

Modelling the impact of surface water management on water conservation and water quality

PETER VERMEULEN

Delft University of Technology, Faculty of Information Technology and Systems, Section of Applied Mathematical Analyses, PO Box 5031, 2600 GA Delft, The Netherlands

e-mail: p.vermeulen@nitg.tno.nl

HANS GEHRELS

Delft University of Technology, Faculty of Civil Engineering, Section of Hydrology and Ecology, PO Box 5048, 2600 GA Delft, The Netherlands; and

Netherlands Institute of Applied Geoscience TNO–National Geological Survey, PO Box 6012, 2600 JA Delft, The Netherlands

CHRIS TE STROET & TON KREMERS

Netherlands Institute of Applied Geoscience TNO–National Geological Survey, PO Box 6012, 2600 JA Delft, The Netherlands

Abstract A combined surface water–groundwater model was developed to investigate a new water management strategy focused on water conservation and improvement of water quality. This new strategy aims at more natural conditions by implementing a surface water control allowing for higher water level dynamics than has been common practice. A more flexible surface water level control was simulated using an adapted MODFLOW RIVER package in which the fixed river stage is replaced by a band width. Furthermore, a surface water model (QROUTE) was developed that simulates the routing of surface water through a system as a result of net infiltration and drainage in a number of distinct regions. QROUTE also calculates conservative transport resulting from surface water and groundwater components. The adapted RIVER package and the surface water–groundwater model were applied to Reeuwijk, a polder area in the Netherlands.

Key words dynamic surface water control; MODFLOW RIVER package; The Netherlands; surface water routing model; water management

INTRODUCTION

Long-term changes, such as an expected sea level rise and a changing climate, will affect the hydrology of coastal areas such as The Netherlands. In addition, the water management of these lowland areas (below sea level) is faced with problems resulting from centuries of intense drainage and reclamation, i.e. the deterioration of natural vegetation by poor water quality (eutrophication and salt water intrusion) and compaction of peat and clay soils. The present water management practices do not consider these problems and future developments. Instead, water levels are kept at constant and usually low levels to facilitate agriculture. Hence, during wet periods, excess water is discharged quickly, and vice versa during drought, i.e. surface water is channelled to recharge groundwater. The channel water is different, and often poorer quality than the water which naturally evolves in an area.

Management solutions should aim at restoration of the more natural, dynamic behaviour of the water system, because this will minimize the volume of water discharged from the area (maximize water conservation) and minimize the water channelled into the area (improve water quality). Dynamic surface water control in polder areas is one of those strategies (Gehrels *et al.*, 2000). Dynamic surface water control implies that greater water level fluctuations are allowed within the constraints of agricultural activity and safety. To simulate more dynamic conditions, the MODFLOW RIVER package (McDonald & Harbaugh, 1988) was adapted. A surface water routing model (QROUTE) was developed, to evaluate the effects on the hydrological system, particularly the quantity and quality of the surface water. The model can quantify the volumes of surface water in an area, which are subdivided into recharge, seepage, and inlet water.

COUPLED SURFACE WATER-GROUNDWATER MODEL DEVELOPMENT

Adapted RIVER package to simulate dynamic surface water control

In MODFLOW, the interaction between surface water and groundwater can be schematized in several ways. One way is by using the RIVER package, which allows for both drainage and infiltration. Drainage occurs when the groundwater level rises above a threshold, called the stage (Fig. 1(a); condition gwl_1), and infiltration occurs when the groundwater level is below the stage (Fig. 1(a); conditions gwl_2 and gwl_3). The groundwater will thus be discharged or recharged immediately whenever the groundwater level is different from the exact stage height. This corresponds very much to the present water management practice in e.g. the Netherlands, but it does not allow for a more dynamic and natural water table.

To enable surface water control where the water table is allowed to move freely within a certain band width, a *dynamic* RIVER package was developed, in which the stage is replaced by a range with an upper limit and a lower limit. Infiltration from the river to the aquifer will occur whenever the groundwater level is below the lower limit (Fig. 1(b); condition gwl_3). Drainage, on the other hand, will occur only when the groundwater level is above the upper limit (Fig. 1(b); condition gwl_1). When the groundwater level is between the lower limit and the upper limit, there is no interaction between the river and the aquifer (Fig 1(b); condition gwl_2).

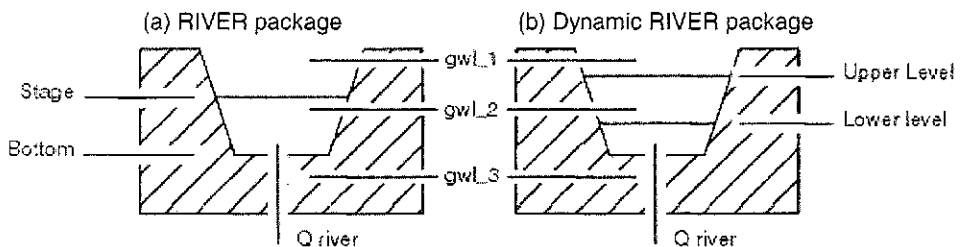


Fig. 1 Cross-section of a stream in an aquifer, depicting the Stage and Bottom in the conventional RIVER package (a), and the Upper Level and Lower Level in the adapted RIVER package (b).

A new surface water routing model

We developed a surface water model (QROUTE) that describes a continuous surface water system in which smaller regions with a specified surface water stage are interconnected. These specified regions are bounded by fixed inlet and outlet locations. The model evaluates the water quantity (net drainage or infiltration within regions) and water quality (conservative mass transport) throughout the system. The model does not involve the physical principles and laws of fully dynamic one-dimensional open channel flow, but only solves the equation of continuity with respect to channel flow (here called segment flow). The model does not calculate surface water stages, and hence does not influence the groundwater flow model calculation, but routes the segment flow afterwards using the fluxes calculated by the groundwater model. This simplification is allowed because we are not interested in backwater conditions and waves at time scales smaller than the groundwater model time step, which here is only 14 days. The total calculated net drainage or infiltration within a region determines whether a region lacks water or has a surplus, which drives the surface water model.

Model codes for stream flow routing already exist, such as STREAM (Prudic, 1989), which is directly coupled with MODFLOW. However, a major disadvantage of STREAM is that the direction of the streamflow must be known and input to the model. This problem can be solved by using surface water models, such as BRANCH (Schaffranek *et al.*, 1981) or DUFLOW (Duflow, 1995), which are also coupled with MODFLOW (in MODBRANCH (Swain & Wexler, 1991) and MODUFLOW (Ngo, 1994), respectively). An integrated modelling approach to a surface water system, as described earlier, could be to model only the main channels with MODBRANCH and to calculate the total outflow to, or inflow from, a specified region with the DRAIN or RIVER packages of MODFLOW. This outflow to or inflow from a region can then be connected to MODBRANCH using STREAMLINK (Swain, 1993). However, if one is not interested in calculating stages or backwater conditions, MODBRANCH requires an excessive amount of input data including cross-sectional data, slopes, and Manning's roughness coefficients that are largely unknown for our study area and require a considerable computational effort. A simpler module is therefore desirable.

Description of computational scheme

The QROUTE surface water model consists of two main parts. In the first part, the continuity equation is solved for the segment flow of the entire surface water system (Fig. 2(b); Q -terms). In the second part, the conservative mass balance components are routed through the network based on the calculated segment flow.

Continuity equation for segment flow As shown in Fig. 2(a) and (b) the modelled surface water network consists of several regions (IO -terms) and connections (C -terms), linked with each other by segments (Q -terms). A region is a predefined area containing several grid cells of the groundwater model. Each region has an inlet and outlet (e.g. a surface water pumping station), where net infiltration or drainage occurs:

$$IO_{region} = \sum_{cell=1}^{ncell} Q_{cell}^{inf} - \sum_{cell=1}^{ncell} Q_{cell}^{dm} \quad (1)$$

where IO_{region} is the total inflow or outflow to or from a region, Q_{cell}^{inf} is infiltration, and Q_{cell}^{dm} is drainage for a grid cell. In the case that IO_{region} is negative, the region lacks water and needs to be supplied by surface water from outside the region. Because the simulation with QROUTE occurs after the groundwater model simulation, the total surplus or shortage for the entire network of connected regions can be calculated and translated to the boundaries of the surface water system (Fig. 2(b); B_1 and B_2). The water balance for the entire network can be written as:

$$\sum_{i=1}^n B_i = \sum_{j=1}^m IO_j \quad (2)$$

where B_i is a boundary term at location i and IO_j the inflow/outflow term for region j . The summation of inflow and outflow at n inlet/outlet boundaries B_i is equal to the summation of m inflow/outflow terms IO_j from the regions. A quantity restriction can be imposed on the boundaries for either the inflow or outflow volumes to simulate, for example, a maximum capacity of a pumping station.

The water balance for segment flow (Q -terms) is expressed in terms of segment flow components related to a specific region (region flow) or to a connection (connection flow). By definition, a region is connected with a maximum of two segments, see Fig. 2. In the case of two segments, regional flow can be expressed as:

$$Q_i - Q_j + IO_{region} = 0 \quad (3)$$

A connection can have more coupled segments, see Fig. 2. Connection flow can then be expressed as:

$$Q_1 - \sum_{i=2}^n Q_i = 0 \quad (4)$$

Let us consider the system in Fig. 2 as an example. Segment flow through segment 4, Q_4 can be written as: $Q_4 - Q_3 + IO_3 = 0$. Q_4 can also be expressed as connection flow: $Q_4 - Q_5 - Q_{15} = 0$. There are 16 unknowns, $Q_1 \dots Q_{16}$. The 10 inlet/outlet points of the regions and six connecting nodes (two boundary nodes and four internal nodes) provide 16 independent linear equations (3) and (4) involving these unknowns. The system of linear equations is solved using LU factorization, see Press *et al.* (1992). Figure 3 illustrates the surface water system of Fig. 2 in matrix notation.

Conservative mass balance components Conservative mass transport is calculated by routing the components of groundwater seepage and precipitation recharge drained from the regions through the surface water system. If the concentrations of a conservative solute in recharge and seepage water are known, the surface water quality can be calculated in each segment and consequently at the outlet. For each grid cell in a region with a drainage surplus, the drainage water is labelled proportional to the amount of recharge and seepage. The drainage water surplus from a region is routed through the network. The surface water quality in the segment downstream of the region is calculated proportional to the flow components of the region and the upstream segment according to:

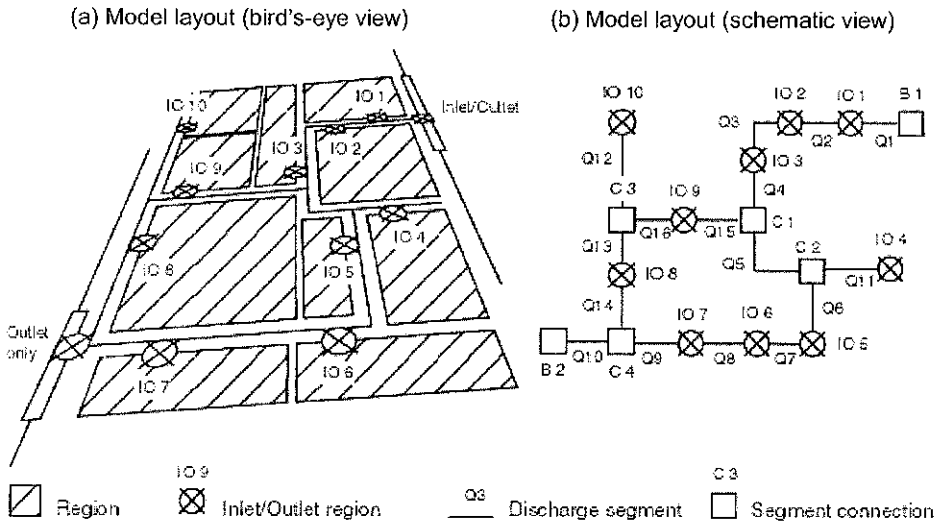


Fig. 2 Definition of a hypothetical model layout (a) and the schematic transformation for the surface water routing model (b).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	IO-terms	Q-terms
1 (B1)	1																	50	50
2	-1	1																-5	45
3		-1	1															-20	25
4			-1	1														-35	-10
5				-1	1										-1			0	-10
6					-1	1					-1							0	-15
7						-1	1											-10	5
8							-1	1										-20	-15
9								-1	1									-10	-25
10									-1	1				-1				0	-150
11											1							25	25
12												1						25	25
13												-1	1		-1			0	-75
14													-1	1				-50	-125
15				-1	-1										1			0	0
16															-1	1		-100	-100
17 (B2)										-1							1	150	0

Fig. 3 Coefficient matrix and solution for segment flow (Q -terms) for the hypothetical polder layout shown in Fig. 2, in which the total lack of water ($200 \text{ m}^3 \text{ day}^{-1}$) divided over the inlet B1 ($50 \text{ m}^3 \text{ day}^{-1}$) and B2 ($150 \text{ m}^3 \text{ day}^{-1}$). Flow terms to/from the regions (IO -terms) are known from the groundwater model.

$$\alpha_i = \frac{\alpha_i * Q_i + \alpha_{region} * Q_{region}}{Q_i + Q_{region}} \tag{5}$$

for the recharge component, where α_i is the fraction of recharge in segment i and α_{region} the recharge fraction in the specific region, and similarly:

$$\beta_i = \frac{\beta_i * Q_i + \beta_{region} * Q_{region}}{Q_i + Q_{region}} \quad (6)$$

for the seepage component, where β is the fraction of seepage. The third component in the system is the surface water inflow, described by:

$$\gamma_i = \frac{\gamma_i * Q_i}{Q_i + Q_{region}} \quad (7)$$

where γ_i is the surface water inflow fraction. The surface water inflow component will be diluted as regions contribute water to the segments. All incoming flow components are processed up to a connection to calculate the correct surface water quality. The surface water quality is then routed in the direction of the flow to the next region and/or connection. In this way the surface water quality changes during the routing depending on the alternation and sequence of draining and infiltrating regions.

APPLICATION TO THE REEUWIJK AREA

Reeuwijk is a polder area below sea level with a very dense surface water system and several pumping stations to regulate surface water levels (Fig. 4). This results in large volumes of the excess water being discharged from the area during wet periods and water being recharged into the area during dry periods. Dynamic surface water control was simulated to assess the potential reduction of water inflow and outflow. A regional MODFLOW model was constructed and calibrated on groundwater head (Gehrels *et al.*, 2000) using the method of representers (Valstar, 2001; this volume). The calculated groundwater fluxes were then coupled with the surface water network in QROUTE.

RESULTS

Measured and simulated flow rate

The measured and simulated surface water inflow (negative) and outflow (positive) components from the entire surface water system of the Reeuwijk polder area are shown in Fig. 5. Only the positive outlet values are comparable, because only the water outflow is measured at the pumping station. The figure shows that there is good agreement between the measured and simulated outflow.

Dynamic surface water control

The effect of dynamic surface water control is shown in Fig. 6. Under the present conditions, water is discharged immediately after a rainstorm to keep the water levels constant, resulting in sharp discharge peaks at the pumping station. Consequently, water inflow is needed regularly. In the case of dynamic surface water control, water levels will rise after rainstorms and fall in dry periods, and hence water inflow and

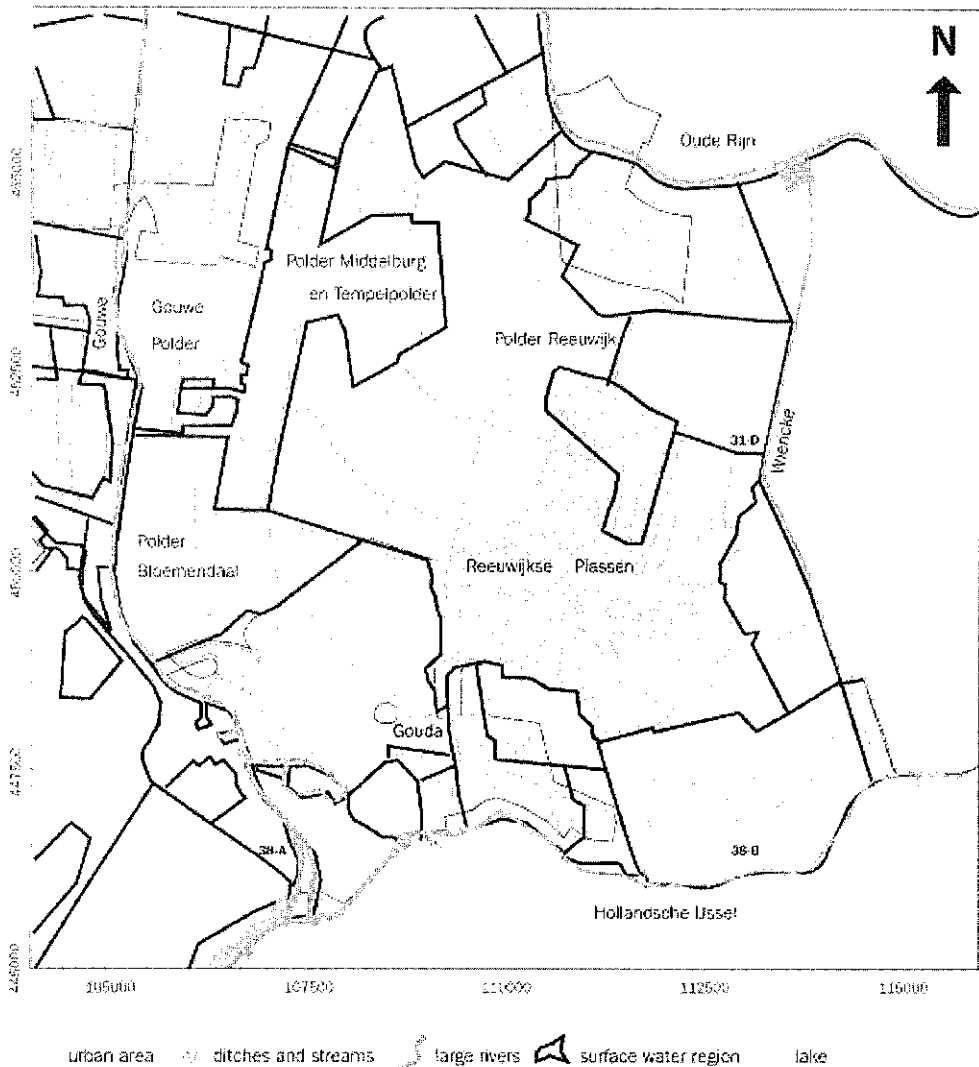


Fig. 4 Map showing the Reeuwijk area in The Netherlands and the surface water system divided into regions with a specific inlet/outlet.

outflow will be substantially reduced. Under the conditions simulated for the scenario of Fig. 5, with a realistic groundwater level range of 40 cm, the outflow volume was reduced by 30% and in the inflow volume was reduced by 85% over 1996.

Decrease of chloride concentration

The surface water quality in the Reeuwijk area is poor because of high chloride concentrations, both in the brackish seepage water as well as in the surface water inflow. Dynamic surface water control increases the conservation of precipitation in the area, and in this way, decreases the surface water chloride concentrations. The Cl

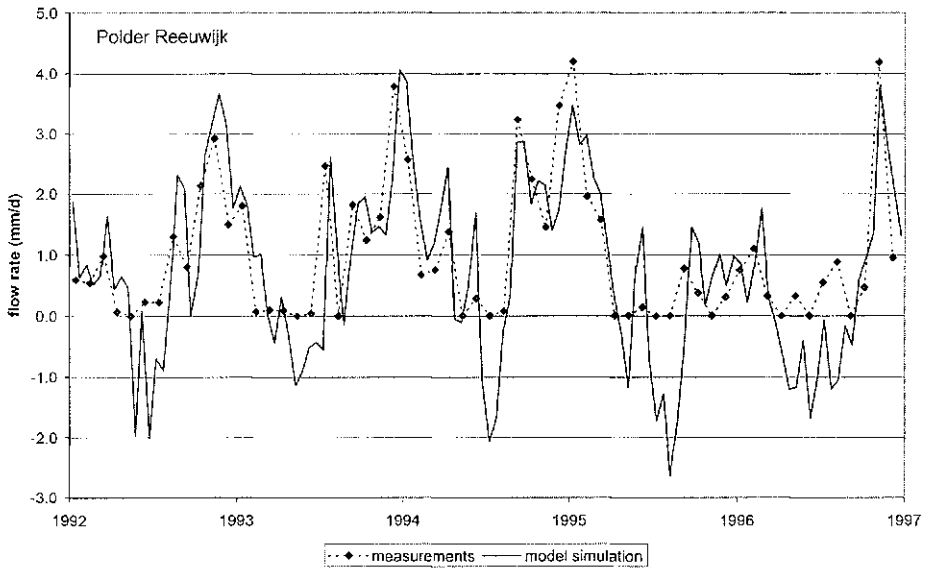


Fig. 5 Surface water outlet (positive) and inlet (negative) flow rate from the Recuwijk polder area, monitored at the pumping station (symbols) and simulated (solid). Note that only water outlet is monitored, inlet is unknown.

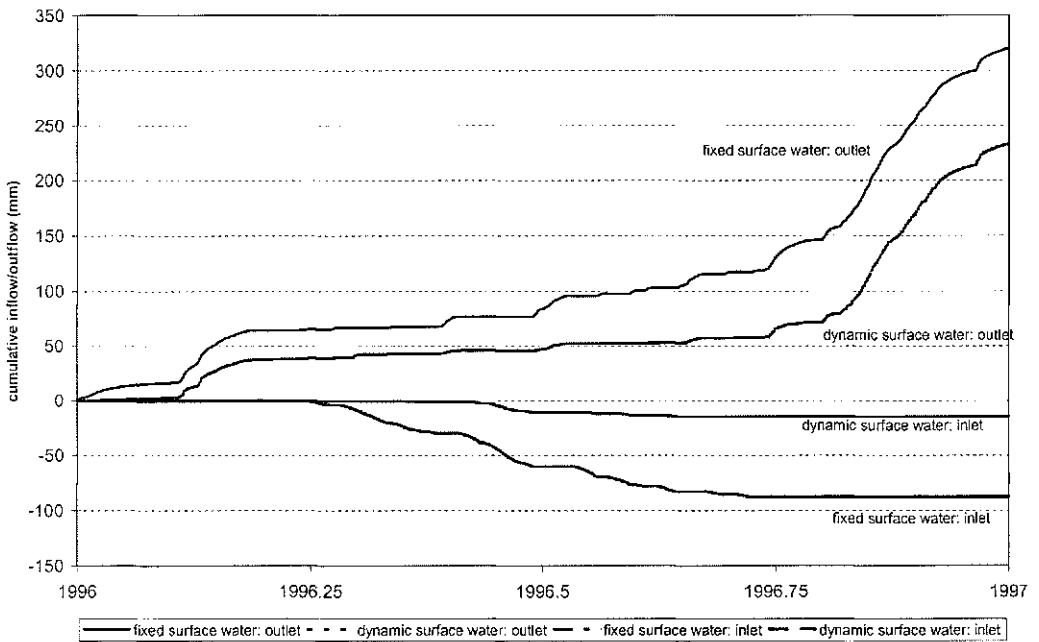


Fig. 6 Cumulative outlet (positive) and inlet (negative) flow rate (mm), calculated on a daily basis with the QROUTE-MODFLOW model for the present situation of fixed surface water control and for the dynamic surface water control alternative.

concentrations at the pumping station outlet decreased on average from 74 to 64 mg l^{-1} . Expressed in mass, the relative reduction was larger, from 2900 kg day^{-1} to 2200 kg day^{-1} , as the flow rate also decreased.

CONCLUSIONS

The MODFLOW RIVER package was adapted to be able to simulate dynamic surface water levels. A new surface water model was developed that is capable of routing water and conservative mass through a groundwater driven surface water system. The model code, QROUTE, was combined with MODFLOW to analyse the effects of dynamic surface water control on water conservation and water quality in a polder area in The Netherlands. The study shows that dynamic surface water control can result in a substantial conservation of precipitation water within the area. For Reeuwijk as shown here, this also resulted in an improvement of the water quality.

REFERENCES

- DUFLOW (1995) A micro-computer package for the simulation of one-dimensional unsteady flow and water quality in open channel systems. Manual, edition 2.1. Published jointly by IHE, Ministry of Public Works, Delft University of Technology, Agricultural University of Wageningen, Stowa. Distributed by EDS, Leidschendam, The Netherlands.
- Gehrels, J. C., Kremers, A. H. M., Te Stroet, C. B. M., Vermeulen, P. T. M., Van Wirdum, G., Van der Gun, J. A. M. & De Lange, G. (2000) Analysis of sustainable water management in the rehabilitation area of Reeuwijk: dynamic water as a guideline for water conservation and dynamic surface water control (Uitwerking duurzaam waterbeheer in het Herinrichtingsgebied Reeuwijk; Bruisend Water als leidraad voor waterberging en dynamisch peilbeheer). *NITG-00-128-B*, Netherlands Institute of Applied Geoscience TNO-National Geological Survey, Delft, The Netherlands.
- McDonald, M. G. & Harbaugh, A. W. (1988) A modular three-dimensional finite-difference ground-water flow model. In: *US Geological Survey Techniques of Water-Resources Investigations Report*, book 6, chapter A1.
- Ngo, T. (1994) *Coupled Groundwater and Surface Water Model Moduflow* (Koppeling tussen grondwatermodel en oppervlaktewatermodel Moduflow). Report, published jointly by Delft University of Technology, Waterworks Overijssel (WMO), Delft, The Netherlands.
- Press, W. H., Teukolsky, S. A., Vetterling, W. T. & Flannery, B. P. (1992) *Numerical Recipes in Fortran: The Art of Scientific Computing* (second edn). Cambridge University Press, Cambridge, UK.
- Prudic, D. E. (1989) Documentation of a computer program to simulate stream-aquifer relations using the modular, finite difference, groundwater flow model. *US Geological Survey Open-file Report OF 88-0729*.
- Schaffranek, R. W., Baltzer, R. A. & Goldberg, D. E. (1981) A model for simulation of flow in singular and interconnected channels. In: *US Geological Survey Techniques of Water-Resources Investigations Report*, book 7, chapter C3.
- Swain, E. D. & Wexler, E. J. (1991) A coupled surface-water and ground-water flow model (MODBRANCH) for simulation of stream-aquifer interaction. *US Geological Survey Techniques of Water-Resources Investigations Report*, book 6, chapter A6.
- Swain, E. D. (1993) Documentation of a computer program (Streamlink) to represent direct flow connections in a coupled ground-water and surface-water model. *US Geological Survey Techniques of Water-Resources Investigations Report 93-4011*.
- Valstar, J. (2001) Inverse modelling of groundwater flow and groundwater mass transport. In: *Impact of Human Activity on Groundwater Dynamics* (ed. by H. Gehrels, N. E. Peters, E. Hoehn, K. Jensen, C. Leibundgut, J. Griffioen, B. Webb & W. J. Zaadnoordijk) (Proc. Symp. at Maastricht, The Netherlands, July 2001). IAHS Publ. no. 269 (this volume).