vulnerable to surface contamination as it is protected only by a thin and discontinuous layer of sandy till. As nitrate and micro-organisms indicating faecal origin were identified in previous studies (Municipality of Lac-Beauport, 1995), the potential for groundwater quality degradation is becoming a critical issue, not only concerning the resources preservation but also the health of residents. Municipal authorities are seeking a scientific basis to take actions on septic systems, well installations and land use planning.

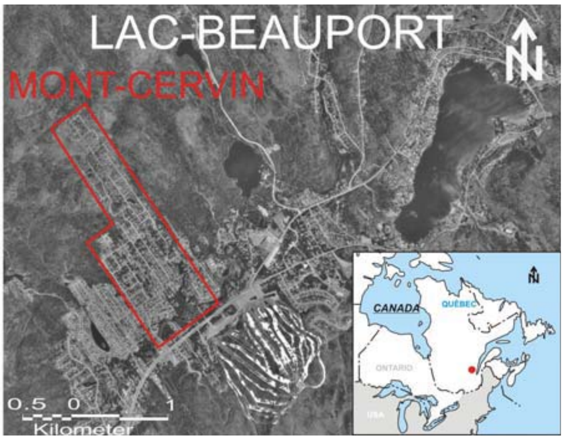


Figure 1 : Location of the Mont-Cervin housing development

This paper summarizes the present understanding of the hydrogeological context related to the impact of septic installations on the aquifer of Mont-Cervin. The presence of nitrate and pathogenic micro-organisms is used as an indicator of the human impact in assessing the effects of land development on groundwater quality. The 1995 initial results showed that nitrate concentrations were found above background value (0,01 mg/L) in most of the wells sampled and over 1 mg/L for more than 75% of the wells (Municipality of Lac-Beauport, 1995). For the Mont-Cervin area, bacteria were present in only 20% of the wells with no particular distribution pattern. The characterization campaign of 2002-2003 was intended to give an update on the groundwater quality and on the identification of hydrogeological factors contributing to the presence of contamination in private wells.

2. BACKGROUND INFORMATION

2.1 Topography

The study area is a housing development named Mont-Cervin located southwest of Lac-Beauport, Qc. It covers 1.3 km^2 and is located on a terrain with a 3% to 10% southward slope. The topography is typical of the Laurentians with elevation ranging from 200 m above sea level (masl) at the base to 340 (masl) at the top of the residential development (Figure 2).

2.2 Geology

The region is located at the southern limit of the Canadian Shield. Rock is mostly orthogneiss and paragneiss belonging to the Grenville province. The surficial geology consists predominantly of glacial sediments, mainly loose sandy till overlying bedrock. The till is generally thin and discontinuous (less than 1 m) in the upper part of the mountain while moderately thick (1 to 3 m) and getting continuous in the lower part where alluvial sand fills the center of the Lac-Beauport valley with a thickness reaching up to 25 m (Bolduc et al., 2001, SIH). The origin of the Quaternary sediments is essentially glacial. The sandy tills and sands are characterized by a relatively high permeability.

2.3 Hydrology

The Mont-Cervin area is surrounded on its eastern and western limits by small systems of lakes and creeks flowing toward the Jaune River located to the south. The north side constitutes a topographic high forming a water divide. Based on meteorological data from 1971 to 1998, the average precipitation in the region is 1300 mm/year (MENV, 2000). The mean value for the estimated recharge is 10% of the total precipitation and the minimal and maximal estimated values are respectively 5% and 15% of the total precipitation (Technorem, 2004).

3. METHODOLOGY

Field characterization work was carried out during the summers of 2002 and 2003. It was aimed at defining the geological and hydrogeological context of the area and water quality regarding nitrate, enterococcus and faecal coliform bacteria. Table 1 summarizes the main activities carried out during the field campaigns.

Table 1. Summary of the characterization program

Data review
Questionnaire for residents
Existing literature and reports review
In 107 private wells
Groundwater sampling
Measurement of in-situ physical properties
Water level measurements
Measurement of well casing length
Nitrate and bacteria analyses
In one multi-level well drilled in 2003
Slug test in open borehole
Multi-level water sampling (12) with packers
Packer tests for hydraulic conductivity profile
Installation of 4 level permanent piezometer
Composite water sample
Water level measurements
Fractures characterization on outcrops (20)
Strike and dip measurements

Nitrates mass balance and numerical simulations were used to better understand the groundwater flow and the migration of contaminant in the Mont-Cervin aquifer. These tools are also used for assessing the impact of the future housing development on the groundwater resources.

4. RESULTS

4.1 Hydrogeology

Figure 2 presents the piezometric map of the rock aquifer generated with the water level measurements done in 66 private wells during the field work of summer and fall 2002 and 2003. The map was interpolated and smoothed to simplify the flow pattern. The average depth to the water table is increasing with altitude and ranges from about 3 m to a maximum of 40 m at the highest elevation. The observed horizontal hydraulic gradient ranges from 0.02 to 0.06 m/m respectively for the low and high elevation areas. The general groundwater flow direction is southwards in an oblique flow coming from the forested area to the cast of Mont-Cervin.

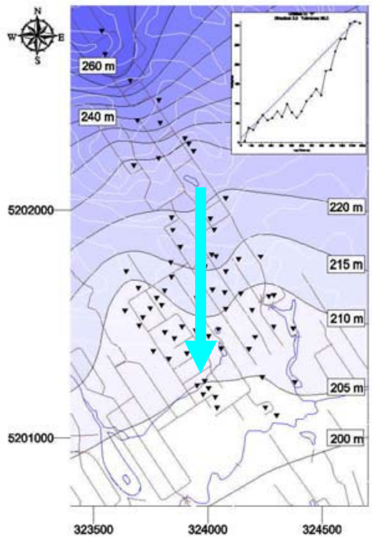


Figure 2. Piezometric map of the Mont-Cervin

4.2 Hydraulic properties of the rock aquifer

The regional aquifer is under unconfined conditions and is composed of a fractured Precambrian metamorphic rock.

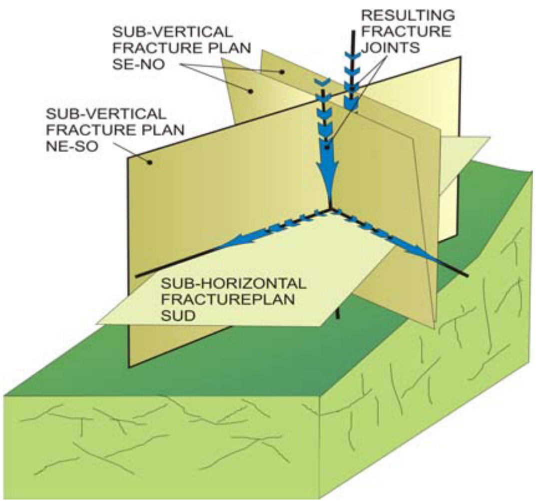


Figure 3. Principal fracture plans for Mont-Cervin

The uppermost part of the rock aquifer was found to be more permeable than the rock layers at greater depth in the formation. The hydraulic properties of the rock formation were investigated to better understand its effect on groundwater flow. Observations show a very irregular topography of the roc, partially hidden by quaternary sediments. Strike and dip were measured on 20 out-crops (Figure 3). Two sub-vertical fracture plans were identified and are relatively symmetrical to the natural topography and groundwater flow. One sub- horizontal plan of fractures also show a southward slope parallel to the Mont-Cervin, facilitating groundwater flow towards the base of Mont-Cervin. Intersections of these fracture plans may create sub-vertical preferential channels that can act as good hydraulic links between the top and lower layers of the aquifer.

A borehole, located in the middle of the housing development, was drilled to a depth of 65 m. The open borehole corresponds to the top of the rock aquifer. Packer tests were made in 29 intervals of 2 m allowing estimation of hydraulic conductivity ranging from 9.7×10^{-10} to 2.8×10^{-6} m/s. Figure 4 shows four different characteristic zones: the first zone is permeable fractured rock from top to 9.4 m depth, the lower zones are relatively less permeable and a particularly low hydraulic conductivity was estimated at 25 m corresponding to the beginning of the non altered granite.

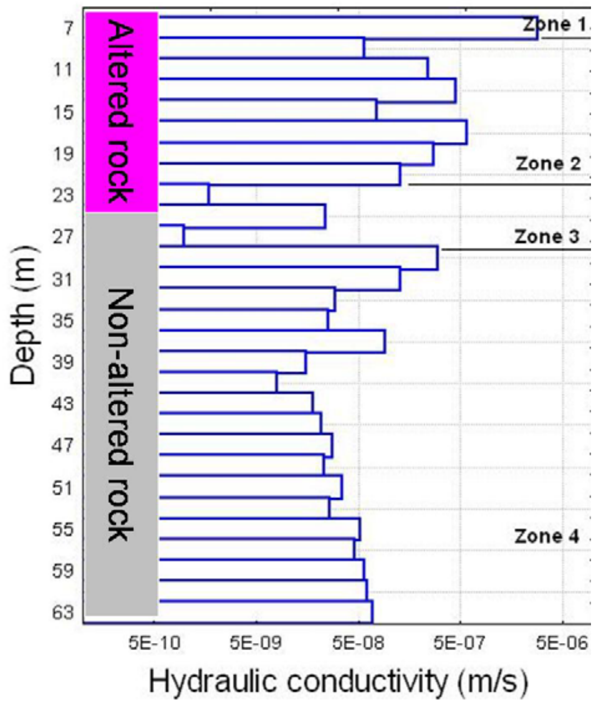


Figure 4. Hydraulic conductivity from packer tests (spacing of 2 m)

4.3 Groundwater quality

The groundwater quality of the Mont-Cervin area was determined from 107 samples collected in private wells in 2002 (56) and 2003 (51). To study the evolution of groundwater quality, the 2002 results were compared to the 92 results of the two sampling campaign of May (44) and September (48) 1995 also held in the same wells. All samples were analyzed for nitrate, enterococcus and faecal coliform bacteria and three samples for complete geochemical parameters (major ions and anions, etc.). In some areas, the pH of the groundwater tends to be slightly acidic with values under 6.5. Such groundwater is characteristic of a granite aquifer. The hardness ranges from 112 mg/L to 254 mg/L of $CaCO_3$ with high values of calcium and manganese that give the water a more incrusting tendency. Figure 5 presents the groundwater quality results for nitrate.

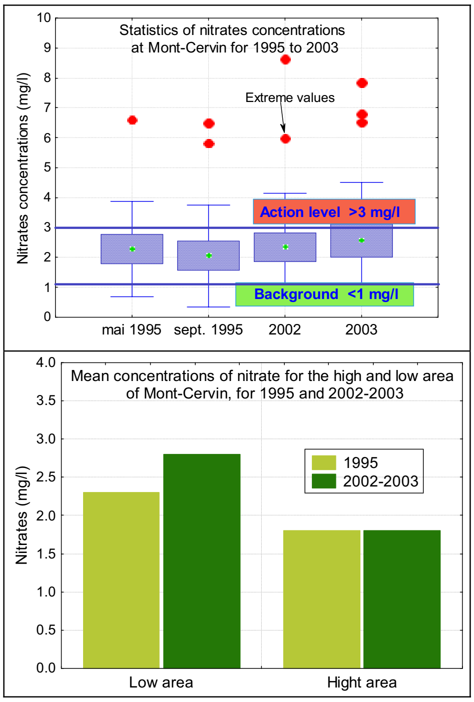


Figure 5. Statistics of nitrate concentrations in wells

Results shows that nitrate have been detected in most of the sampled wells but none over the 10 mg/L drinking water criteria (MENV, 2001). More than 70% of samples show concentrations higher than 1 mg/L (indicator of human activity) and 35% shows concentrations above 3 mg/L. The boxplot (Figure 5) shows that mean and extreme values for nitrate are higher for 2002-2003 than 1995. The histogram of the number (in %) of wells by classes of nitrate concentrations, also show an increase in higher values even if results are variable from one year to another. The histogram of nitrate concentrations for the low and high area of MC for 1995 and 2002-2003 is showing that nitrate concentrations are averaging 1 mg/L higher at the base than at the top of Mont-Cervin. That difference could be explained by two factors; 1) there are more septic tank installations, 2) the hydraulic gradient is 3 times lower at the base, allowing local and temporary accumulation of the contaminants. The results are also showing that values have only increased in the lower part of the Mont-Cervin. Another important finding is that the nitrate concentrations measured in the same wells sampled respectively in 1995 and 2002, are showing the same range of values over time with generally less than 1 mg/L difference (Figure 6). These results suggest that the mixing pattern of groundwater flow traveling by preferential fracture networks is constant over time and thus is playing an important role in the distribution of contaminant. In opposition, biological indicators do not show that type of correlation.

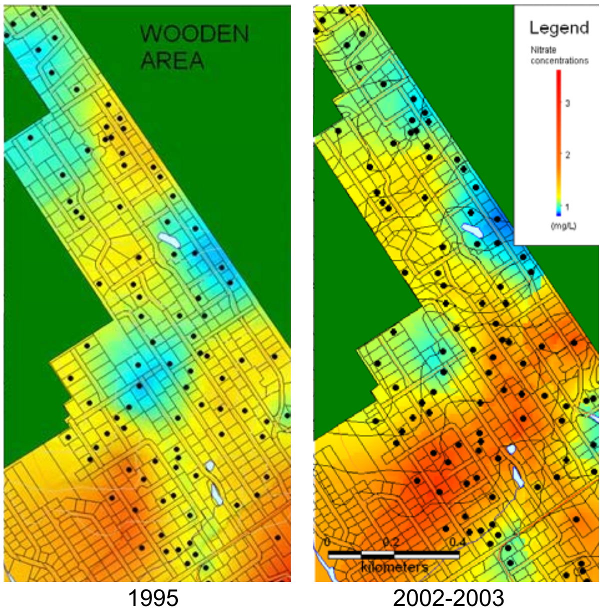


Figure 6. Interpolated nitrate concentrations for 1995 and 2002-2003 for the Mont-Cervin area

Even if the percentage of affected wells for Enterococcus was found to be in the same range of value for the sampling campaign of 1995 and 2002 with respectively 20% and 23% they do not affect the same wells. The presence of faecal coliform is also much more variable with values ranging from 2%, 4% and 5% for respectively May and September 1995 and 2002, while 2003 has shown no presence in any of the 51 sampled wells. Compared to nitrates, the transport and presence of pathogenic micro-organisms in wells seem to be more affected by local conditions of the aquifer, such as fracture openings. Local sources of contamination such as small pound and pet waste could also account as important contributors to the water quality degradation. In addition of these results, the sampling campaign in the 4 multi-level wells is demonstrating important trends in the nitrate concentrations with depth (Figure 7). Nitrate analyses are all showing lower concentration in the top level piezometer and increasing values with depth. The same trend is observed for the chlorides and other inorganic chemicals (not presented here). Also the presence of Enterococcus bacteria is detected in greater number in the top level of the rock but also in the three other piezometers, even 60 m deep. These results confirm (1) that the sub-surface water is in contact with the surface (precipitation), (2) surface waters are diluting the nitrate and other chemicals concentrations near the surface, (3) the presence of bacteria at the bottom of the well is showing that the fracture network allowed a high velocity flow in groundwater to greater depth, (4) the increased nitrate concentrations with depth suggest that the aquifer is affected by septic installations contamination to a certain and unknown extent.

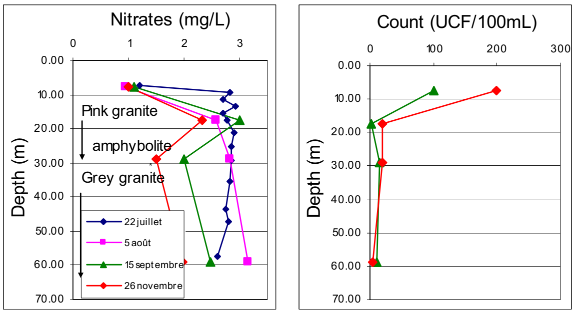


Figure 7. Nitrate and bacteria concentration vs depth in multi-level well

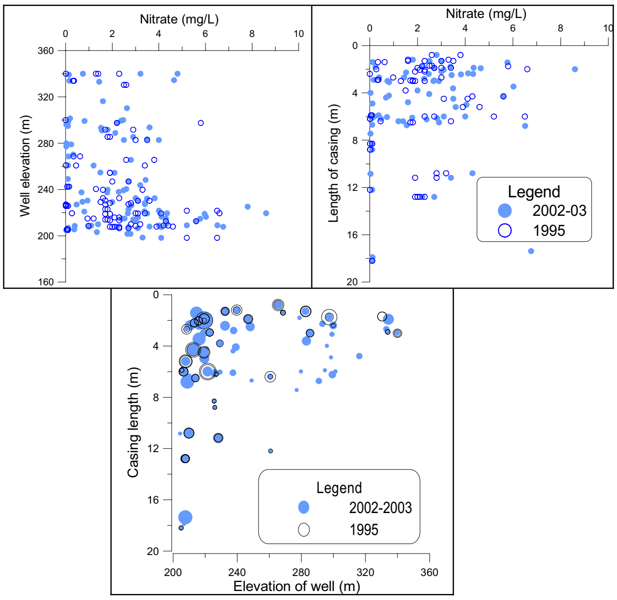


Figure 8. Nitrate concentrations vs. elevation and casing length

4.4 Analysis of factors related to wells conditions affecting the presence of contamination in well

Five hydrogeological factors related to well conditions were statistically (multiple regressions method) and graphically compared with nitrates and Enterococcus results as a possible contribution to their presence in wells. These factors are well elevation, casing length, water column length, water depth, and well depth. As an example of the analysis, Figure 8 is presenting the graphics of the elevation of the wells on Mont-Cervin and the casing length. The graphic of nitrates vs. the elevation is confirming the trend that there are higher concentrations at the base of Mont-Cervin. But the elevation strongly influences most of the other factors so their effect on the presence of contaminant in the wells becomes difficult to point out. The graphics of nitrates concentrations vs. casing length gives an example of that interaction as the casing length is correlated with the thickness of the surficial sediments and thus with the elevation of wells. The third graphic of Figure 8 present the nitrates concentrations as dot size vs. the elevation and the casing length. The graphic show that casing length does not seem to affect nitrate concentrations but confirm the trend with elevation.

Table 2 summarizes the results obtained for the 5 factors. Except for the position of the well, given by the elevation, no strong statistical correlation (given by [**-0.31**]) or even graphical trend can be observed between all other factor and the presence of contaminant in wells. The general conclusion from these results is that fracture networks have a strong influence on the presence of contaminant in wells by controlling the water flow entering wells more than any other factors related to well installations.

Table 2. Statistics results of contaminant vs. factors

Factors	Trend on NO_3	Trend on Ent.
Well elevation	Yes, negative trend (NT) [**-0.31**]	Yes, NT, higher number at the base
Casing length	No trend [**-0.29**]	No trend
Water column length	No trend [**-0.11**]	No trend
Water depth	Weak NT + 25 m	No trend
Well depth	No trend	No trend

5. MASS BALANCE MODEL

Mass balance calculations can be used as a simple tool to help better understand the effect of septic installations on the groundwater flow system of the aquifer (Lowe et al., 2002). Moreover, it can help in planning future land use. The method was adapted to the Mont-Cervin characteristics in order to reproduce actual concentrations of nitrate in groundwater. Figure 9 depicts the conceptual model of the groundwater flow for the Mont-Cervin area. The model assumes that the impact of septic installations on groundwater quality largely depends on the total volume of wastewater and the dynamics of the hydrological cycle, mainly the groundwater recharge. It also supposes that there is no denitrification process in the aquifer. Based on groundwater quality results, on hydrogeological characteristics (gradient and surficial sediment thickness) and urban setting (180 houses for the upper part and 280 for the lower part), the area was splited in two zones indicated as the upper and the lower area.

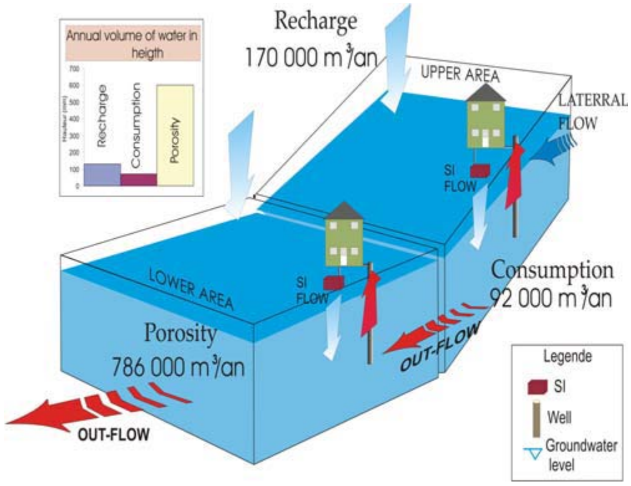


Figure 9. Conceptual model and annual water budget

Water consumption volume is estimated at 92 000 m^3/y (220 L/day/pers), while the volume of the annual recharge is 170 000 m^3/y (precipitation is 1.3 m/y for a Nitrate concentrations in the aquifer system are calculated on the basis of the theorical mass in nitrate producted by septic installations (2.25 kg/pers/an, Dome, 2003) added to the background mass in the aquifer and diluted to the groundwater available for mixing. The mixing volume is the sum of groundwater available in the rock matrix plus the recharge volume and the waste water flow from septic installations, assuming to be 90% of the water consumption (Dome, 2003) net infiltration of 10 % by an area of 1 310 000 m^2) and available water volume in the aquifer is 786 000 m^3/y assuming a theorical porosity of 1% (Domenico and Schwartz, 1990) and an aquifer thickness of 60 m. Based on these volumes, the consumption of water by residents represents more than 50% of the recharge and more than 10% of the volume in the pore matrix. Since the mixing of fluid in the matrix is not complete and most of the recharge occurs in spring time, it is realistic to estimate that waste water is avereging 10% of the water pumped by residents.

Table 4. Present the values that were used for the mass-balance calculation based on field and estimated theorical data;

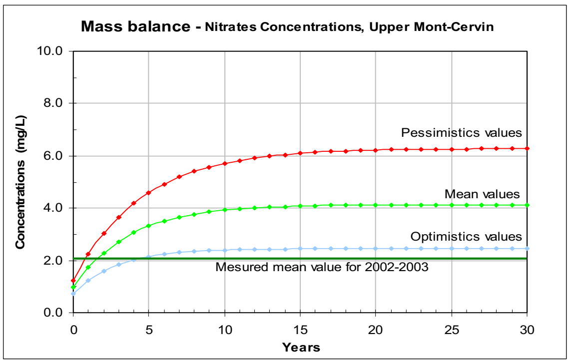
Parameters	**Range of possible value**		
	Pessimistic	Mean	Optimistic
Recharge (%)	5 %	10 %	15 %
Mass NO_3 (kg/y)	6	5	4
Sector	**Upper**	**Lower**	
Houses per area	180	280	
Area (m)	587 600	722 710	
Volume recharge (m^3)	76 388	93 952	
Tickness of aquifer (m)	60	60	
Volume of pore (m^3)	352 560	433 626	
Volume of wastewater produced	38 850	51 110	

Equation (1) represents mass balance calculation for the nitrate concentration of the upper and lower part of Mont-Cervin.

$$C_N = (M_{NIS} + M_{NBG} / V_R + V_P + V_{IS} + V_{Am} - V_S)*Df \qquad (1)$$

C_N = Nitrate concentrations in the aquifer
M_{NIS} = Nitrate mass from septic installations
M_{NBG} = Nitrate Mass in the background (aquifer)
V_R = Volume from recharge
V_P = Volume in the pores of the rock matrix
V_{IS} = Volume from septic installations
V_S = Volume flowing out of the system
V_{Am} = Volume from upper area (lower half of Mont-Cervin)
Df = Dilution factor

The equation is given by the total mass of nitrate divided by the total volume of water available for mixing. In addition, a correction factor (estimated at 50%) was used to represent dilution from lateral and subsurface water flow. For the lower area, the model is adding the flow volume and the mass of nitrates coming from the upper part of Mont-Cervin. Also, on the hypothesis of existing denitrification conditions in the septic tank (anaerobic environment rich in organic matter) the model allows the elimination of the nitrate pumped by the wells from the aquifer (Eastburn and Ritter, 1984, Chen and Harkint, 1998). Figure 10 presents the results of nitrate concentrations for the upper and lower part of Mont-Cervin. The calculation was iterated for a period of 30 years (1970 until today) in order to show the evolution of nitrate concentration with time.



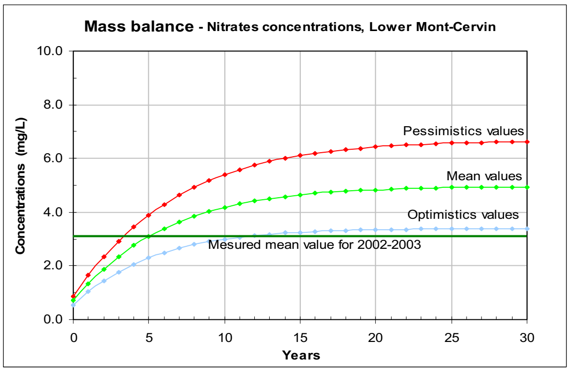


Figure 10. Mass balance of nitrate for upper and lower Mont-Cervin

The three curves, are presenting mean, optimistic and pessimistic nitrate concentrations values based on recharge and mass of nitrate from the septic installations. Calculation for both the upper and lower areas shows that the closest nitrate concentration to the mean field values for 2002-2003 are given with the optimistic value of recharge (higher at 15% of the total precipitation) and mass (least) of nitrate rejected by the septic installations (4 kg/house/y) (USEPA, 2002). The model reproduces the difference in concentration (1 mg/L) measured in the wells between the upper and lower part of Mont-Cervin. The calculation shows that nitrate concentrations are reaching a steady-state level after 15 years, which is mostly affected by the porosity value given to the roc matrix. The pumping of nitrified effluent in the groundwater remixed with septic tank effluent provides a needed denitrification service comparable to existing recirculating sand filter systems (Watershed Protection Techniques, 1995, USEPA, 2002). Septic installations are acting as a treatment system for the entire area. That assumption allows estimating that 200 kg is removed from the aquifer (transformed into N_2) every year at steady state conditions.

6. NUMERICAL SIMULATIONS

A detailed numerical model is currently being developed. The objectives of the model are to reproduce the measured concentrations of nitrates in the groundwater over the 30 years period of existence of the housing development of the Mont-Cervin in order to confirm the conceptual model. If satisfactory, the model will then be used to evaluate the impact of projected housing development in the surrounding areas actually covered with mixed forests. It is anticipated that changes in the groundwater flow could decrease the potential for diluting the outflow of wastewater disposal in the Mont-Cervin with a negative impact on groundwater quality.

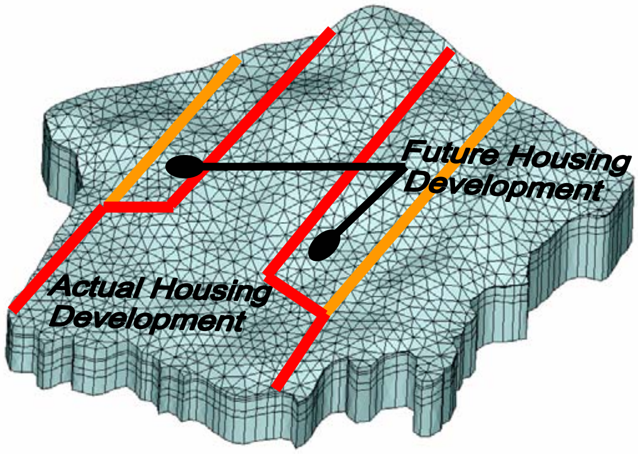


Figure 11. Representation of the domain and the mesh of the numerical model with the future developed areas

7. CONCLUSION

Based on the 2002-2003 field results, the following general observations can be drawn:

The sampled wells of Mont-Cervin in 2002 and 2003 show the presence of pathogenic micro organisms (20% presence in the) and nitrate (low area = 3.1 mg/L, high area= 2.1 mg/L).

There is a small increase (10%) of nitrate concentrations for 2002-2003 compared to 1995 results in the lower area of Mont-Cervin but a steady state situation for the upper area since 1995. But there was no increase observed in the presence of micro-organisms.

The fractured roc aquifer is vulnerable to surface contamination, mostly were surficial deposit are small or inexistent and also because of very altered and fractured rock at the surface (hydraulic conductivity at 10^{-6} m/s). Results on groundwater quality samples from the top piezometer of the multi-level well are showing less nitrate and more bacteria suggesting that the sub-surface water is in close contact with the surface (precipitation) and surface waters are diluting the nitrate and other chemicals concentrations near the surface while facilitating micro-organism transport. The presence of bacteria in the lower piezometer is showing that the fracture network allowed a relatively fast circulation of groundwater to greater depth. The nitrate concentrations at greater depth are averaging the mean nitrate concentrations measured in the wells in 2002 and 2003 (2.3 mg/L and 2.6 mg/L). These results suggest that the aquifer is affected by septic installations waste water to a certain and unknown depth.

Hydrogeological factors related to well installations are in complex interaction with one another making it difficult to find any correlations, except for the elevation factor showing negative trend with nitrates concentrations. Other factors such as casing length and length of water column in wells show no trend with the presence of contaminants in wells.

-Based on similar groundwater quality results in the same wells for the 1995 and 2002, the concentration of nitrate in wells maybe controlled by steady flow pattern in the fractured network of the rock. In opposition, the presence of bacteria does not follow any particular trend, suggesting that they are more affected by hydrogeological and possibly meteorological conditions. It is also possible that local sources as animal waste are important contributors to the presence of pathogenic micro-organisms in groundwater. Winter sampling would probably provide interesting clues on that issue.

Residents are using a great proportion of the groundwater resources available in the aquifer system. The water budget for the area of Mont-Cervin show that water consumption and rejection from septic installations represent 50% of the recharge volume and 10% of the available volume in the roc matrix. The fast renewing of groundwater within the aquifer and the low capacity of the aquifer to accumulate contaminants probably help in keeping the nitrate and other inorganic contaminants in relatively low concentrations.

Mass balance calculation of nitrate in the aquifer show that nitrate concentration should be at steady-state at the present time. Therefore, the level of contaminant in the aquifer should not increase in the future as long as the hydrogeological conditions and the sources of contamination are not changing.

Numerical simulation will be use to foresee the contaminant evolution of nitrate concentrations based on various urbanization scenarios of the actual forested areas surrounding the residential development. It is suspected that these areas are playing an important role in the contribution of fresh water to the aquifer of Mont-Cervin.

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9. AKNOWLEDGEMENT

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