ground
water

Historical Note/ David Deming, History Editor

Development of an Analytic Element Ground Water Model of the Netherlands

by Willem J. de Lange[1]

Introduction

In 1985, I attended the first course on analytic element modeling in the Netherlands, where Professor Otto Strack of the University of Minnesota presented his newly conceived analytic element method (AEM; Strack 1989) at the Technical University Delft from which he graduated years before. While he explained the principles and applications of the method, I started to realize that the AEM might be uniquely suited to modeling detailed ground water flow systems covering large regions because it enables cutting, pasting, and linking of entire models as well as of model parts.

In 1987, at the National Institute for Inland Water Management and Waste Water Treatment in the Netherlands (RIZA), there was much interest in national modeling in the Netherlands because of serious water management problems that first became apparent during the major drought of 1976. In fact, there existed a national water management system of models, called PAWN (Policy Analysis for Water management in the Netherlands; Rand Corporation 1982). PAWN is an integrated system of models for simulating the distribution over the numerous national and regional surface waters in this wet country and the effects on agriculture, nature (ecology), power plants, shipping, flushing of coastal areas against salt water intrusion, and drinking water. PAWN was lacking treatment of the ground water reservoir, which had become apparent in the policy analysis of 1985 (Pulles 1985). The NAtional GROundwater Model (NAGROM) should cover this gap as part of PAWN.

The Birth of NAGROM

During a single and short conversation in September 1987 with Ton Sprong, a department head at RIZA, I opined that building a national ground water model should be possible when using analytic elements. In reply, he simply decided to start such a project, be it on a low budget. Within 1 month of that decision, I found myself on a plane to Minnesota to work with Strack laying the technical foundations for this project. Little did we know that our enthusiasm and hard work at that time would evolve into a multidecadal and multimillion dollar modeling odyssey: a truly national ground water flow model of the Netherlands called NAGROM (De Lange 1996b).

While the early version of Strack's code, MLAEM (Multi Layer Analytic Element Model), was tested on a multiaquifer system in Minnesota, it was by no means a fully operational multiaquifer code when we started the NAGROM project. Moreover, the scale of our model region was unprecedented (30,000 km^2). Existing ground water maps did not cover the entire country (TNO 1960–1990), while management of the data that were available was a daunting task; Geographical Information Systems (GIS) did not yet exist. In fact, some hydrologists in the Netherlands declared the development of a ground water flow model on a national scale to be unfeasible, if not worse. As an example of this, even after the work on the national model was well under way, Querner, who was associated with another national research institute on hydrology, in reaction to the first NAGROM report (De Lange 1991) stated in his Ph.D. thesis that "The application of a stationary ground water model at a national scale is 'a bridge too far'" (Querner 1993).

I decided to develop the national model through a number of so-called "supraregional" models, bounded by major hydrological features (lakes, rivers, canals), nine in total for the country, except the Wadden islands to the north of the mainland, which were not included in the model (Figure 1). The idea was to connect the nine models at the end of the project to effectively form one national ground water flow model, NAGROM. By doing so, these models could be worked on independently and concurrently. Each of these nine supraregional models covered areas of 5000 to 10,000 km^2 and had to be constructed in phases. The nine regions have generally different hydrogeologic characteristics, which required different conceptual models. However, aquifers and aquitards had to be identified for the entire supraregion at once; in fact, they

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had to be defined in such a manner that the supraregions could be merged into a single national model down the road. In the absence of GIS, we (a team of students and I) used scissors, markers, scotch tape, and many weeks of our time to construct cardboard models of fence diagrams to obtain a three-dimensional cross-sectional overview of the geohydrology in each region (Figure 2).

Developing NAGROM and MLAEM

At the start of the project, it was clear that the AEM itself, through its implementation in MLAEM, needed to be further developed alongside the NAGROM model. One of the most important outcomes of the NAGROM project is an improved understanding of ground water movement in multiple aquifer systems, specifically leakage between aquifers. This understanding appeared essential for the successful development and application of NAGROM.

Getting the Leakage Right

In typical analytic element modeling practice, individual analytic elements should be interpreted as individual hydrologic features. Streams, canals, and brooks are modeled by line elements (straight or curved) that infiltrate or withdraw water from the aquifer. Infiltration areas, polders (reclaimed land at the bottom of a former lake), and lakes, as well as leakage between aquifers, are modeled using areal elements (Figure 1). In fact, the layout of the areal analytic elements looks a lot like that of a finite-element model, except that the elements are very large as a result of the one-to-one relation between element and hydrologic feature (leakage area), and the results in terms of flow and head within elements are quite different (Figure 1). Our early attempts to reproduce realistic ground water elevations and flows into or out of surface water, however, met with varying success. It worked in some areas but not in others.

I started to realize that there were some fundamental problems with our conceptual model design and that these were strongly related to our inability to properly represent the leakage distributions between the various aquifers. I went back to the drawing board and looked at known analytic solutions to elementary ground water flow problems in leaky aquifers. It appears that these solutions, such as flow toward a well or flow underneath and into a lake, always involve the same type of parameter, called the “leakage factor” (Hantush and Jacob 1954; Verruijt 1982). This parameter depends on the aquifer transmissivity and the resistance to flow offered by the bounding aquitard and has the dimension of length. This leakage factor serves as a kind of “characteristic leakage length.” If it is small, leakage occurs very locally near a well, a stream, or a lake boundary. Conversely, when the characteristic leakage length is large, the leakage distribution is spread out over a rather large area (De Lange 1996a). This observation explained many of our problems. Our large areal elements, used for modeling leakage, worked decently in areas where the leakage is spread out but failed miserably in areas where the leakage is

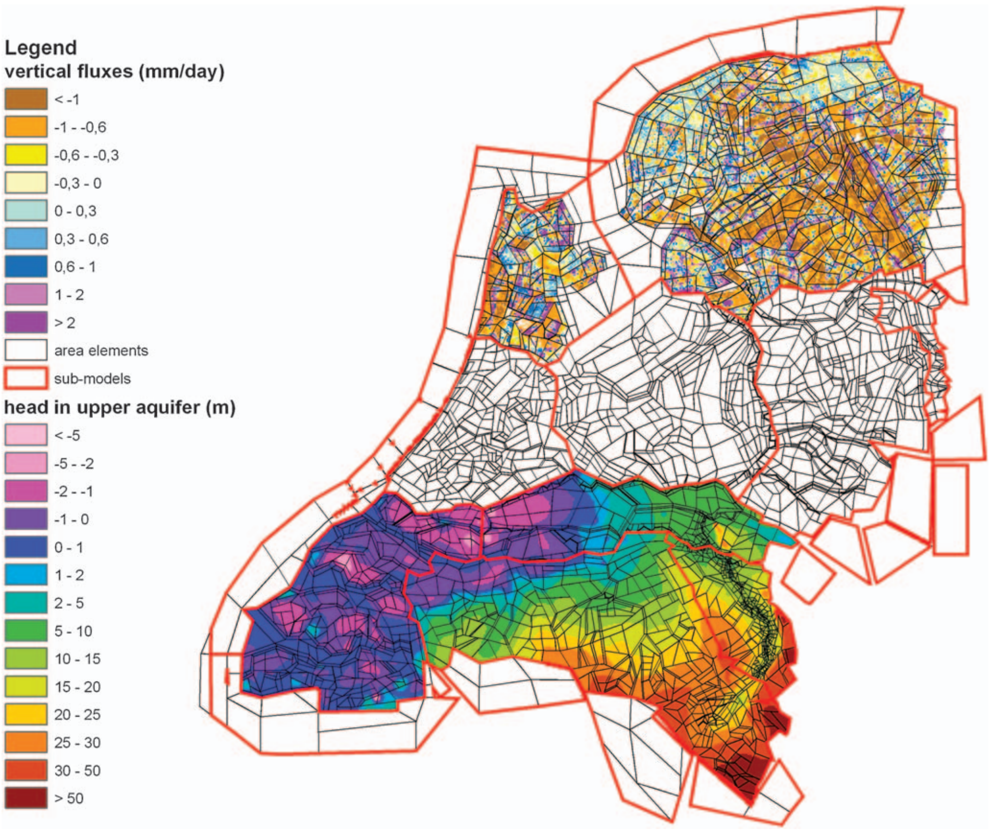

Figure 1. Overview of supraregional models in NAGROM covered by analytic areal elements and computed fluxes (northern part) and heads (southern part) in the upper model layers.

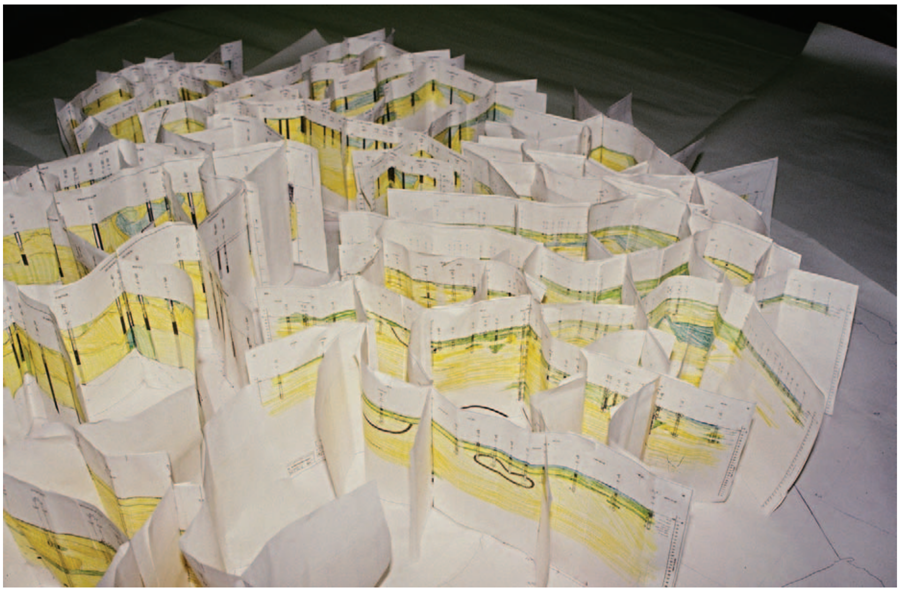

Figure 2. Paper sectional model for the NAGROM model of the northern part of the Netherlands.

more concentrated near surface water, wells, or boundaries between differing aquifer properties and recharge rates. As a result, ground water exchange between aquifers was modeled inaccurately in those areas. To make our large multiaquifer model work, we needed to do better in representing leakage into surface water or between aquifers. Incidentally, the role of the characteristic leakage length parameter in the behavior of leakage is also of importance to MODFLOW or finite-element modelers. For instance, MODFLOW models with cells that are larger than the characteristic leakage length can be expected to perform poorly (Haitjema et al. 2000).

New and Improved Analytic Elements

Our improved understanding of ground water flow in leaky aquifers prompted many model design changes as well as the development of new analytic elements in MLAEM. We learned that changes in hydrological circumstances, such as surface water level jumps or surface water–land surface boundaries, in the upper aquifer may have a distinct "signature" in the various aquifers below it, depending on the value of, indeed, the characteristic leakage length. Also, abstraction wells in lower aquifers generate a signature in the aquifers above. This kind of variation in leakage required modifications in the size of elements as well as in the capabilities of the analytic elements themselves.

To account for the signature of wells in multiple aquifer systems, Strack developed a specific type of element that can be used in combination with the existing large areal elements but properly include local leakage effects of wells. He also developed areal elements bounded by polygons in which the leakage can vary to better fit the actual leakage distributions. These new elements helped to resolve some, but not all, of the major problems in modeling the leakage distribution. (As of this writing, a new generation of elements is being developed that can model the leakage nearly exactly for any given conceptual model. These new developments have been funded by RIZA and will soon be implemented in the NAGROM model [see also Strack 2005].)

First Success

By Christmas 1988, the Dutch national agencies were working hard to complete the third national policy document on water management (Anonymous 1989). Recent drought problems had received national attention, but policy analyses could only be based on the existing PAWN model. Now, Ton Sprong needed results. Yet, the first submodel of NAGROM (the northern part of the Netherlands) had been under development for more than a year. Many technical problems had been solved, the geohydrology was pretty well understood, and we learned how to combine analytic elements in virtually any situation. The model, however, did not behave. Our lack of understanding at that time of how to model leakage resulted in poor modeling results that prevented its use for policy making. Were the critics right after all? Was NAGROM "one bridge too far"? If we could not deliver now, there would be no need to deliver later; the project would be dead. For more than a year, the NAGROM team had struggled with the representation of leakage between the various aquifers. Late at night, before I had to present our results, I decided to modify the network of leakage elements to make them identical in each layer. It worked! It was only a few hours before the meeting when I compiled the results of the first modeling scenarios that I was expected to present.

Finally, after more than a year of hard work by many students and staff of RIZA, the national model had proven to be a relevant tool for national policy making; its first computational results were presented in the technical report supporting the national policy document. The AEM had appeared useful, indeed crucial, in building a model of a supraregion of 10,000 km^2 and with relatively limited resources.

Adding Sea Water

The Dutch have been reclaiming land (polders) from the lakes and the sea for centuries. In the coastal area, ~50% consists of this reclaimed land called "polders" (Figure 3). In order to keep these polders dry, the water table in the polders must be lowered below land surface. This is accomplished by means of a dense network of ditches, drain pipes, and canals that drain the polder lands. Permanently dewatering polders, however, comes at a cost: constant ground water withdrawals at the surface cause deep, salty water in the aquifers to rise underneath the deeper polders such as the ones reclaimed from lakes. This salt water enters the polders, threatening its use for agricultural purposes (among others). The combined effect of many polders on both the ground water flow and the ground water salt concentration is significant. The national ground water model had to account for these complex three-dimensional variations in density (salt concentration) in the entire coastal region of ~200 km long and 50 km wide. Thousands of irregularly distributed measurements were available and had to be incorporated into the model. Both the scale and the resolution of this density-dependent flow model would surpass all similar modeling attempts to date.

Following a proposal by Strack, we decided to represent the density distribution by a network of radial interpolator functions (Hardy 1988) that can handle our large set of density measurements and include them as an "analytic function" within the AEM (Strack 1989; Strack and Bakker 1995). This new approach to density-dependent flow modeling was implemented in NAGROM in 1993 to 1994. For the first time ever, provincial hydrologists (comparable with hydrologists working at state geological surveys in the United States) were looking at a complete three-dimensional picture of the salt concentrations in the ground water underneath their province. We also found that the incorporation of density effects was of critical importance to a successful calibration of the NAGROM submodels. Without the proper density distribution, the models never would have been calibrated within the set limits (De Lange and van der Meij 1992–1994).

Figure 3. Deep polder (reclaimed land, green grassland at left) in the western part of the Netherlands.

Using this density-dependent form of the model, NAGROM has provided important information for planning future ground water developments, including assessing response to climate change and assessing the flushing of salty water seeping into the deep polders (Haasnoot et al. 1999).

Concluding Remarks

The NAGROM project has been a major stimulant in the development and improvement of various analytic elements and formed an important testing ground for the technique. The project contributed significantly to our knowledge of how to model complex situations with analytic elements. For instance, in addition to concerns about leakage and density effects, we also learned how to include anisotropy, a sloping aquifer base, and tens of thousands of surface waters through a lumped parameter approach (De Lange 1999). In summary, the NAGROM project demonstrated that the AEM is uniquely suitable for large-scale ground water flow modeling while maintaining local detail.

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References

Anonymous 1989. *Water in the Netherlands: A Time for Action*. The Hague, The Netherlands: Ministry of Transport, Public Works and Water Management.

De Lange, W.J. 1999. A Cauchy boundary condition for the lumped interaction between an arbitrary number of surface waters and a regional aquifer. *Journal of Hydrology* 226, no. 3–4: 250–261.

De Lange, W.J. 1996a. NAGROM, a groundwater model for national groundwater management and regional and local studies. *Environmental Water Pollution Control* 6, no. 5: 63–67.

De Lange, W.J. 1996b. Groundwater modeling of large domains with analytic elements. Ph.D. diss., Delft University of Technology, Delft, The Netherlands.

De Lange, W.J., and J.L. van der Meij. 1992–1994. Series of 9 reports on the NAGROM (NAtional GROundwater Model). TNO-GG (at present NITG-TNO)/RIZA Reports. Delft (presently at Utrecht), The Netherlands.

De Lange, W.J. 1991. A groundwater model of the Netherlands. RIZA Report 90066. Lelystad, The Netherlands: RIZA.

Haasnoot, M., J.A.P.H. Vermulst, and H. Middelkoop. 1999. Impacts of climate change and land subsidence on the water systems in the Netherlands. RIZA Report 99.049. Lelystad, The Netherlands: RIZA.

Haitjema, H.M., V. Kelson, and W.J. de Lange. 2000. Selecting MODFLOW cell sizes for accurate flow fields. *Ground Water* 39, no. 6: 931–938.

Hantush, M.S., and C.E. Jacob. 1954. Plane potential flow of groundwater with linear leakage. *Transactions of the American Geophysical Union* 35, no. 6, part 1, 917–936.

Hardy, R.L. 1988. Theory and application of the multiquadric-biharmonic method. *Computational Mathematical Applications* 19, no. 8–9: 163–208.

Pulles, J.W. 1985. *Beleidsanalyse van de waterhuishouding van Nederland*. The Hague, The Netherlands: Rijkswaterstaat.

Querner, E. 1993. Aquatic weed control within an integrated water management framework. Ph.D. diss., Agricultural University, Wageningen (also Report 67 Wageningen, The Netherlands: DLO Winand Staring Centre [now: Alterra]).

Rand Corporation. 1982. *Policy Analysis of Water Management for the Netherlands*. Santa Monica, California: Rand Corporation. N-1500/1-12-Neth.

Strack, O.D.L. 2005. The Development of New Analytic Elements for Transient flow and Multiaquifer flow. *Ground Water* 43, doi: 10.1111/j.1745-6584.2005.00148.x.

Strack, O.D.L. 1995. A Dupuit-Forchheimer model for three-dimensional flow with variable density. *Water Resources Research* 31, no. 12: 3007–3018.

Strack, O.D.L. 1989. *Groundwater Mechanics*. Englewood Cliffs, New Jersey: Prentice Hall.

Strack, O.D.L., and M. Bakker. 1995. Validation of a Dupuit-Forchheimer formulation for flow with variable density. *Water Resources Research* 31, no. 12: 3019–3024.

TNO. 1960–1990. Grondwaterkaart van Nederland (Ground water map of the Netherlands). Series of TNO Reports. DGV-TNO, Delft (presently: TNO-NITG, Utrecht), The Netherlands.

Verruijt A. 1982. *Theory of Groundwater Flow*, 2nd ed. Mc Millan, London.