Beyond Darcy’s Law

Dr. ir. S.M. Hassanizadeh

\[ Q = AK \frac{\Delta h}{L} \]

\( h_{in} \) \hspace{1cm} \( L \) \hspace{1cm} \( h_{out} \)

\( \Delta h \) \hspace{2cm} \( A \) \hspace{2cm} \( Q \)

Faculty of Civil Engineering and Geosciences
Beyond Darcy’s Law

Inaugurele rede

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door

Dr.ir. S.M. Hassanizadeh
Let us not read that book wherein a fresh wind does not blow.
Nor that book wherein the dewdrop’s skin isn’t moist.
Nor that book wherein living cells hold no hidden depth.

Let us not flick the mosquito off the fingertips of nature.
Let us not drive the panther out the gates of creation.
Let us realize that if but the worm had not been, life something would lack.

And that if there were no thorns, the natural law of trees would be violated.
And that if there were no death, our hands would grope and reach out for something.

Verses from *Footsteps of Water*
by Iranian poet and painter *Sohrab Sepehri*

Translation by *Arash Hassanizadeh*
Mijnheer de Rector Magnificus, leden van het College van Bestuur, collega's hoogleraren, docenten en medewerkers van de universiteit, dames en heren studenten, vrienden en collega's van buiten de universiteit, zeer gewaardeerde toehoorders, dames en heren,

Eerst wil ik uw goedkeuring vragen om mijn rede in het Engels te voeren, en dat om twee redenen: ten eerste gaat onze universiteit een nieuwe fase in waar internationalisering hoog in het vaandel staat en ten tweede heb ik voor mij belangrijke buitenlandse hoogleraren te gast en ik wil hun graag ook deelgenoot maken van mijn betoog.

Ladies en gentlemen,

INTRODUCTION

My area of expertise is geohydrology. Geohydrology is concerned with the quantity and quality of groundwater, one of our most valuable natural resources, and its interaction with soil and underground structures. Traditionally, geohydrology research has dealt with the groundwater quantity, mainly in relation to drinking water supply. But, it has undergone a significant change in character during the last few decades. In addition to quantity, a huge area of research on groundwater quality has developed. This has occurred as a consequence of social concerns about threats to our groundwater resources caused by human activities (domestic, industrial, agricultural, development of infrastructure, etc.) and the need for cleaning and/or protecting them. The thrust of research in this area has been on the spreading of contaminants in soil and groundwater, their effects on soil and water quality and underground structures, and design of remedial measures. This new dimension of the geohydrology research has generated challenging technical-scientific research issues whereby soil heterogeneities, physical and chemical properties, and even biological issues have to be taken into account.

The story of geohydrology has been the story of man's quest to exploit groundwater, man's ignorance in polluting and depleting it, and, more recently, man's endeavor to restore and/or protect its quality.

There is of course nothing wrong with exploiting groundwater. This is one of the few natural resources that are naturally replenished. The problem could arise if there is overproduction: withdrawing more groundwater than nature can replace. But, a much greater problem regards the quality of groundwater; something that human beings have been very careless about. Through our many activities above ground and underground, we have released impurities into the groundwater. This has led to the deterioration of quality of
vast expanses of groundwater resources; in some cases making it unfit for human consumption. Groundwater quality is an extremely vulnerable “commodity.” One liter of oil can pollute up to one hundred thousand liters of groundwater. Once polluted, it is extremely difficult and costly to clean the groundwater. Remediation works of a polluted site may take 30 to 40 years (Lyles, 1998). Another important feature of the groundwater system is that it is very complex and multifaceted. Many physical, chemical and biological processes occur in the subsurface. That is why it is so extremely important to acquire a thorough knowledge of the subsurface. Otherwise, even in our attempts to remediate the groundwater and clean it from pollutants, we may do more damage. In this speech, I shall give you examples of how we can unknowingly damage this fragile system. I'll try to convince you that we must do comprehensive and fundamental research to learn as much as possible about various processes occurring in the subsurface and to describe and model them as well as possible. I will also give you examples of the kind of research that is currently carried out in our Geohydrology Group.

**QANATS IN IRAN**

The value of groundwater as a natural resource was probably not known to the human being until a few thousand years ago. Springs were of course a known element of the natural landscape in many areas of the world. But, their source being groundwater was not a known fact. Perhaps the early inhabitants of the Iranian Plateau were the first people to learn of the value of groundwater. More than three thousands years ago, they invented an ingenious system to exploit it. I am referring to what is known as “qanat,” or in Persian Karez. Let me briefly explain how this system works.

There is much groundwater available in Iran. But, especially in older times, it has not been easy to have it as continuously running surface water. The groundwater could flow underground and pass the city and possibly discharge into a river or feed springs downstream the city (Figure 1). Another situation that may arise is that groundwater could appear as springs upstream the city. Although one could lead the water through canals to the city, but in the warm Iranian climate, much of it would evaporate. Canals are also susceptible to pollution. Moreover, spring discharge could fluctuate too much. A qanat would provide steady supply of cool and clean water. Qanat is an underground canal, a tunnel that leads the

![Groundwater Table](image)

**Figure 1.** The groundwater was not always easily accessible. It could pass under the city and discharge downstream into a river.

...and those in agriculture, and that the water might be used for irrigation. Moreover, they found that the water could be used to produce power. The qanat was a remarkable engineering achievement, and it is still in use today. It is a remarkable testimony to the ingenuity of the ancient Persian engineers.**

...and those in agriculture, and that the water might be used for irrigation. Moreover, they found that the water could be used to produce power. The qanat was a remarkable engineering achievement, and it is still in use today. It is a remarkable testimony to the ingenuity of the ancient Persian engineers.**
Qanats were constructed, and are still being constructed, by means of extremely simple tools: ropes, buckets, picks, shovels, windlass (Figure 3), and manpower. They have irrigated lands and provided domestic water supply for many centuries in Iran, and to other regions in Middle East, Western China, and North Africa, where the technology spread quickly from Iran. Some qanat tunnels have been more than one hundred kilometers long and mother wells of more than one hundred meter deep exist. Qanats are visible from the air, marked by the line of openings of access or construction shafts with a toroidal heap of mined dirt around them (Figure 4). According to Wulff (1968), around 25 years ago, there were about 22000 qanat units running in Iran, comprising more than 270,000 kilometers of underground channels. They delivered about 540 cubic meters of water per second; equivalent to 75%

of discharge of the Euphrates River. Although many of them still exist and supply water to small towns and villages, a large number of qanats have disappeared. This has been mainly caused by thoughtless installation of deep pumping wells, overproduction, and subsequent drying of mother wells of qanats. Also, in some cases, where a switch has been made to surface water supplies, the qanats have lost value and have fallen in disrepair. It is now recognized that this has been a bad mistake, especially for smaller communities. Aquifers are almost permanently depleted and surface water supplies have proven unreliable, due to seasonal fluctuations. There are now efforts to revive the construction and use of qanats in the region. But, of course, a system that has been developed over a period of thousand years cannot be restored quickly.

The story of geohydrology is the story of man’s quest to exploit groundwater, his ignorance in depleting and deteriorating it, and his endeavor to restore and protect it.
POISONED GROUNDWATER IN BANGLADESH

The problem is that too often we have the tendency to go for easy solutions. Practical and economical issues are usually considered to be the determining factors. We fail to consider long-term effects of our choices and/or look into fundamental issues. In our quest to conquer and harness the forces of nature, we act arrogantly. We think that we understand how these forces work and, thus, we think we can make them do whatever we want. How often have we been proven wrong! I am not talking about widespread contamination of groundwater as a result of careless and/or irresponsible introduction of myriads of agricultural and industrial pollutants into groundwater. I am not talking about accidents such as Chernobyl or accidental release of poisonous agents into rivers, in Switzerland or Romania. I am not even talking about the supposedly profitable irrigation projects such as those leading to the destruction of the Aral Sea. I am talking about supposedly well-researched, well-thought and well-meaned projects. Take the poisoning of groundwater by arsenic in Bangladesh.

Until about three decades ago, major sources of drinking water in rural Bangladesh were community ponds or rivers. As a result, widespread epidemics occurred very often. Each year, a quarter of a million children would die as a result of waterborne diseases. An ambitious plan instigated by the United Nations Children’s Fund (UNICEF) called for the construction of millions of tubewells to tap into the cheap and plentiful sources of “clean” groundwater. Scientists from the British Geological Survey helped to evaluate quality and quantity of groundwater resources. Using millions of dollars aid money, every single village was bestowed a tubewell. And it worked. The spread of epidemic diseases ended. But, the biggest outbreak of mass poisoning in history began, simply because the engineers and scientists failed to properly study the consequences of massive groundwater withdrawal. There are various explanations of what has gone wrong. One main explanation is that sediments in deltaic aquifers of Bangladesh contain arsenic minerals naturally. These minerals, however, are insoluble as long as there is no oxygen in the water. Except for the upper layers that are in contact with air, there is no oxygen in groundwater. After the start of the tubewells project, the groundwater table went down, regions of oxygenated groundwater came into contact with sediments naturally containing arsenic, and the arsenic minerals interacting with oxygen dissolved into water. The concentrations are low, but arsenic accumulates in the body and causes severe poisoning. Nowadays, tens of millions of people in Bangladesh depend on arsenic-laced groundwater (Figures 5 and 6). Thousands of people are suffering from painful and deadly symptoms of...
arsenic poisoning. Seventy million Bengalis are at risk of contracting arsenic-related diseases. This is an environmental disaster much greater than Chernobyl. There are many organizations and research groups trying to find solutions for purifying the produced water and, more importantly, for restoring the quality of groundwater. Interest groups in Bangladesh have started lawsuits against UNICEF and the British Geological Survey; they are being held partly responsible for this disaster. In my view, villagers of Bangladesh have a point. If we mess around with a natural system, we must know damn well how that system works and how it may react to our actions. It is not enough to have good intentions; it is necessary but not sufficient. It is also necessary to have a thorough knowledge of the system we are dealing with. Such knowledge must be based on sound theories as well as experience and experiments.

METAMORPHOSIS OF DARCY’S LAW

Many geohydrologists would dismiss such pleas as they would say “What are you talking about? We do have sound theories. We have Darcy’s Law and we have Fick’s Law.” Well, that is exactly what I am talking about. Darcy’s Law and Fick’s Law lie at the heart of our geohydrological theories. Any quantitative description of flow and transport phenomena in soil and groundwater is based on the validity of these two equations. Computations of groundwater flow velocities, rate of spread of contaminants in groundwater, and the efficiency of various techniques for cleaning of soil and groundwater are based on Darcy’s and Fick’s laws. Our computations and predictions are as good as these two equations are. Yet, these are empirical and relatively simple equations that were originally proposed for very simple systems. Over the years, as geohydrologists had to deal with more complex systems, they simply assumed that these equations, perhaps with some modifications, would apply to the more complex system. It was as if they added bells and whistles to the equations to make them look more complicated and, thus, applicable to more complex systems.

Take Darcy’s Law. This equation was introduced by Henry Darcy in 1856. He was the chief engineer of the Precinct Côte d’Or in France. He designed a plan for drinking water supply of the city of Dijon. The plan included collecting about 500 m³/hr of water from the Rosoir Spring 13 km outside the city. The water had to be filtered and he needed to determine the flow of water through a sand filter. In analogy with Fourier’s Law of heat transfer, he proposed the following formula (see Figure 7 for definition of symbols):

$$Q = AK \frac{\Delta h}{L}$$

This equation was tested by Darcy on a sample of sand in a laboratory column. It certainly works very well for steady-state slow one-dimensional flow of almost pure water in saturated homogeneous isotropic nondeformable sand under
constant temperature. But, we have needed an equation to describe the three-dimensional flow of two or more compressible (immiscible) fluids, with lots of dissolved matter, in nonhomogeneous anisotropic deformable porous media under non-isothermal conditions. Over the last 150 years, Darcy's law has gone a metamorphosis and has been extended and extended to more and more complex systems.

So, for one-dimensional flow in a homogeneous aquifer, equation (1) was extended and written in differential form:

\[ q = -K \frac{dh}{dx} \]  

(2)

For three-dimensional flow in a homogeneous and isotropic aquifer, equation (2) was extended to:

\[ q_i = -K \frac{\partial h}{\partial x_i} \]  

(3)

The extension to an anisotropic and heterogeneous aquifer was made by replacing the constant hydraulic conductivity with a tensor \( K_{ij} \) with spatially variable components:

\[ q_i = -K_{ij} \frac{\partial h}{\partial x_j} \]  

(4)

Now, if the medium is deformable and if the water is compressible, then, supposedly all we need to do is to re-interpret \( q_i \) and \( h \); \( q_i \) is the velocity of water relative to the velocity of the solid, \( v_i' \) (Terzaghi, 1924):

\[ q_i = v_i'' - v_i' \]  

(5)

and \( h \) is defined in terms of Hubbert's potential (Hubbert, 1940):

\[ h = Z + \int_{P_0}^P \frac{1}{\rho(P)g} dP \]  

(6)

For non-isothermal situations, i.e. when the temperature of the medium changes, and/or when the water density may change, equation (4) is simply re-written in terms of pressure:

\[ q_i = -k_{ij} \frac{\partial p}{\partial x_j} - \rho g j \]  

(7)

where \( k_{ij} \) is called intrinsic permeability and \( \mu \) is dynamic viscosity. Even if a large amount of salt or other substances are dissolved in the water, equation (7) is assumed to hold.

As mentioned above, Darcy's Law was originally formulated for a fully saturated medium. Obviously, equation (4) does not hold if the pores are filled not only with water but also air is present (i.e. for the unsaturated zone above the groundwater table). Yet, the same equation has been employed and only hydraulic conductivity is assumed to be a function of saturation, \( S \) (Buckingham, 1907). Thus, the equation for unsaturated flow is the same as (4) with:

\[ K_0 = K_0(S) \]  

(8)

So, it is assumed that in terms of forces that act on water, there are no differences between saturated and unsaturated flow.
Now, how about if two or more immiscible fluids flow simultaneously in the pores? Well, then again it is assumed that equation (4) holds for each fluid. We just need to write it as many times as there are fluids. For example, for simultaneous water and oil flow, we will have:

\[ q_i = -K_i \frac{dh_i}{dx_i} \]  
\[ q_i = -K_i' \frac{dh_i}{dx'_i} \]  

where \( K_i \) and \( K_i' \) are assumed to be functions of saturation. That’s what I call adding bells and whistles to the equations. In terms of driving forces, there is no difference between equations (9) or (10) and the simple equation proposed by Darcy. The question is whether all major forces that are operative in a complex system as in multiphase flow are properly included in these ad-hoc extensions of Darcy’s Law.

Many practically-oriented geohydrologists would say “What is all the fuss about? Darcy’s Law works for all practical purposes.” Well, apart from the fact that this statement is not true, the point is that we have a responsibility to develop and use theories with sound fundamentals. We must not be satisfied with patch-ups.

The excuse that “It works for practical purposes” reminds me of an interesting exposition in the book “Physics for Poets” by Robert March (1992). In this book, views of Aristotle and Galileo about the free fall of objects are compared. According to Aristotle, objects fall at a constant velocity. The velocity depends on the shape of an object and the medium wherein it falls, and is proportional to the weight of the object. Indeed, if an object is released from rest, say in air or water, it will quickly reach a constant terminal velocity. In the air, this may take only a few seconds. Thus, if the velocity of fall of an object is measured and plotted against time, data points will look like those shown in Figure 8. Except for the short initial period, where the velocity rises from zero to the terminal value, the theory of Aristotle doesn’t look bad at all. Aristotle and scientists who followed him could not explain the deviation of the theory in the early time. But, they were satisfied with it as it worked for all practical purposes. Until Galileo came along. He focused on the early time behavior and set out to provide a more general explanation of the motion of objects. He proposed a new theory: “In the absence of resistance, all falling bodies experience the same constant acceleration.” This is a universal law that led to the discovery of gravity by Isaac Newton 50 years later. The plot of speed of fall of an object by this theory, however, would result in the

![Figure 8. Comparison of theories of Aristotle and Galileo for the free fall of objects.](image-url)
NEW THEORY OF CAPILLARITY

Take the example of capillary pressure, in unsaturated flow or two-phase flow. In these cases, pressures of the immiscible fluids filling the pores are different and the difference is called capillary pressure. For example, for unsaturated flow, capillary pressure is equal to the difference in pressures of air and water:

\[ p^c = p^w - p^v \] (11)

Capillary pressure is assumed to be a function of saturation, S. The assumed relationship can be obtained only by experiments. During the last 60 to 70 years, enormous effort has been invested in measuring \( p^c - S \) curves for various fluids and different soils. Hundreds, if not thousands, of papers

![Figure 10](image)

Figure 10. Measured capillary pressure-saturation data points, obtained under equilibrium conditions.

line shown in Figure 8. It is obvious that Aristotle’s theory does a much better job of matching experiments. But, we now know better. Suppose that Galileo had not changed our world of science, and the subject of free fall of bodies was on the research frontier now. Many PhD projects and millions of research money would have been dedicated to the relation between the terminal velocity of bodies and all possible combinations of shape, size, weight, medium, etc. Advanced research would have looked into the effect of roughness and grooves on the surfaces of bodies on the terminal velocity! Plots similar to the one shown in Figure 9 would have been proudly displayed in conferences and in illustrious papers! If you think this is not actually happening nowadays, you are mistaken. Enormous effort is spent by researchers in various fields of science to find relationships among different physical quantities without looking into the underlying physics.
and reports have been devoted to the relationship between capillary pressure and saturation. Thousands of plots similar to those shown in Figure 10 have been prepared and presented. The curves are obtained under equilibrium conditions, i.e., when there is no flow of fluids. Although it is a known fact that there is no unique relationship between capillary pressure and saturation, there is a constant search for such a relationship. In vain. We have a primary drainage curve, a primary imbibition curve, a main imbibition curve, a large number of main drainage scanning curves, a large number of main imbibition scanning curves, and even more secondary imbibition scanning curves, and secondary drainage scanning curves, and an unlimited number of dynamic drainage and dynamic imbibition curves.

We believe it is possible to mold this mess into a coherent theory. This is done in a theory developed during twenty-five years of collaboration with my former advisor Professor William Gray of University of Notre Dame, who has truly honored me with his presence here today. According to this theory (Hassanzadeh and Gray, 1990), in order to describe and model capillary phenomena in porous media, in addition to capillary pressure and saturation, one has to introduce the specific interfacial area formed between fluids that occupy the pores. The premise of this theory is that there is a unique relationship among capillary pressure, saturation, and interfacial area for a given soil, under equilibrium conditions. The existence of such a relationship has been investigated, and more or less established, using computational models. Valuable research in this regard has been done by the research group of Professor Michael Celia of Princeton University, whose presence here today is a true honor for me. Using pore-scale network models, they have shown that all equilibrium drainage and imbibition curves, main or scanning, fall on a

Figure 11. Three-dimensional surface showing the relation among interfacial area, saturation, and capillary pressure under equilibrium conditions (Held and Celia, 2001). A single surface under certain conditions (Figure 11; see Reeves and Celia, 1996; Held and Celia, 2001). This is an elegant result that needs to be investigated experimentally.

Figures 10 and 11 are based on results obtained under equilibrium (no-flow) conditions. It is known that, under dynamic conditions, i.e., when the fluids move, data points fall outside the plotted range. Indeed, our theory prescribes a more general equation under dynamic conditions. The new equation, which should replace (11), reads (Hassanzadeh and Gray, 1993):

\[ p^n - p^m = p^s - \tau \frac{\partial s}{\partial t} \]  

(12)
where $\tau$ is the dynamic capillary pressure coefficient whose value has been determined from published experimental data (Hassanzadeh et al. 2002). This new equation and the significance of the new term has been studied by various research groups. In particular, researchers from Sandia National Laboratories and University of Minnesota have shown separately that our theory is able to model the phenomenon of fingering of wetting fronts in unsaturated flow, which cannot be modeled by the classical Richard's equation (Dautov et al., 2002).

As part of our new theories, an extended form of Darcy’s Law for multiphase flow is obtained too. The new equation takes into account forces that are not present under saturated flow conditions. The new form of Darcy’s law reads:

$$q_i^w = -\frac{k_i^w}{\mu^w} \left( \frac{\partial p^w}{\partial x_j} - \rho g_j + \lambda_n \frac{\partial \phi^w}{\partial x_j} + \lambda_u \frac{\partial u^w}{\partial x_j} \right)$$

(13)

where $\lambda_n$ and $\lambda_u$ are new coefficients. The introduction of a new variable, i.e. the fluid-fluid interfacial area, i.e., $a^{wn}$, and a better description of the capillarity phenomenon are not without a price. It brings about other difficulties and problems. So, it is necessary to have an additional governing equation, which inevitably will contain new coefficients. Also, measurement of interfacial area is not a trivial task; far from it. But, when there is a need, there is a way. Researchers are working on finding novel ways of measuring interfacial area (see e.g. Saripalli et al., 1998). Among these efforts is a research being carried out in The Dietz Lab as part of an NWO-financed project we have with my colleague Hans Bruining of the Reservoir Engineering Section.

**FICK’S LAW OF DISPERSION**

As mentioned earlier, geohydrology deals not only with the flow of fluids, but also Role of bacteria in the degradation of organic pollutants of soil and groundwater: Contamination of soil and groundwater by organic pollutants, such as oil products, is a serious environmental problem. Considerable efforts are invested in cleaning and remediation of the soil and groundwater. Active remediation techniques, such as excavation and disposal or treatment of soil, pumping and treating the groundwater, injection of chemicals into groundwater, and various heating or oxidation techniques, are expensive and time consuming. One of the alternatives that are being considered is based on the natural ability of the subsurface to retard the spreading of dissolved pollutants and/or to reduce its concentration. For example, there exist bacteria in the subsurface that can feed on dissolved organic pollutants and thereby reduce the concentration of harmful substance; this is called biodegradation. Thus, one may be tempted not to carry out any remediation activity and rely on the bacteria to get rid of the pollutants. This is of course a very inexpensive alternative. But, one has to be sure that the biodegradation process will reduce the concentration of harmful substances to acceptable levels within a reasonable period of time. Therefore, it is extremely important to be able to model the biodegradation process and its effect on the spreading of organic pollutants as well as possible. In this project, a combination of laboratory experiments and numerical work will be employed to acquire the necessary knowledge for understanding and modeling of coupled biodegradation and two-phase flow processes. The results will be used to develop guidelines for assessing bioremediation alternatives.

$$\left(1 + \beta |J|\right) J_i = -\rho D_j \frac{\partial \omega}{\partial x_j}$$

(15)
where $\beta$ is a new coefficient that has been determined experimentally (Hassanizadeh and Leijnse, 1993, Schotting et al. 1999, and Watson et al., 2002). This new equation has been investigated through various experimental researches carried out at RIVM (Hassanizadeh et al., 1988), the Technical University of Berlin (Moser, 1995), and at the University of Western Australia (Anderson, 1997). The results have been most promising.

**PRACTICAL RESEARCH**

Do not misunderstand me. I am not denying that Darcy’s Law was a milestone in the history of geohydrology. On the contrary, Darcy’s Law was the dawn of quantitative study of groundwater flow. But that was almost 150 years ago, and it was meant for a simple system. Are we going to use the same basic formula 150 years from now? For increasingly more complicated systems? Is there any more beyond Darcy’s Law? And beyond Fick’s Law? It is our responsibility to find out.

I am pleased that the Strategy Document of our University recognizes this responsibility and puts fundamental and innovative research at the core of the mission of our university. This takes vision and courage. It is a strong indication of taking ourselves and the role of the university in the advancement of science and technology seriously. Fulfilling such a pledge will certainly bring our university up to the rank of top technical universities in the world. Fundamental research is a strong foundation upon which applied research and high-quality education can be based. Our university has a tradition of being active in fundamental research in various fields of water in general, and in geohydrology in particular. I must mention Professor Gerard de Josselin de Jong who contributed to the formulation of basic theories of dispersion in porous media in the 50’s (de Josselin de Jong, 1958).

Obviously, fundamental research can comprise only a fraction of the main body of research. The research at our Geohydrology Group, ranges from fundamental to practical research, with the majority of projects relating to practical issues and problems. Here is a brief list: upscaling two-phase flow phenomena from pore to core, upscaling two-phase flow phenomena from core to field, role of chemical osmosis in the containment of contaminants, determination of the role of bacteria in the degradation of organic pollutants of soil and groundwater, determination of zone of protection of groundwater contributing to a water production well, characterization of subsurface heterogeneity through integration of soft and hard information, identification and modeling of processes causing the clogging of water production wells, the role of mixing processes in the fate of contamination plumes, design of monitoring systems for detecting contamination of groundwater under and around landfills, change of properties of oil blobs trapped within soil and groundwater, dynamics of groundwater table fluctuations, natural capacity of soils for alleviating the effects of pollutants on groundwater, salt water intrusion and optimization. Let me give you a little more details on two of these research projects.

**Role of bacteria in the degradation of organic pollutants of soil and groundwater:** Contamination of soil and groundwater by organic pollutants, such as oil products, is a serious environmental problem. Considerable efforts are invested in cleaning and remediation of the soil and groundwater. Active remediation techniques, such as excavation and disposal or treatment of soil, pumping and treating the groundwater, injection of chemicals into groundwater, and various heating or oxidation techniques, are expensive and time consuming.
One of the alternatives that are being considered is based on the natural ability of the subsurface to retard the spreading of dissolved pollutants and/or to reduce its concentration. For example, there exist bacteria in the subsurface that can feed on dissolved organic pollutants and thereby reduce the concentration of harmful substances; this is called biodegradation. Thus, one may be tempted not to carry out any remediation activity and rely on the bacteria to get rid of the pollutants. This is of course a very inexpensive alternative. But, one has to be sure that the biodegradation process will reduce the concentration of harmful substances to acceptable levels within a reasonable period of time. Therefore, it is extremely important to be able to model the biodegradation process and its effect on the spreading of organic pollutants as well as possible. In this project, a combination of laboratory experiments and numerical work will be employed to acquire the necessary knowledge for understanding and modeling of coupled biodegradation and two-phase flow processes. The results will be used to develop guidelines for assessing bioremediation alternatives.

**Clogging of water production wells:** Water work companies in the Netherlands produce more than one billion cubic meters of water every year through about 2500 water wells. About 50% of these wells experience severe clogging problems. This results in extra costs of about 12 million Euro a year for all waterworks companies. Well clogging is also harmful to the environment due to chemicals used for well treatment and extra energy needed for the water pumps. Although mechanisms that cause clogging of wells are known but a general and comprehensive model of well clogging processes has yet to be developed. Thus, rehabilitation methods are ineffective and the well design is far from optimal in preventing or limiting clogging. A research project has recently started, financed by the Technical Stimulations Fund, in cooperation with KIWA, Brabant Water, Water Works of Limburg, Hydron, Hoekloos Co., and IF-Technology Co. This project aims at acquiring a fundamental understanding of clogging mechanisms, developing a numerical model, and applying it to various production wells and fields in the Netherlands.

![Schematic representation of a water well. Clogging commonly occurs at borehole wall around the filter or at the filter slots.](image)
COLLABORATIONS

The research in modern geohydrology is highly multidisciplinary and must be carried out in cooperation with experts from other disciplines. We have sought cooperation with national and international research groups both informally and in the framework of projects. Our research projects are carried out in cooperation with various universities within Europe and the Netherlands, with national research institutes such as TNO-NITG, TNO-MEP, KIWA, GeoDelft and RIVM, with local government offices such as the Engineering Office of Rotterdam Municipality, Port of Rotterdam, with regional water authorities such as HYDRON, Brabant Water, and with consulting companies such as TAUW, IF-Technology, BioClear, and Royal Haskoning. We benefit immensely from such a diverse range of collaborations. We also benefit from close cooperations in research and teaching activities with various groups within our university. In particular, I must mention our valuable cooperation with the Reservoir Engineering Section within the Centre for Technical Geosciences.

As part of the Research Portfolio Operation for our Faculty, the Executive Committee of our university has envisaged “new initiatives in shallow subsurface”. We believe this is an excellent and timely recommendation. Nowadays, the shallow subsurface is not only the medium where groundwater resources are found, but also the space where many activities take place and many underground structures are constructed. As I emphasized earlier, if we mess around with nature, we must be aware of the consequences of our actions. Being a technical university, we have a responsibility to take a leading role not only in research but also in education. In this regard, I am pleased to announce that, as part of the new initiatives in shallow subsurface, we have plans to start a new M.Sc.

program in Environmental Geohydrology. This would be an interfaculty program in cooperation with Reservoir Engineering, Geotechnical Engineering, Engineering Geology, and Microbiotechnology. A proposal for this program will be submitted to the Executive Committee of the university.

Another recent positive development has been the decision by the university management to choose water as one of the focus research areas of our university. Our Faculty will have a leading role in this research area. Our Geohydrology Group shall work hard alongside other groups in Water Resources Engineering and Hydraulic Engineering Departments in order to offer a strong research and teaching program in water.

ON THE MOTIVATION OF SCIENTIFIC STAFF

Mijnheer de Rector Magnificus, allow me to go back to the declared ambition of our university to rank among top technological universities in the world. I am quite sure that the scientists and teachers of our university have the capacity and capability to fulfill this ambition. However, capacity and capability are not enough. Many other factors must play a positive role in this process. One major factor is motivation. I know that this factor has the attention of the university. The introduction of the Antonie van Leeuwenhoek professorship for associate professors and regular promotions of talented assistant professors (UD in Dutch) to associate professorship (UHD in Dutch) is a clear indication of this attention. Indeed, UD’s and UHD’s are the sources of scientific innovation and hold the future of our university. They must be motivated.

Unfortunately, there is a great obstacle in this regard, not only at our university but at all Dutch universities. And that is the outdated and rigid hierarchical system that prescribes the
rights of scientific staff. In this system, UD’s and UHD’s are denied a number of important rights, so that there is a huge gap with full professors. So, for example, UD’s and UHD’s cannot be official academic advisors (in Dutch: “promotors”) of PhD-students. Members of PhD committees are preferably chosen from among professors and only occasionally from UHD’s. UD’s cannot be voting members of a PhD committee. Members of nomination committees for key positions of the university (e.g. deans, section heads) are almost exclusively professors. Members of strategic committees defining various educational and research policies are always only professors. In short, UD’s and UHD’s are treated as second-rank citizens! This situation is in my view of great impedance to any effort to motivate the largest group of scientists in the Netherlands. Nowadays, financing a PhD position is not a trivial task. Researchers, for the most part UD’s and/or UHD’s, have to write project proposals. These must be proposals of high quality and should contain new ideas in order to pass successfully through stringent review processes of funding agencies such as EU and NWO. Once the project is accepted, the same UD or UHD supervises the student for four years or so, guides him through the successful completion of PhD and helps with the various stages of writing papers and PhD thesis. Yet, at the end, the name of someone else, a professor, appears on top of the PhD thesis as the ‘promotor’. The best the UHD can hope is to be a co-promotor. A UD cannot be a co-promotor. I know of supervisors who were not even a member of the PhD committee. The Dutch law is that only professors can be promotors. As if UD’s and UHD’s are by definition scientifically unqualified. They do all the work, and someone else gets the first prize. This is unjustified, unjust, and unacceptable. We are not in the scientific business for financial rewards. We are in this business for honor and for credit. I am calling to all Dutch scientists, in particular Dutch professors, to join me in demanding a change to the status of UD’s and UHD’s at our universities. Our concrete demand must be that UD’s and UHD’s must have the right to be promotors. Obviously, there must be stringent regulations to ensure the quality of PhD research and PhD thesis. I have come to know the Dutch people and the Dutch society as truly progressive. It is time for Dutch universities to follow the tradition of progressiveness and to meet the new realities of scientific research at the universities. This is the case in top (technological) universities in North America and U.K. I myself was one of the very first graduate students of Professor Gray in 1975. He had obtained his PhD only three years earlier and had just become assistant professor at Princeton University. He was my supervisor as well as my promotor. I guess we can say that he did a great job. Dear Bill, let me take this opportunity to express my deepest gratitude for your guidance, collaboration, and friendship during the past 27 years. I wish every PhD student could have a promotor like you, even if only an assistant professor.

ACKNOWLEDGEMENT

Ladies and gentlemen,
I have always had the strong desire to learn and to teach. My dream was to become a professor. But I never dreamed of being a professor in The Netherlands. More than 17 years ago I came to Delft to follow post-graduate courses at IHE. Although my family joined me within two months, we were planning to stay only one year. But, it was meant to be otherwise. And we are not complaining. On the contrary, I want to thank the Dutch people and the Dutch society for being such a wonderful host to me and my family. I particular, I am grateful to my employers RIVM (for more than 10 years) and TU Delft (for the last seven years) for the opportunities.
they have given me to develop myself and build a wonderful career.

During the first weeks of my arrival in Delft I was fortunate to meet now-professors Kees van den Akker and Toon Leijnse. While following courses at IHE, I wanted to do some research. They agreed to take me in at the Centre for Mathematical Methods of RIVM; Kees was the head of the Centre and Toon was a group leader. Since then, we have stayed together. Dear Kees, thank you for your kindness, your support, and your confidence in me during all these years. What I have valued in you as a scientific manager, both at RIVM and TU Delft, is that you give a lot of freedom to researchers. You rely on their sense of responsibility. It has been a true pleasure to work for you and with you.

Dear Toon, you are a wonderful colleague, an excellent scientist, and an invaluable friend. We have done many projects and much research together; I have benefited immensely from our cooperation. I am extremely pleased that, in the framework of our Delft Cluster collaboration, TNO-NITG has agreed to “lend” you to our Section for one day a week. I am sure this will further strengthen our fruitful collaboration.

My strong interest in learning and science has been seeded and stimulated by my parents. It is a great satisfaction to me that they are present here to witness the fruits of the seeds they sowed. Please allow me to say a few words to them in Persian.

Undoubtedly the greatest influence on my life in general, and scientific life in particular, comes from my wife Forooz. Through constant and warm encouragement, unlimited understanding, and unparalleled dedication, you have created ideal conditions in my life for me to advance my career.

Without your support, I would have never succeeded. I cannot thank you enough. I also want to thank my son Arash and my daughter Bahareh for their support and understanding and for believing in me all along.

Our Hydrology and Ecology Section is truly a great place to work. Thanks to colleagues, PhD students and MSc students, we have a friendly and active work environment. The PhD students have been source of liveliness and research inspiration for the Section. They have a close relationship and provide mutual support to each other. This has given a different dimension to the Section. I would also like to highlight the role of my colleague Ruud Schotting within our Godhydrology Group. With his contagious enthusiasm, steadfastness, friendliness and broad knowledge of mathematical analysis and modeling, he is a great asset to our Section. Ruud, it is a pleasure to work with you.

Mijnheer de Rector Magnificus, members of the Executive Committee of the University, members of my Nomination Committee, management of the Faculty of Civil Engineering and Geosciences, thank you for giving me this recognition.

Ladies and gentlemen, thank you for your attention.
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