Salt Water Intrusion; Analysis, Research Needs and Opportunities

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Looking backward

The first SWIM took place in 1967 in Hanover, very informal, at the initiative of the late dr. Richter of the Bundesanstalt für Bodenforschung, presently Bundesanstalt für Geowissenschaften und Rohstoffe. Only three countries were represented, Germany (ca. 12), the Netherlands (3) and Denmark (1). Dr. Richter and his co-workers were confronted with the problem of salt water intrusion in the northern part of the Federal Republic of Germany and some of his co-workers had experiences abroad. Rightly he felt that an exchange of experiences would be useful. We decided that such a meeting should be repeated some two years later. The second meeting took place in the Netherlands in 1970. Since then more and more European countries became involved, and with intervals of two and incidentally 2½ years we had a SWIM. This term was introduced by prof. De Breuck who organized the fourth SWIM in Ghent, Belgium. There was always a country, sometimes even more than one, which volunteered to organize the next SWIM. So, after several meetings around the North Sea, we met also near the Baltic Sea, in Uppsala, and in Gdansk, and the Adriatic Sea, in Bari, and the Mediterranean in Barcelona and Cagliari. The papers presented did not only relate to Europe. Some European participants presented their experiences in other continents and incidentally we had participants from other continents, with and without papers. They were and are still most welcome. Time and again we concluded that we should continue. The number of participants was rarely below fifty and never over hundred. With these numbers it was possible to have good discussions during the meetings and moreover to have good personal contacts. The SWIM-participants have become good friends and young coming men came in and felt at ease in this informal group. Though we have seen great developments in the investigations and research, the practical problems have increased considerably during the past decades. This is due to increased abstraction of fresh groundwater and the delayed effects thereof.

From the very beginning the contributions to the SWIM in the form of papers and posters have been subdivided into, mostly, six categories, which can roughly be described as follows:

- cases,
- geophysical methods,
- hydrochemical and isotope studies,
- modelling,
- prevention, control and remediation,
- special subjects, such as studies on the (changing) sub-soil properties, other sources of salt, non-conventional techniques of salt water intrusion abatement (e.g. with electric currents) or fresh water recovery from submarine springs in karstic areas.

As, in this keynote, I would like to present my views on the future rather than to look back, I will be brief in my review of the past and give only very concise comments on what we have heard and seen in these categories during the past decades, just as a starting point for my prophecies about the future.

Category 1, "Cases", has always been well represented. Interesting, but often ending with problems and not always with solutions, which was not always possible, either by lack of data or uncertainty, or simply because the situation was spoiled and could not be restored for technical or economic reasons.

Category 2, "Geophysical methods", was usually small. Electrical resistivity prospecting was known and applied from the very beginning. We have seen improvements in geophysical well-logging and the introduction of electromagnetic methods, which are easy to carry out, but have another resolution than the electrical resistivity methods.

Category 3, "Hydrochemical and isotope studies", was there from the very beginning. In the beginning the number of papers was modest. The number of elements considered was only small and the conclusions that could be drawn and have been drawn were only limited. At present this is a category of big growth.

Category 4, "Modelling", shows even more growth. In the first SWIM we saw sets of differential equations for fresh and saline groundwater in one-dimensional horizontal flow in steady state with a sharp interface. As analytical solutions were either impossible or too complex the differential equations were solved numerically by the first computers. No need to say that the computer technique has developed progressively and that two-dimensional transient problems with gradually varying densities are common practice now and that realization of the dream of models which can handle 3D transient cases with gradually varying densities and even accounting for chemical reactions is not far off. In the mean time a new approach, the analytic element technique, has come up and will compete with the customary finite difference and finite element methods.

Category 5, "Prevention, control and remediation", is perhaps the most important one because, in contrast to the categories 2, 3 and 4 which are the more scientific ones, this relates to the practical application of measures and their results. Perhaps our group hosted more scientists than practitioners, because this important category is somewhat lagging behind.

Category 6, "Special subjects", has always been small and diverse, but interesting.

It should also be noted here that the legislative and socio-economic aspects have rarely been discussed here and if so, it was only as a side-aspect.

Looking forward

After the foregoing concise description of the development and the present state in the six categories, we will now see what the prospects are.

Without adequate human interference the practical problems will increase for the following two reasons. The increase of the world population and the growing water demand per capita makes that more fresh groundwater is needed. This alone makes the problem of salt water intrusion even more pressing than at present. The second reason is that even without any further increase of the abstraction of fresh groundwater and reclamation of new land in coastal areas, the present situations will generally continue to deteriorate for a long time ahead due to the time lag between previous and ongoing causes and their effects. Even in case the present situation just continues, the ultimate dynamic equilibrium will often be unacceptable. Then, wells and well-fields will have to be abandoned. This implies that measures have to be taken, based on the lessons learned so far, on the results of field studies and on calculations. Thus more work of the same nature. This makes that any measure that leads to better, faster and/or cheaper results is welcome. This holds primarily for the exploitation of the groundwater, but evidently also for the preceding studies and their scientific bases.

Research needs and opportunities

Climate change and sea level rise

In the past the climate has changed continuously and slowly. This holds also for the natural recharge of groundwater. The relative movement of the mean sealevel with respect to the land surface is partly due to climate changes and partly due to tectonic forces. Due to the delayed effects of these slow natural processes in terms of the distribution of fresh and saline groundwater, a state of dynamic equilibrium has not yet been reached in many cases. At present the climate change is strongly believed to be accelerated due to human activities. Despite the fact that, world-wide, much attention is paid to climate change and its direct consequences, little attention has been paid, so far, to the impacts of changes in the water balance terms and in sea level rise on the groundwater regime in coastal areas and small islands. Though the impacts of such changes will take place gradually, their delayed effects can be considerable in the distant future. Therefore it is recommended to start, now already, studies for orientation on what might happen in terms of salt water intrusion and on the sensitivity of the results for the underlying assumptions, the uncertainty in the (geo)hydrologic data and the stresses by human activities. The results of such studies indicate where to concentrate upon in data collection and groundwater monitoring.

Time lags

As was mentioned before, the time lag between cause (groundwater abstraction, landreclamation) and effect (salt water intrusion) can be great, in the order of decades or even centuries. This has two aspects. A favourable one is that there is mostly no immediate danger and thus time for study and for implementation of measures, which however entails the danger that such studies are postponed too long. The other side of the medal is the unfavourable fact that the effects of countermeasures or compensating measures will also be delayed. If such measures are taken late they should be more rigourous; if they are taken too late the situation may even be spoiled. Restoration may still be possible, but only after reduction or even interruption of the abstraction of fresh groundwater and/or relocation of groundwater abstraction works, which is at least costly. This leads to the recommendation to study the present transient situation and, based on the results, to design and execute adequate measures.

Sustainability

The term sustainability, introduced in 1987, in the Brundtland report, is not sharply defined because it relates to an infinite variety of subjects and conditions, but yet the principle is well understood. It can also be applied to the dynamic equilibrium between fresh and saline groundwater. In any particular situation with a known natural recharge, supplemented or not by artificial recharge, one can never abstract more than the mean annual recharge. The fraction of the total mean annual recharge that can be abstracted sustainably depends on the location of the abstraction wells in relation to the geometry of the aquifer and on the variation of the rates of recharge and abstraction over the year and even from year to year. The greater the mean rate of abstraction the smaller the volume of fresh groundwater in store and the greater the risk of failure in periods of small recharge and/or great demand. This leads to an interesting problem of risk assessment, followed by a decision problem. If a decision is made where the required mean volume of fresh groundwater in store is smaller than the present volume, the difference can partly be consumed, which is acceptable mining. The other part will disappear as discharge by natural outflow. In the opposite situation, where the present volume of fresh groundwater in store is smaller than the required mean volume, the aquifer should be restored by increased rates of (artificial) recharge. It may be clear that the choice to be made requires calculations, based on data which must first be collected if not yet available. The result will certainly be rewarding for the society and give satisfaction to the various scientists who study this optimization problem.

Storage

The mentioned optimization problem will be even more complex and interesting in case the annual cycles of abstraction and recharge (including artificial recharge) are out of phase because of seasonal variations of the demand (irrigation, tourism) and the available quantity of water of good quality for artificial recharge (if any). Then the volume of fresh water in store will vary over time, either regularly or irregularly. These changes manifest themselves by fluctuations of the phreatic groundwater tables and even more by vertical displacements of the transition zones between the fresh groundwater and the underlying saline groundwater. These displacements lead to a higher degree of mixing of the fresh and saline groundwater in the transition zone, unavoidably resulting in a percentage of loss of the recharged fresh water. The results of some interesting experiments have already been reported in previous SWIM's. These results are certainly dependent on the variations of the abstraction and recharge regimes and on the local subsoil properties. So, in my view, there will be ample scope for more such experiments and studies under various conditions.

Conjunctive use of surface and groundwater

In the light of the foregoing considerations with respect to the fluctuations over time of demand and recharge and the resulting fluctuations in storage of fresh groundwater it may be worthwile to study conjunctive use of surface and groundwater. This widens the scope of the groundwater experts, who then have to cooperate with surface water experts and with systems experts who can assist in the determination of optimal solutions. One step further and we enter the domains of integrated water management and environmental issues. These will be left out of consideration in this lecture.

Skimming wells

Skimming wells have been applied where the thickness of the fresh groundwater lens is only thin, which is mostly the case in local lenses of small lateral extent. In such cases skimming wells were applied in reaction to upconing of saline groundwater in wells which were to heavily pumped. Thus the application of skimming wells is based on the practical experience that in such cases it is better to pump at moderate or low rate in a great many of wells at short spacings and at small rates of pumping than in only few wells at greater distances and at high pumping rates. This experience should be kept in mind when projecting new well-fields under such circumstances.

Scavenger wells

Scavenger wells are applied to abstract saline groundwater below the interface or transition zone with the pumped fresh groundwater in the upper part of the same aquifer. When pumping the saline groundwater at a properly adjusted rate, upconing of saline groundwater under and into the fresh water wellscreen is avoided. This is a good solution, provided that the vertical distribution of the salinity is continuously monitored and the ratio of the pumping rates of the fresh and the saline water are adjusted accordingly. A practical problem might be how to dispose of the saline water, as the local water authorities may not allow the discharge of saline groundwater into fresh surface waters and saline surface waters may be too far away. Desalting could be a technical solution, but it is questionable whether the costs are justified. So far only few applications of scavenger wells to control the salinity distribution under a pumped well have been reported. In cases of scarcity of fresh water it may in some places become necessary to resort to scavenger wells. The exploitation of such wells must be based on continuous monitoring and will be a matter of practical adjustment rather than of scientific research.

Abstraction of saline groundwater

In contrast to scavenger wells, which are applied in combination with individual abstraction wells and which are effective below and in the immediate vicinity of such wells, the designation "abstraction of saline groundwater" relates to large scale abstraction of saline groundwater in thick and large aquifers. By drawing down the piezometric level of the saline groundwater by pumping, the piezometric level of a thick layer of fresh groundwater in the upper part of the same aquifer will also be drawn down. This implies that the seaward gradient of the fresh water head will decrease and therewith the outflow of fresh groundwater, which otherwise is a loss. The gain is the recovery of fresh groundwater which would otherwise be lost. The price to be paid for it is the installation, exploitation and maintenance of the deep wells for the salt water abstraction. Again the disposal or desalting of the saline groundwater is a matter of serious concern. In case of desalting the products are an additional source of fresh water and a much smaller volume of highly concentrated brine. An interesting problem will be to optimize the location and the capacity of the abstraction wells in particular cases. So far no practical cases have come to my knowledge. The more pressing the demand for fresh water, the more the abstraction of saline groundwater will come to the fore as a possible means to increase the exploitable fresh water resources.

Modelling

After the foregoing review of the achievements in this category one may question when and in what stage this development comes to an end. With the rapidly increasing capacities and speeds of the computers we will soon be in a position that the bottle-neck is no longer in the computer capacity but in the available data and the uncertainty of the many types of spatially varied input data. This is not as bad a situation as it looks like. When making different assumptions for the missing or uncertain data one can check the sensitivity of the model solutions for the various parameters and thus learn where to concentrate the field-work on. This can save a lot on the expenditure for the high costs of boreholes, pumping tests, etc. and to a lesser extent of the less expensive geophysical exploration techniques.

Geographical Information Systems

Geographical Information Systems (GIS) have been developed during the last two decades for application in a large variety of subjects. As in saltwater intrusion problems both the input and the output data are geographically distributed, GIS appeared to be a useful tool for our problems as well. This is an opportunity. The latest development is a coupling of a GIS with a numerical groundwater model or, in our case a salt water intrusion model.
Several cases have already been reported and undoubtedly this will soon become current practice.

Artificial neural networks

Like GIS, artificial neural networks (ANN) are a new opportunity. The rather sophisticated theory of ANN has been developed only recently in the domain of artificial intelligence. An ANN is trained to reproduce a given set of output vectors for a corresponding set of input vectors. These vectors may represent values of physical parameters (e.g. flows) or patterns of numbers (e.g time series). ANN are able to simulate almost any complex physical system, even if the governing equations of the system are not well defined. If a relationship between input and output data is unknown, but acknowledged to exist, an ANN can be trained to learn that relationship to a high degree of accuracy. So ANN might compete with traditional (geo)hydrologic modelling. This opportunity should be further explored in order to be able to judge whether this is the case indeed, to what extent, under what conditions and what limitations there are.

Chemical composition, trace elements and isotopic properties

As mentiond before studies of the chemical composition and isotopic properties of groundwater have been presented from the very beginning of the SWIM. Since then the number of elements, trace elements and isotopes studied has increased due to improved resolution of existing and new detection methods. The results can learn us from where the sampled water originates, how old it is and what exchange processes have taken place. The results should, of course, be in agreement with the present and past flow patterns and with the results of the numerical modelling of the groundwaterflow. If so the different methods of study corroborate one another. Regrettably this was and is not yet always the case. Therefore it is necessary to analyse the reasons for such discrepancies before any definitive conclusion can be drawn. The results of such studies can lead not only to better and correct pictures of the situations under consideration, but also to improvement of the different methods of investigation.

Remote sensing

Remote sensing has first been developed for military purposes. As such the techniques and results were classified. Since the late sixties remote sensing has become available for civil applications as well and since then the resolution of the various techniques has increased considerably. It is true that remote sensing gives images of the land and water surfaces and not directly of the subsoil, our domain. However the features of the surface: topography, drainage patterns, geologic structures such as faults, and the vegetation give at least some indication of what structures and conditions one may expect in the subsoil and incidentally even in terms of the depth and/or the salinity of the groundwater. In speakers view this additional information is not yet fully utilized in field studies. Therefore it is strongly recommended to take advantage of this source of additional information.

Socio-economic aspects and communication

Salt water intrusion can have great socio-economic aspects. For instance, if wells have to be abandoned because of upconing of salt groundwater there is not only damage through loss of invested capital but also the socio-economic aspect that the water supply for domestic use, agriculture or industry is in danger. Failures which have occurred could have been prevented by proper measures in terms of land use planning and rules for proper groundwater management. Therefore it is necessary that the various experts

- cooperate to describe the present situation and to develop plans for restoration, where needed, and exploitation and control of the groundwater systems, and

- subsequently convince the gouverning authorities to ensure the execution of their proposals as an investment to garantee a sustainable exploitation of the groundwater resources.

Opportunities

It is not surprising that recently a number of initiatives has been launched (not yet implemented!) to pay more attention and to take action to prevent and where necessary to restore situations where the limits of sustainability have been exceeded. To mention a few:

a. Two years ago, at the 13th SWIM, in Cagliary, mr. Pallas of FAO and myself reported about an expert meeting held in 1993 in Cairo, at the initiative of FAO, to draw attention to the problem of salt water intrusion, its technical, legislative and socio-economic aspects, which resulted in a recommendation to install pilot projects where all relevant aspects could be studied, resulting in practical solutions. This of course requires funds and time. The funds should be provided by all interested parties and not only or predominantly by organizations as FAO and UN.

b. The recently launced EC plan to set up a Task Force "Environment. Water", which has a budget and intends to work along the following four foreseen axes:
   - fight against pollution,
   - rational use of water,
   - fight against structural deficits,
   - prevention and management of crises (e.g. droughts).

   The Task Force will work out the plan.

c. The new UNESCO programmes "Environment and Development in Coastal Regions and Small Islands" (of UNESCO's Division of Hydrology) and "Maintaining and Managing Coastal Ecosystem Productivity for the Sustainable Development of Human Communities" (of UNESCO's Human Habitat Unit) offer a nice opportunity to bring together hydrologists, urban sociologists, architects and townplanners and to draw their attention to, among others, the problem of salt water intrusion and how to prevent it. To that aim UNESCO invited some experts from those circles to attend the present SWIM and to engage a dialogue with SWIM and SWIMers.

These are opportunities which we, the SWIM-community, should pick up. We, scientists and some practitioners, should present our gospel to a wide audiance and convince colleagues from other disciplines and decisionmakers that it pays off to invest in measures to prevent further salt water intrusion and to restore situations which have already been spoiled or are on the way to be spoiled and thus to take the necessary technical and legislative measures, based on field investigations and research.

SWIMeetings

Coming to the end of this keynote-lecture do I need to ask whether we should have come to an end with SWIM? I do hope and expect to have convinced you that there is still a long way to go for us, but also to widen our scope in the sence that we should present our results and messages better to those who need them and who do not always realize that there exist salt water intrusion problems, but fortunately also solutions.