Groundwater impact assessment of infiltration structures for urban drainage control

Evaluation des impacts des structures d'infiltration sur les eaux souterrraines

Dr Alexandra R Finotti

University of Caxias do Sul
Department of Chemical Engineering
Av. Francisco Getúlio Vargas, 1130. Caxias do Sul – RS - Brazil. 95070-560
(arfinott@ucs.br)

RESUME

Nous avons proposé dans ce travail le développement des protocoles pour évaluer les impacts quali-quantitatifs des structures d'infiltration sur les aquifères. Des protocoles ont été créés considérant le profil de sol en trois compartiments : structure d'infiltration, sol partiellement saturé et aquifère. Pour chaque compartiment nous aurons besoin d'un modèle ou d'une équation qui calculent le flux de sortie au prochain compartiment. Nous testons des équations simples et des logiciels populaires et gratuits d'écoulement et transport de polluents. Le premier logiciel testé était Chemflow. Sa réponse a été considérée bonne pour la prévision de l'écoulement pour un bassin d'infiltration avec les niveaux d'eau variables. Nous n'avons pas encore testé le transport de contaminant. Nous avons commencé la définition des catégories d'impact qui seront améliorées avec l'évolution des protocoles.

ABSTRACT

We have proposed in this work the development of protocols to evaluate quali quantitative impacts of infiltration structures in aquifer. Protocols were created considering soil profile in three compartments: infiltration structure, vadose zone and aquifer. For each compartment we will need a model or an equation that calculate the outlet flux to the next compartment. We are testing both simplifying equations and popular softwares of flow and transport. The first was Chemflow. Its response was judged adequate for flow prediction above a retention basin with varying levels of water. The contaminant transport has not being tested yet. We have started the definition of impact categories that will be improved as the protocols project proceeds.

KEYWORDS

Alternative techniques, Groudwater contamination, Impact assessment, Infiltration.

1 INTRODUTION

The increasing urbanization in the last few decades has aggravated urban drainage problems in the Brazilian cities. One of the water cycle stages that more suffer influence is infiltration in function of land covering by impervious surfaces that normally follows the urbanization process. As infiltration is the basis for underground recharge, also the aquifer levels can be modified by the process.

Beyond the quantitative alteration of the hydrological cycle, the urbanization can promote alteration in aquifers water quality. The infiltration water in urban space has its quality modified in function of the washing effect that it promotes when running in urban areas. If these waters infiltrate they can contaminate underground waters. As infiltration is reduced in the urban areas the mayor concern, in terms of water quality, falls on the drainage control structures that promote forced infiltration on soils.

As many of the alternative techniques in urban draining stimulate infiltration for runoff peaks control, the impact assessment may be an important tool for evaluation of water quality maintenance or recuperation. In recent years they had started to be published works that deal with quality and quantity problems of infiltration in urban drainage (Legret et al, 1999; Barraud et al, 1999; Alfakih et al, 1999, Gromaire-Mertz et al. 1999; Jacopin et al. 1999).

Some studies had evaluated the contaminant percolation in structures that were installed many years ago. Others, as in Legret et al (1999) work, had evaluated the aspect of the contamination for heavy metals in experiments in laboratory and then used the mathematical model of transport LEACHM for extrapolating results to more than 50 years. He evaluated porous pavements as urban drainage control structure. Soil samples below the structure were analyzed and presented lead, copper and zinc within. These metals presented fast reduction of concentration in relation to the depth and reached 35cm deep. Cadmium was also analyzed and presented a lesser reduction. It was detected until 70cm deep. On the other hand the authors warn that for such type of structure, infiltration does not have to be the only form for precipitation volumes withdrawal. In case of very high aquifer water level the structure performance can be harmed and the contamination risk increases. They observe the importance of soil retention capacity evaluation before the control alternative selection.

Barraud et al (1999) evaluated the impact of forced infiltration of urban draining in underground water by monitoring two control structures: a pond and a rectangular chamber excavated for infiltration. The quality of the percolating water and soil samples had been evaluated. Soil in place presented high hydraulic conductivity (10^{-2} m/s). Soil samples presented high concentrations of metal and hydrocarbons in the first centimeters, with concentrations decreasing quickly with the depth. In long term soil can be contaminated in a 1m radius of the structure but with concentrations bellow the standard of the German norm for agricultural soils. The impact in underground waters can be considered low, but in monitoring wells they observed increase of the metal concentrations. These results demonstrated that soil retention was not enough to prevent contaminant migration to the aquifer. The contamination was motivated by the proximity of underground level to the base of the structure and the high water conductivity for that soil. This study demonstrate the necessity of previous evaluation of the aquifer and soil parameters since these can established very favorable conditions of infiltration and unfavorable conditions for retention and purification.

In this work we propose the development of protocols for impacts evaluation of structures of urban drainage control pose to groundwater. The protocol will focus on quality and quantity impacts for those structures that force soil infiltration.

The objective of these protocols is to previously subsidize the planning designer or to aide the choice of technique in function of the importance of its impact on underground water resources. If the impact is above certain value the designer is supposed to consider other alternative.

This kind of protocol may be a very useful tool to support decision in the design phase. There are lack of tools with this characteristic (Tucci et al. 2003) and when our project is concluded we may have contributed to the development of structured process for decisions in the urban area.

2 METHODS

The protocols design started with a conceptual model to state which phenomena are involved and how they are integrated. We decided to separate quantitative and qualitative impacts in two different protocols. After, the protocols followed three steps. First, the parameters and project methodology that are commonly used for projecting the selected structures of urban drainage control were analyzed. The project methodologies had been evaluated for porous pavement, infiltration basins, infiltration wells, trenches, and ponds / wetlands. On the basis of these analyses is possible to identify the main parameters to be considered in the protocols and to evaluate as its variation can influence, increase or reduce impacts. The second step is evaluation and section of mathematical models of flow and transport. We have evaluated simple equations and the use of traditional softwares in order to verify its applicability in calculation volume flows and contaminant concentration to analyze impact of control structures. Models selected for study are those traditional ones and that are free for use. Analysis are based on the applicability to the qualitative and quantitative propagation of flow and contaminant migration to allow the impact evaluation on underground waters. The previously selected models had been Vleach, Chemflo2000, Leachm, Mofat, Hydrus and Femwater/Lewaste. Finally the major aspects of the structure and its performance are evaluated in an impact analyzes basis.

We have finished the first part of the project. The most common methods for structure design are compiled. Most of these methods focus only in evaluation of velocity of infiltration. In respect to quality the only parameter that is identified in the methodologies analyzed is distance to water table. We are verifying which parameter can be added to the protocol to allow impact evaluation. The retention capacity of the soil is the first considered. But we have to indicate the analytical form for evaluating the parameter that can be easily adopted by the designer. A list of parameter will be evaluated until the end of the work and the most suitable will be selected to the protocol. The model evaluation has also being started. Model Chemflo is the first one tested and it was considered adequate in flux propagation but have not being tested yet for contamination.

3 RESULTS AND DISCUSSION

3.1 Conceptual model for the protocols

Protocols were designed based in the problem physical analysis in the system: structure-soil-aquifer. We decided to divide it in three compartments: the infiltration structure for drainage control, the soil non saturated zone and the aquifer. And we also have four levels of analyses for these compartments: data requirements, equation, results of equation application and impact criteria for analysis. Conceptual model were divided for quantitative and qualitative impacts shown in Figures 01 and 02 respectively. Its important to note that to evaluate concentration evolution in soil profile is necessary to evaluate in first its flow. That's why the qualitative protocol must be preceded for quantitative one.

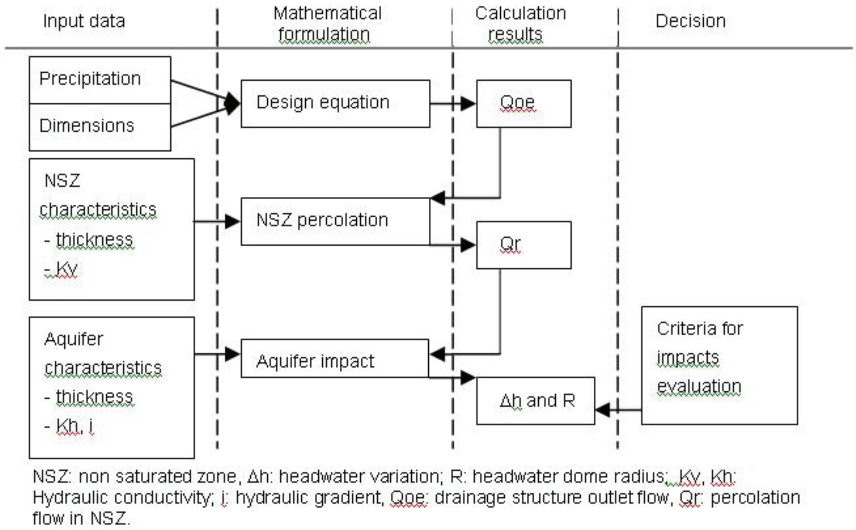

Figure 01. Quantitative protocol

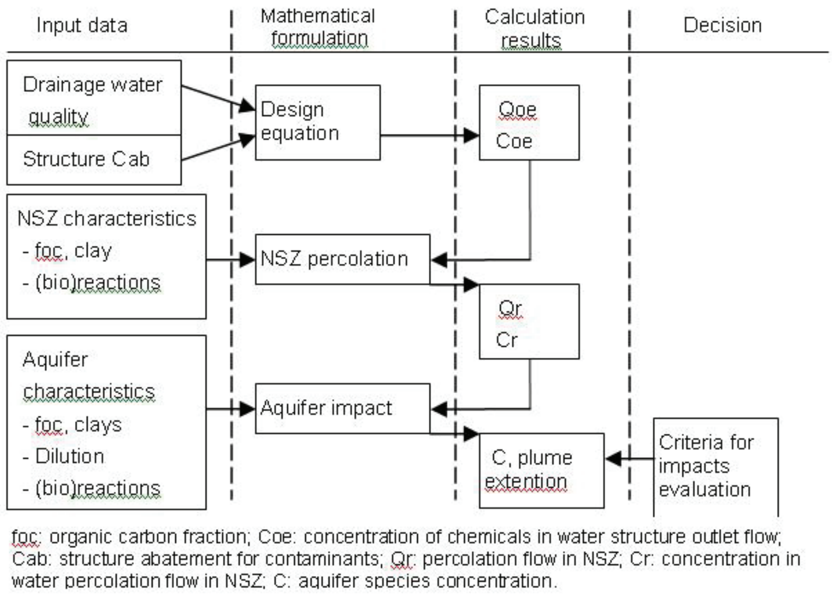

Figure 02. Qualitative protocol

In quantitative protocol the first level is the infiltration structure itself. The input parameters are the capacity of the structure such as project flux and its dimensions.

The output parameter is the infiltration volume (or flux) throughout the structure. This flux is the input parameter for soil non saturated percolation. The output of this compartment is the effective aquifer recharge that is the input parameter to the third compartment, the aquifer. The output for the aquifer is the water level elevation

The same procedure is used in the qualitative protocol, but the focus are the contaminant concentrations associated to fluxes. In the structure compartment its necessary to evaluate the contaminant abatement. In the vadose zone percolation two characteristics of soil are very important in transport: the organic carbon fraction and the fraction of clays and also the capacity for supporting reactions or bioreactions. Which are also important in the aquifer.

3.1.1 Infiltration structures for drainage control – design parameters

The most common project parameters for drainage structures that promote infiltrations were obtained from bibliographical review. The parameters are shown in Table 01.

Equation that calculates outflow from drainage structures $Q_s = \alpha . q_{as} S$

Qs: structure outflow (m^3/s);
α: security coefficient to accounts for clogging;
q_{as}: infiltration capacity by surface unity ($m^3/s/m^2$)
S – infiltrating surface (m^2)

Drainage Structure	Infiltration capacity (q_{as})	Surface evaluation
Porous pavements	First approach by hydraulic conductivity	Infiltrating surface above porous pavement.
Infiltration basins	First approach by hydraulic conductivity	Infiltration surface in base and laterals (m^2). Depends on basin water level
Infiltration wells	$q_{as} = \frac{V_{p75-25}}{a_{p50} . t_{p75-25}}$ V_{p75-25}: water volume between 75 e 25% of levels during slug test; a_{p50}: surface inside well considering 50% of test level including the base area; t_{p75-25}: time level takes to vary from 75 to 25% high.	Consider only the infiltration capacity of laterals. These value is taken from S_L to $0,5S_L$ in accordance with operating criteria, maintenance frequency and drainage water quality (Azzout et al., 1994) S_L: lateral surface.
Trenches	Depends on water level in trench. First approach, in case of deep water level, can be the hydraulic conductivity considering hydraulic gradient equals 1.	Infiltration by laterals and base. It is function of operating criteria, maintenance frequency and drainage water quality. Varies from $0,75(S_L+S_b)$ to $0,33.S_L$ (Azzout et al., 1994). S_b: base surface.
Ponds / wetlands		Infiltration surface corresponding to maximum capacity of pond or wetland. Consider horizontal projection.

Table 01. Design parameters for infiltration drainage structures (adapted from Azzout et al. 1994)

3.1.2 Percolation in non saturated zone

Evaluating flow in non saturated zone is a complex task specially for hydraulic conductivity variation with water content (Le Roch, 19991; Chocat, 1997; Chocat et al, 2001; Silveira et al. 2001). During drainage structure operation many intervals of infiltration and dry periods alternates and water content varies enormously. Meanwhile it is possible to adopt some simplifying approaches or apply traditional software of flux and transport in vadose zone.

A simplifying approach is to consider a water balance to the non saturated soil as a reservoir. This approach was implemented by Morin et al. (1995) in software CEQUEAU module for water balance in vadose zone. This approach was considered by Bernard-Valette (2000) and results were consistent for her proposes. The conceptual model considers the non saturated soil zone as a reservoir and its water levels. The inlet flows are infiltration and the outlets are evaporation, surface flow and deep percolation to aquifer.

Water percolation through non saturated zone and outflow flux from this compartment is traditionally modeled by Richard's equation. Appling this equation is difficult for the amount of data needed. There are some simplifying approaches that allow calculating the aquifer effective recharge flow. For example, Bernard-Valette (2000) has proposed that propagation through NSZ should be modeled by a sequence of attenuation reservoirs. We are going to test the application of this water balance and simultaneous reservoir approach.

3.1.3 Quantitative aquifer impacts

Three situations can take place above an infiltration structure. Just after infiltration initiate the evolution of a wetting front develops. When aquifer level is deep this is the situation to be considered. After there is dome formation in aquifer in response to a local aquifer level elevation. This situation is common when infiltration is not permanent and the aquifer is not so deep. The dome importance is more pronounced as smaller is the distance from aquifer top to structure base. In this situation the dome creates a region of resistance to flux.

It is possible to apply some equations developed to calculate the dome high. These equations are summarized in Detay (1997). It's the solution of two dimension equation and is dependent of structure shape. The equation to infiltration basins of circular shape were proposed by Warner et al. (1989).

$$H_0 = \frac{Q.t}{w_d}\left(1 - \exp(-u) + u.W\left(\frac{1}{u}\right)\right); \qquad u = \frac{a^2}{4.\alpha.t}$$

Where: H_0: high of dome centerline; W(u): well function; α: transmissivity =T/w_d; a: infiltration basin radius; t: time since dome formation initiates

After some time steps, without new infiltration event, the dome dissipates. The dissipation takes more time as minor is the aquifer hydraulic conductivity, in this situation, also dome formation is more quickly and higher is its levels in centerline.

To other infiltration basins shapes there is the work of Morel-Seytoux et al. (1988) where he evaluates elongated basins in comparision to circular ones. How more elongated more efficient is the structure in percolating higher volumes and maior volumes of effective aquifer recharge. None of the works evaluate the dome high to other structures of infiltration. So, as this approach is simpler this studies may be needed in order to apply the same methodology of calculating to the protocols.

3.1.4 Qualitative impacts

In this section of the work we analyze the applicability of existing software that calculates flux and transport of contaminants in the vadose zone. If we conclude that none of this software are applicable to our problem situation the development of a new program will be needed. Otherwise, the difficulties in modeling this kind of problem, especially because the entries are not constant, and there are variations in fluxes and concentrations are known. But it is important to remember our goals. The protocols must be of easy application and maybe the details are not necessary neither desirable. The same considerations that Kolsky and Butler (2002) have done to the development of performance indicators are valid to our protocols. More than very accurate response, the performance indicators have to aid in decision processes. The same is expected to the protocols. They most be useful in the pre-design phase and must be understood as guide to impact evaluation.

The softwares that had being analyzed are the following.

VLEACH is a one-dimensional, finite difference model for making preliminary assessments of the effects on ground water from the leaching of volatile, sorbed contaminants through the vadose zone.

CHEMFLO-2000: Allows water movement and transport simulation in the vadose zone considering some transformation reactions of contaminants. One of major problems in vadose zone simulation is the variation of heads above soil or contour condition. The program considers the possibility of falling head witch is very suitable for some structures such as infiltration basins. Support for a new falling head boundary condition representing the infiltration of water into a flooded soil covered with a specified initial depth of water. The water potential at the surface decreases as water enters the soil. Infiltration ends when the water on the surface has entered the soil. The definitions of contour conditions in soil surface as in aquifer contact are adjustable what makes model more dynamic and more cases can be simulated.

MOFAT: A two-dimensional, finite element model for simulating coupled multiphase flow and multi-component transport in planar or radically symmetric vertical sections. MOFAT evaluates flow and transport for water, nonaqueous phase liquid (NAPL), and gas. The program also can be used when gas and/or NAPL phases are absent in part or all of the domain.

HYDRUS Simulates water flow and solute transport in a two-dimensional variably-saturated medium.

FEMWATER/LEWASTE three-dimensional finite element model of water flow through saturated-unsaturated media and three-dimensional Lagrangian-Eulerian finite element model of waste transport through saturated-unsaturated media (3DLEWASTE) are related and can be used together.

3.1.5 Impacts evaluation criteria

In order to evaluate impacts of infiltration structures we propose the development of a matrix that establishes ranges to each variable considered and a system of punctuation. The final punctuation achieved for each structure will guide the user in the adoption of alternative or rejection. Intervals for each variable will be created when the modeling phase is terminated and validated with a number of case studies.

As a first approach we have selected the following categories of impact and variables:

a) Distance from structure bottom and aquifer top. This distance must be compared with infiltration dome calculation. This criteria influences both structure performance and risk of aquifer contamination.

b) The soil and aquifer hydraulic conductivity acts in ameliorating the structure performance but augment the risk of aquifer contamination. The protocols should allow designer to find if the structure are suitable for the range of conductivities found in place

c) Structure shape also may impacts performance and contamination risk.

d) Structure, soil and aquifer capacity of contaminant retention.

e) Clogging and its influence in structure performance and pollution retention.

Other criteria may be considered as the protocols design proceeds.

4 CONCLUSION

We have proposed the development of protocols to evaluate impacts of infiltration structures in aquifer both quail in a quali and quantitative manner. We have until now developed a conceptual model for the protocols that divide soil profile in three compartments: infiltration structure, vadose zone and aquifer. For each compartment we will need a model or an equation that from an inlet flux calculate the outlet to the next compartment. We are testing both simplifying equations and popular softwares of flow and transport. Software that we have already tested is Chemflow. Its response was judged adequate for flow prediction above in an retention basin with varying levels of water. The contaminant transport has not being tested yet. We have started the definition of impact categories that will be improved as the protocols project proceeds.

LIST OF REFERENCES

Azzout, Y. Barraud, S. Cres, F. N. & Alfakih, E. Techniques alternatives en assainissement pluvial: choix, conception, realisation et entretien. Paris: Technique et Documentation – Lavoisier, 1994.

Barraud, S.; Gautier, A.; Bardin, J. P.; & Riou, V. The impact of intentional stormwater infiltration on soil and groundwater. Water Science & Technology. v. 39, n. 2, pp. 185-192. 1999.

Bernad-Valette, N. Simulation des impacts sur les eaux souterraines de l'infiltration des eaux pluviales en milieu urbanise. These Doctorat. INSA – Lyon, 2000.

Chocat, B.; Krebs, P.; Marsalek, J.; Rauch, W.; & Schilling, W. urban drainage redefined: from stormwater removal to integrated management. Water Science & Technology. v. 43, n. 5, pp. 61-68. Great Britain: Elsevier, 2001.

Detay, M. La gestin active des aquefères. Paris: Masson, 1997.

Gromaire-Mertz, M. C. Garnaud, S. Gonzalez, A & Chebbo, G. Characterisation for urban runoff pollution in Paris. Water Science & Technology. v. 39, n. 2, pp. 1-8. 1999.

Jacopin, C.; Bertrand-Krajewski, J. L. & Desbordes, M. Characterisation and settling of solids in an open, grassed, stormwater sewer network detention basin. Water Science & Technology. v. 39, n. 2, pp. 135-144. 1999.

Kolsky, P. e Butler, D. Performance indicators for urban storm drainage in developing countries. Urban Water, n. 4, p. 137-144. 2002.

Le Roch, F. Risques de contamination des nappes souteraines par infiltration des eaux pluviales urbaines. Synthese des conaissances. Rennes : Ecole Nationale de la Santé Publique. 1991.

Legret, M.; Nicollet, M.; Miloda, P.; Colandini, V. & Raimbault, G. Simulation of heavy metal pollution from stormwater infiltration through a porous pavement with reservoir structure. Water Science & Technology. v. 39, n. 2, pp. 119-125. 1999.

Morel-Seytoux, H. J. And Miracapillo, C. Prediction of infiltration, mound development and aquifer recharge from a spreading basin or an intermitent stream, Hydrowar Reports Division, 1988.

Morin, G. & Paquet, p. Le modèle de simulation de quantité et de qualité CEQUEAU, guide de l'utilasateur. InRS-Eau, 1995.

Silveira, A. E Goldenfum, J. Urban Drainage control measures. In: Tucci, C. (org.) Urban drainage in specific climates. Paris: Unesco, 2001.

Tucci, C. & Bertoni, J. (org). Inundações urbanas na América Latina.Porto Alegre: ABRH, 2003.

Warner, J. w; Molden, D; Chehata, M. and Sunada, D. K. Mathematical anlysis of artificial recharge from basins. Water Resources Bulletin, 25, 2, 401-411, 1989.