Department of Geotechnical Engineering & GeoSciences

TECHNICAL UNIVERSITY OF CATALONIA (UPC)

Ph.D. Thesis

Integrated Modelling of Clogging Processes in Artificial Groundwater Recharge

ALFREDO PÉREZ-PARICIO

Advisor: JESÚS CARRERA

Barcelona, SPAIN

Submitted: November 2000

Defended: May 2001

SUMMARY

Artificial Recharge of groundwater is an extremely powerful technique to optimise the management of water resources. In order to eliminate sceptical misconceptions concerning its applicability to numerous situations, it is essential to gain insight into the fundamental quantitative concepts. A critical point is the minimisation of clogging of the recharge device. Given the extraordinary importance of this problem, an intensive bibliographic research was conducted to determine the basic processes underlying the clogging of recharge plants. This, in combination with technological information supplied by Artificial Recharge operators, allowed to propose a conceptual mathematical model that could integrate the main processes. Attachment of suspended solids carried by recharge water, mineral precipitation, bacterial growth, gas binding and compaction of the upper soil layer were found to be determinant in clogging development. Based on existing investigation codes, such model was implemented into a three-dimensional finite element code that is able to cope with the referred mechanisms. The code was applied to three laboratory cases and to one field experiment in order to assess the validity of the adopted framework.

This thesis includes the main concepts of the model, its theoretical background, numerical implementation and the application to the referred cases. The variety of simulated conditions and the results achieved with the model confirm that the code can reproduce successfully a wide range of clogging problems, including surface (basins) and deep (wells) systems, vertical and radial flow, multiphase transport and other options. This demonstrates the usefulness of the code to integrate data which are completely different in nature. In spite of the limitations inherent to all mathematical formulations, integrated modelling provides quantitative estimates of the clogging potential. Consequently, can be considered as a basic tool for design and management of recharge plants, and, eventually, for predictive purposes.

RESUMEN

La Recarga Artificial de acuíferos es una técnica extremadamente poderosa para optimizar la gestión de los recursos hídricos. De cara a eliminar actitudes escépticas respecto a su aplicabilidad en numerosas situaciones, es esencial adquirir más conocimientos sobre los conceptos cuantitativos más importantes. Un tema crítico es el de la minimización de la colmatación en dispositivos de recarga. Dada la extraordinaria importancia de este problema, se efectuó una intensa búsqueda bibliográfica que permitiera determinar los procesos básicos que tienen lugar en la colmatación de plantas de recarga. Esto, junto con la información de tipo tecnológico suministrada por gestores de plantas de recarga, ha permitido proponer un modelo matemático conceptual que integra los procesos principales: retención de partículas en suspensión en el agua de recarga, precipitación de minerales, crecimiento bacteriano, generación de gas y compactación. Con la ayuda de códigos ya existentes, dicho modelo fue posteriormente incorporado en un programa de elementos finitos tridimensional que es capaz de tratar los cinco procesos citados. El programa ha sido aplicado a tres casos de laboratorio y a un experimento de campo con el fin de establecer la validez del marco conceptual adoptado.

Esta tesis describe los aspectos principales del modelo, sus fundamentos teóricos, la implementación numérica y la aplicación a los ejemplos citados. La variedad de condiciones simuladas y los resultados logrados confirman que el programa puede reproducir de forma satisfactoria una amplia gama de problemas de colmatación, entre las que se incluyen sistemas superficiales (balsas) y profundos (pozos), flujo radial y vertical, transporte reactivo multicomponente, y otros. Esto demuestra la utilidad del programa para integrar datos de naturaleza completamente diferente. A pesar de las limitaciones inherentes a toda formulación matemática, la modelación integrada proporciona estimaciones cuantitativas del potencial colmatante. Por consiguiente, puede ser considerada como una herramienta básica de cara al diseño y gestión de plantas de recarga y, eventualmente, de cara a la predicción.

RESUM

La Recàrrega Artificial d'aqüífers és una tècnica extremadamente poderosa per optimitzar la gestió dels recursos hídrics. De cara a eliminar actituds escèptiques respecte a la seva aplicabilitat en nombroses situacions, és essencial adquirir més coneixements sobre els conceptes quantitatius més importants. Un tema crític és el de la minimització de la colmatació en dispositius de recàrrega. Atesa la extraòrdinaria importància d'aquest problema, es va efectuar una intensa recerca bibliogràfica que permetés determinar els processos bàsics que tenen lloc en la colmatació de plantes de recàrrega. Això, juntament amb la informació de tipus tecnològic subministrada per gestors de plantes de recàrrega, ha permès proposar un model matemàtic conceptual que integra els processos principals: retenció de partícules en suspensió portades per l'aigua de recàrrega, precipitació de minerals, creixement bacterià, generació de gas y compactació. Amb l'ajuda dels codis ja existents, l'esmentat model fou posteriorment incorporat a un programa d'elements finits tridimensionals que és capaç de tractar els cinc processos citats. El programa ha estat aplicat a tres casos de laboratori i a un experiment de camp amb el fi d'establir la validesa del marc conceptual adoptat.

Aquesta tesi descriu els aspectes principals del model, els seus fonaments teòrics, la implementació numèrica i l'aplicació als exemples citats. La varietat de condicions simulades i els resultats aconseguits confirmen que el programa pot reproduir de forma satisfactòria una ampli ventall de problemes de colmatació, entre les quals s'inclouen sistemes superficials (bassas) i profunds (pous), flux radial i vertical, transport reactiu multicomponent, i d'altres. Això demostra la utilitat del programa per integrar dades de naturalesa completament diferente. A pesar de les limitacions inherents a tota formulació matemàtica, la modelació integrada proporciona estimacions quantitatives del potencial colmatant. Conseqüentment, pot ser considerada com a una eina bàsica per al disseny i gestió de plantes de recàrrega i, eventualment, amb un fi predictiu.

ACKNOWLEDGEMENTS

I am grateful to my supervisor, Jesús Carrera, for teaching me how to face the problems with a more adequate attitude and for giving me an opportunity to grow up both personally and intellectually, in spite of (or thanks, in part, to) our discussions.

The European Union funded most of my research through the project on Artificial Recharge of Groundwater (contract ENV4-CT95-0071). This project was a magnificent opportunity to visit other countries in Europe and to learn from our colleagues in the Netherlands (Pieter J. Stuyfzand, Jos H. Peters), Germany (Uwe Schöttler, Thilo Hofmann), Sweden (Cristina Frycklund) and Denmark (a lot of them). The Spanish Government also funded part of our field research in Cornellà (Barcelona) through a special grant (Solicitud de ayuda para acciones especiales – Programa Nacional de Recursos Hídricos). The Cornellà plant is one of the oldest Aquifer-Storage-and-Recovery [ASR] schemes in the world, as it has been operating since 1969.

I would like to thank Peter Dillon (Centre for Groundwater Studies, CGS, Adelaide) too, because he contributed to my work and enhanced my interest about Artificial Recharge. Paul Pavelic deserves a special mention, because as well as helping my “scientific production” he helped me to live one of the most interesting experiences in my live: a 6-month stay in Adelaide, Oz, Down Under. In this regard, the CGS (Australia) and the Generalitat de Catalunya [Spain] were responsible for the economical support. Stephanie Rinck-Pfeiffer, Craig Simmons and Thomas Nyholm were also very important in Oz.

Mario Lluria (Salt River Project, SRP, Phoenix, Arizona) is also in my heart, not only for his personal and technological support but because of his (contagious) enthusiasm. It has been a pleasure for Lurdes and me to share good times with him in Arizona, the State that corroborates that Artificial Recharge is not only possible but necessary in arid and semi-arid beautiful countries.

I would like to thank too the Departament d’Enginyeria del Terreny, Cartogràfica i Geofísica (*Department of Geotechnical Engineering & GeoSciences*) for hosting me for so many years. Of course, the most important “thing” is people... People like Javier Lambán, Àngel García-Molina, Marisol Manzano, Agustín Medina, Imma Benet, Esther Yoldi, Paulino Fernández, Leonardo Almagro, Mireia Iglesias, Bea and Miguel Rodríguez, Andrés Alcolea, Jordi Guimerà, Enric Vázquez-Suñé, Jorge Jódar and many others were very helpful in both the good and the less good moments. A special mention stands for Germán Galarza, wherever he may be right now.

My current colleagues in the Agència Catalana de l’Aigua (*Water Agency of Catalonia*) are being very patient to me. I am grateful to all of them for their help and hard-working attitude, in spite of the usual cliché. I have been lucky to learn a lot there and to experience a completely new and rewarding stage in my life.

And, finally, is there anything more important than one’s people? All my love and respect to Lurdes, Laura, my grandma and parents, and, of course, to my friends in Pamplona, San Sebastián, Uncastillo and Zaragoza.

Did I say thanks?

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

« Clogging is an American folk dance that has its origins in the southern Appalachian Mountains of the United States of America. While it has strong ties to the step dance of the British Isles brought to the region by white settlers, clogging is also influenced by the traditional dance of native Americans, and the solo "buck & wing" dance of American blacks.

Clogging is a misnomer, since in the U.S.A., it is not performed in clogs. Nevertheless, the name persists, although in Appalachia, this form of percussive dancing is often only known as buckdancing or flatfooting or just plain "dancing" (...) »

By JULIE MANGIN (taken from the Internet)

Artificial Recharge is a powerful technology to enhance groundwater resources. It may form part of conjunctive use schemes, or be applied to increase water availability and/or improve water quality. There are a number of applications of Artificial Recharge, such as:

- storing freshwater in wet seasons (years) for a posterior use in dry seasons (years)
- reducing/preventing seawater intrusion
- augmenting water levels in the aquifer
- restoring wetlands
- improving the quality of water produced at waterworks plants
- providing an additional treatment to wastewater or stormwater
- keeping groundwater levels constant to avoid subsidence problems

Artificial Recharge was initially conceived to infiltrate high quality water into aquifers. Conventional resources -native groundwater, potable water and surface water (from rivers, lakes and reservoirs)- were primarily used. This concept is still in force in Europe, where most of the existing projects are linked to water supply plants in humid climates. Water scarcity in arid and semi-arid regions has led to an increasing recognition of the value of non-conventional water resources. In Israel, Arizona, California and Australia, for instance (PETERS ET AL., 1998), stormwater and treated wastewater are being reclaimed for agricultural, recreational and even urban supply uses. Irrigation returns are often included as non-conventional sources of water, but the vulnerability of groundwater to contamination by nitrate and pesticides is a limiting factor.

In parallel with the growing interest in non-conventional resources, quality and health issues have been raised. Among these, the transport of organic and inorganic micropollutants, fate of pathogens, behaviour of disinfection byproducts and chemical reactions are worth a mention. Artificial recharge systems can be simply classified in deep or surface infiltration systems. Because of the purifying capacity of soils, the latter (basins, trenches) are more convenient when the quality of recharge water is not excellent (BOUWER, 1995). Deep recharge systems, such as conventional wells and aquifer-storage-and-recovery (acronym ASR) wells, are more restrictive, but they possess a number of advantages (CUSTODIO ET AL., 1982; PYNE, 1995). Dry wells are drilled in the unsaturated zone; therefore, they can be considered as an intermediate category.

The most critical issue with regards to the efficiency of recharge plants is clogging. This term refers to the decrease in permeability of a porous medium as a result of physical, biological and chemical processes (OLSTHOORN, 1982; CUSTODIO, 1986; FRYCKLUND, 1992). As a consequence, either the infiltration rate diminishes or the piezometric head increases, depending on the boundary condition imposed at the recharge facility. Therefore, clogging may have a serious impact on the performance of Artificial Recharge facilities, irrespective of the infiltration methodology (mostly surface and deep systems, i.e. basins and wells, respectively). This leads to restrictive conditions on the quality of recharge water, which in turn implies that the pre-treatment stage must be improved, hence increasing the exploitation costs. The long-term sustainability of recharge plants is thus a primary concern (FRYCKLUND, 1998a). DILLON ET AL. (1995) and PÉREZ-PARICIO & CARRERA (1999a) list some international experiences on Artificial Recharge with references to clogging.

Clogging is generally caused by inter-dependent mechanisms that are often hard to distinguish (FRYCKLUND, 1998b). The classification of clogging into physical, chemical and biological processes is quite standard (SNIEGOCKI & BROWN, 1970). The role of suspended particles in clogging was recognised early (IWASAKI, 1937; STEIN, 1940) as it was the practical implication of biologically mediated reactions in soils (ALLISON, 1947). However, it is convenient to identify the following individual clogging mechanisms for the sake of conceptualisation (PÉREZ-PARICIO & CARRERA, 1999a):

1. Attachment/detachment of suspended particles, termed <u>physical clogging</u>. These particles can be carried by the recharge water (MC DOWELL-BOYER ET AL., 1986) or generated within the aquifer due to hydrodynamic or hydrochemical forces (PAVELIC ET AL., 1998).
2. Bacterial growth/die-off, or <u>bioclogging</u>, caused by the accumulation of microbial cells and their extracellular products (VANDEVIVERE ET AL., 1995; BAVEYE ET AL., 1998; HOLM, 1999).
3. Precipitation/dissolution of minerals (LLURIA ET AL., 1991; PETERS, 1994), termed <u>chemical clogging</u>, often catalysed by microbial populations (RALPH & STEVENSON, 1995).
4. <u>Generation of gas</u> (OLSTHOORN, 1982). This can occur by physical motives (pressure drop or temperature raise) or by entrapment of gaseous end-products from bacterial processes. Air bubbles can also form due to cascading (free fall of water) and inappropriate design of recharge wells (negative pressures).
5. <u>Compaction</u> or compression of the clogging layer that develops on the upper layer of surface recharge systems (BOUWER & RICE, 1989).

Given the relevance of clogging, numerous studies have been conducted to improve our understanding of various theoretical and technological issues. In particular, significant efforts have been directed to quantification, including both empirical and theoretical models (PÉREZ-PARICIO, 1998; PÉREZ-PARICIO & CARRERA, 1999a). Modelling clogging is acknowledged to be quite complicated, due to the inter-dependence of the soil clogging mechanisms that are different in nature (VIGNESWARAN & SUAZO, 1987; RINCK-PFEIFFER ET AL., 2000). This explains why there were no comprehensive models capable of simulating the *a priori* basic mechanisms. As stated by SALLÈS ET AL. (1993): “To the best of our knowledge there is no general analytical or numerical tool to study deposition and clogging of porous media”.

In this context, it was decided to formulate an integrated model that could reproduce the five elementary mechanisms. The final goal was to implement this conceptual model into a 3-D finite element code, termed CLOG, and then to apply this code to real clogging data. This study was mostly conducted within a European Union Project on Artificial Recharge of Groundwater (ARGW, 1996-1999).

The organisation of this document faithfully replicates the sequential steps adopted during the whole study. Chapter 2 contains the state of the art on clogging, based on a corresponding literature review (PÉREZ-PARICIO, 1998). This review was later completed in order to prepare a “Clogging Handbook” (PÉREZ-PARICIO & CARRERA, 1999a), which was one of the outcomes of the EU Project. The aim of this document was twofold. On one side, to update information, knowledge and experiences on conceptual and technological aspects of clogging. On the other side, to assess an integrated mathematical model based on the physics of clogging processes.

The conceptual and mathematical model is presented in Chapter 3. It includes five different clogging processes that can be combined (or offset) to reduce porosity and, thus, the conductivity of the medium. Chapter 4 focuses on the numerical implementation of the model into a 3-D finite element code, termed CLOG. This stage of the study was relatively simple because two existing finite element codes were conveniently adapted in a code termed RCB (BENET ET AL., 1998). The first one was aimed at 3-D multiphase flow problems coupled with heat transport and solid deformation (CODE_BRIGHT: OLIVELLA & GARCÍA-MOLINA, 1996). The second code was generated for modelling of reactive transport cases in 2-D media (RETRASO: SAALTINK ET AL., 1997). Specific clogging routines were programmed to include the previously identified processes. Therefore, CLOG is the working version of RCB that accounts for all the clogging mechanisms.

Following the classical procedure, CLOG was applied to various synthetic and real cases. Only the latter are described in Chapter 5, since they are much more interesting from the technological point of view. Case studies comprise:

a) Laboratory experiments:

1. Physical clogging under radial-flow conditions, due to the injection of potable water with fixed concentrations of suspended solids through a sandy 90º sector (OSEI-BONSU, 1996). The 2-D numerical domain was 1.30 m in radial length and 0.01 m in height. Several tests were simulated, with varying conditions of grain size distribution, flowrate and concentration of solids.

2. Bacterial clogging in a sand column following the infiltration of lake water in Arrenæs, Denmark (ALBRECHTSEN ET AL., 1998, 1999; PÉREZ-PARICIO ET AL., 1999b). The simulated domain was 1-D and 0.25 m long.

3. Physical and bacterial clogging and chemical unclogging in an aquifer column flushed with tertiary effluent (RINCK-PFEIFFER ET AL., 1998; 2000). Recharge water consisted in secondary effluent from the Bolivar wastewater plant (North Adelaide, Australia), post-treated by dissolved air flotation-filtration (DAF/F). The aquifer was mainly formed by calcite and silica. A 1-D, 0.16 m long, numerical model was used to simulate the three clogging processes.

b) Field experiments:

Clogging at the Langerak site, in the Netherlands (TIMMER ET AL., 1999; PÉREZ-PARICIO ET AL., 1999b), was interpreted. The refined model was 2-D and included the gravel-pack (0.35 m thick) and the sandy aquifer material.

Clogging was caused by straining of iron flocs in the aquifer pores. Iron flocs were generated during the preparation of recharge water from native groundwater. No more cases were analysed because of the difficulty to obtain well-documented data from operative recharge plants.

Results obtained from the simulation of all datasets are subsequently discussed in Chapter 6. It is evident that the simulated examples do not cover all the possibilities of Artificial Recharge. For instance, all the experiments were performed under saturation conditions, and there are no 3-D simulations. But all of them involve a range of conditions that are typical in recharge studies.

That is, properties and parameters that have been varied include:

- Recharge water sources (potable water, lake water, tertiary treated effluent, groundwater)
- Aquifer materials (sand, calcite)
- Flow regimes (radial and vertical flow) and flowrates
- Clogging processes (only physical; only biological; mix of physical, biological and chemical)
- Hydrochemical systems being considered by the model

Finally, the main conclusions of the thesis are listed.