Impact assessment of measures in the upstream part of Dutch basins to reduce flooding

ERIK QUERNER & MENNO RAKHORST
Alterra, PO Box 47, 6700 AA Wageningen, The Netherlands
erik.querner@wur.nl

Abstract Flooding in the northern part of The Netherlands has caused serious economic threats to densely populated areas. Therefore a project has been carried out in a 1200 km^2 area to assess the retention of water in the upper parts of river basins as a way to reduce the downstream flooding. The physically-based groundwater and surface water model SIMGRO was used to model the hydrology of the basins. The model was calibrated using discharges and groundwater levels. Scenarios of measures to assess the possibility of retaining water in the upper parts of the basin were defined and tested. One measure was the retention of higher discharges using culverts or gates, the other was to make the streams shallower and thereby, increase flood plain storage. The analysis indicates that holding water in the upstream parts of the basins proved to be feasible and can result in significant reductions of peak flows.

Key words drainage basin; rainfall; evapotranspiration; groundwater; surface water; modelling; river basin; scenario

INTRODUCTION

Worldwide there has been an increase in the number of floods and droughts that effect large numbers of people and cause enormous economic losses. In the period 1990 to 1998 the number of recorded flood disasters in Europe was higher than in the previous three and a half decades (EEA, 2001). Because of this situation it is clear that measures have to be taken to reduce the impact of these extreme hydrological events. To analyse such extreme events and possible mitigation measures, tools were used to evaluate them in terms of eco-hydrological impact and their effect on agriculture.

The Netherlands was originally a marshy delta formed by the rivers Rhine and Meuse. A rise in sea level, coupled with subsidence of the ground level means that more than half the country is now below sea level (the low-lying part); the remainder is only slightly above sea level. Throughout the country the water table is shallow (between 0.3 and 2.5 m below the soil surface) and a dense network of engineered watercourses is needed to drain the land. Because of these engineered watercourses, water can flow quickly from the upper part of the basins. However, during recent extreme rainfall events in the northern part of The Netherlands the rapid flow from the upper parts of the basin caused by the flooding of polders resulted in a serious threat of flooding of densely populated areas downstream.

After a Dutch national study "Water Management in the 21st Century" a policy was adopted to retain more water in the upper part of river basins in order to avoid flooding in the downstream parts. As part of this national study, measures designed to retain water were analysed in six basins across The Netherlands (Querner, 2002). Understanding the hydrology in these basins provided a proper basis for decision making on feasible measures. Analysis of the complex, and engineered Dutch river systems requires the use of a combined groundwater and surface water model to predict the effect of measures on a regional scale. In this study the SIMGRO model was used (Querner, 1997). This model simulates the flow of water in the saturated zone, the unsaturated zone and the surface water. The model is physically-based and therefore suitable for use in situations with changing hydrological conditions.

In order to make an integrated river basin management plan for the northern part of The Netherlands, one of the problems to solve is how to reduce the peak discharge. The question is: How to retain more storm water in the upper parts of basins? In this paper we report on a project carried out to assess the possible retention of water in the upper part of a river basin. It describes very briefly the SIMGRO model, the schematization of the study area, the input data and then the scenarios and results.

SIMGRO MODEL

SIMGRO (SIMulation of GROundwater and surface water levels) is a physically-based distributed model that simulates regional transient saturated groundwater flow, unsaturated flow, actual evapotranspiration, sprinkler irrigation, streamflow, groundwater and surface water levels as a response to precipitation, and groundwater abstraction. For a comprehensive description of SIMGRO, including all the model parameters, readers are referred to Querner (1997) or van Walsum *et al.* (2004).

To model regional groundwater flow, as in SIMGRO, the system has to be schematized geographically, both horizontally and vertically. The horizontal schematization allows input of different land uses and soils, in order to model spatial differences in evapotranspiration and moisture content in the unsaturated zone. For the saturated zone, various subsurface layers are considered. The finite element procedure is applied to the flow equation which describes transient groundwater flow in the saturated zone. The unsaturated zone is represented by two reservoirs, one for the root zone and one for the underlying soil. The calculation procedure is based on a pseudo-steady state approach. The height of the phreatic surface is calculated from the water balance of the subsoil below the root zone, using a storage coefficient. Evapotranspiration is a function of the crop and moisture content in the root zone.

In the model the surface water system is considered as a network of reservoirs. The inflow of one reservoir may be the discharge of the various watercourses, ditches and runoff. The outflow from one reservoir is the inflow to the next reservoir. The water level depends on surface water storage and on reservoir inflow and discharge. In the model, four drainage subsystems are used to simulate the interaction between surface water and groundwater. This interaction is calculated for each drainage subsystem using a drainage resistance and the difference in level between groundwater and surface water.

The SIMGRO model is used within the GIS environment Arcview. This allows the possibility of using digital geographical information (soil map, land use, watercourses, etc.) in order to convert these to input data. Further use is the presentation of results and analysis of these together with specific input parameters.

STUDY AREA AND MODEL SCHEMATIZATION

The modelling area covers 1200 km^2 and is located in the northern part of The Netherlands (see Fig. 1). The area of main interest is approximately 750 km^2 and covers the basins of the river Drentsche Aa and Peizerdiep. The ground surface slopes from about 24 m above NAP (reference level in the Netherlands) in the south to about –1 m in the north. The area consists of sandy soils in the upper parts with clay and peat in the stream valleys and the lower part. Land use is predominantly agricultural and forest. About 42% is in pasture, 24% is arable land, 18% is woodland, 11% residential and 5% is other. For the meteorological input data five stations spread over the area were used (Querner *et al.*, 2005).

For the SIMGRO model the groundwater system needs to be schematized by means of a finite element network. The network, comprising 49 050 nodes, is spaced at about 200 m in the interest area, but in the stream valleys it is spaced at 75 m. For the modelling of the surface water the basin is subdivided in 5625 sub-basins. The difference in height of about 25 m means that 570 weirs were constructed in the past to control the water level and flow. Most of the weirs are adjustable, so that the target water level in summer can be raised. The lower part near or below sea level has 58 pumping stations and 41 inverted siphons.

The geology of the area is quite complex, due to influences from the Pleistocene period, permafrost, tectonic movements, and influences from wind and water. A major influence on the groundwater flow patterns is the resistant impermeable layers formed by boulder clay that cause large areas with perched water tables. The groundwater system in the model is build up of four aquifers that are interlaid with three less permeable layers. The second layer consists of the boulder clay. The interaction between groundwater and surface water is characterized by a drainage resistance. This resistance is derived from hydrological parameters and the spacing of the water courses.

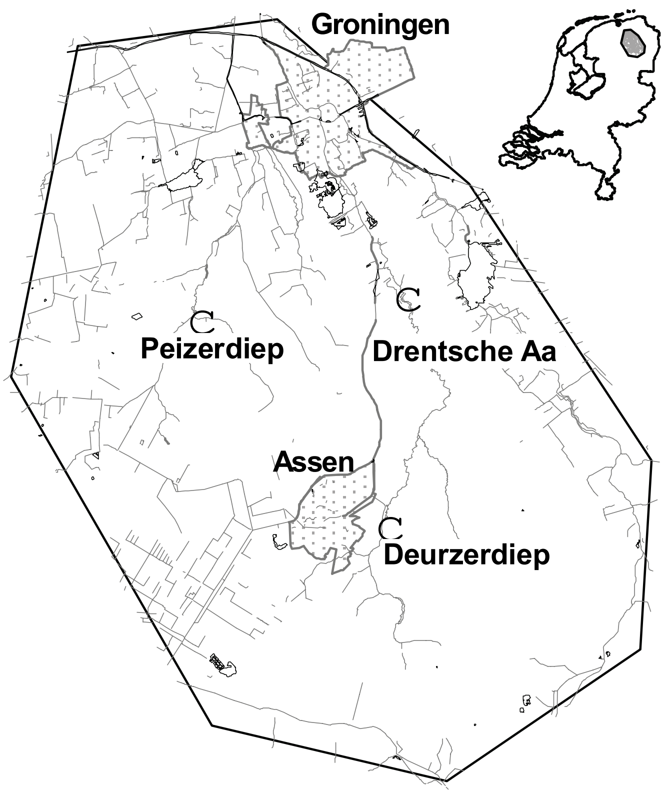

Fig. 1 Location of the modelling area and the main water courses in the northern part of The Netherlands (Rakhorst, 2005).

Perched water tables

The initial Simgro model was not able to simulate the perched water tables caused by the boulder clay (model layer 2). In large areas this resulted in phreatic groundwater levels that were 1–3 m too low. Therefore the model was adjusted so that, on the basis of the hydraulic head below and above the boulder clay, the vertical resistance is corrected to simulate the flux through this clay layer correctly. Also the storage coefficient above and below the clay layer was changed during the calculations depending on the presence of the perched water table. After the model was improved, calculated phreatic levels were close to the measured ones (see next section).

RESULTS OF SIMGRO MODELLING

Present situation

Simulations were carried out for a period of 10 years (1989–1999). The results were compared with measured river discharges (nine locations) and groundwater levels (about 800 piezometers). For three main gauging stations, as shown in Fig. 1, Table 1 gives the measured and calculated discharges. The discharges are given for a recurrence interval of once in five years to a recurrence interval of 15 times per year (denoted as 15× year^{-1}). The last column in Table 1 gives Q95, the flow occurring less than 5% of the time. For the Drentsche Aa the calculated discharge is a bit higher than measured (about 8–20%). For the other two streams the differences are smaller, in the order of 2–14%. When comparing hydraulic heads, for more than half the total number of piezometers, the difference in measured and calculated head is less than 0.25 m. Comparing only the phreatic levels: for the 332 phreatic piezometers there are 239 with a difference less than 0.5 m and 145 with a difference less than 0.25 m. These differences between measured and calculated results were regarded as small, so it was concluded that the final model can be used to analyse possible measures to hold water in the upstream part of the basin.

Table 1 Measured and calculated discharges for three gauging stations ($m^3 s^{-1}$) in the northern part of The Netherlands (for recurrence intervals see text).

Gauging station		Discharge for the given recurrence interval:				
		5 year	1 year	5× $year^{-1}$	15× $year^{-1}$	Q95
Drentsche Aa	Measured	11.02	8.91	6.97	5.48	0.57
	Calculated	13.63	11.57	7.58	6.24	0.36
Deurzerdiep	Measured	14.45	11.52	6.34	4.00	0.27
	Calculated	14.05	11.59	6.24	4.31	0.14
Peizerdiep	Measured	13.64	10.45	6.57	5.01	0.08
	Calculated	13.44	10.47	5.97	4.37	0.12

Mitigation measures and the impact

Mitigation measures were defined that would reduce the peak discharges to acceptable volumes. In this research the following measures were analysed:

- **Restrict peak discharges**
  Peak flows can be restricted by installing sluice gates or culverts of such a dimension that only the higher peaks are reduced. In the simulations, the opening of these constructions was such that the flow will be restricted when the flow is higher than occurring one day a year.
- **Make the streams shallower**
  Reducing the depth of the water course will result in water overtopping the side banks and thus increase the amount of water that is stored on the flood plain. The storage of the water on the over banks will reduce the flow propagations and thus reducing the peak flow.

In Fig. 2 the upstream part of the Drentse Aa where measures were considered is shown. At eight locations the flow was restricted and over a length of 29 km the streams were made shallower. In Table 2 the results are shown for the two sub basins; it gives the discharge for the reference situation, the two measures and the change in flow. The impact of the first measure (restrict peaks) is more than the second (shallower streams). Limiting the flow by introducing gates or culverts,

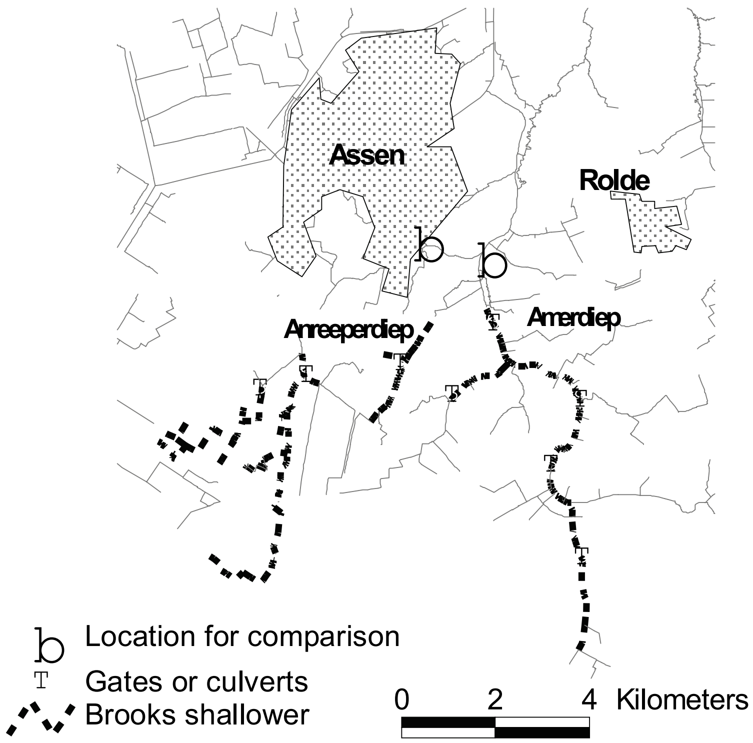

Fig. 2 Location of the mitigation measures carried out in the upstream part of the Drentsche Aa.

Table 2 Change in discharges ($m^3 s^{-1}$) for two sub basins and the two measures as shown in Fig. 2.

Location	Scenario	Discharge for a given recurrence interval				
		10 year	5 year	1 year	5x year^{-1}	15x year^{-1}
Amerdiep	Reference	13.180	9.620	5.418	3.078	2.227
	Gates	5.321	4.980	4.603	3.138	2.245
	Reduction (%)	60	49	15	–2	-1
	Shallower streams	10.078	9.056	4.994	3.071	2.246
	Reduction (%)	24	7	8	0	-1
Anreeperdiep	Reference	9.121	5.807	3.379	1.939	1.472
	Gates	6.973	3.741	3.019	1.972	1.476
	Reduction (%)	24	36	8	–2	0
	Shallower streams	8.475	5.526	3.438	1.929	1.433
	Reduction (%)	7	4	2	1	1

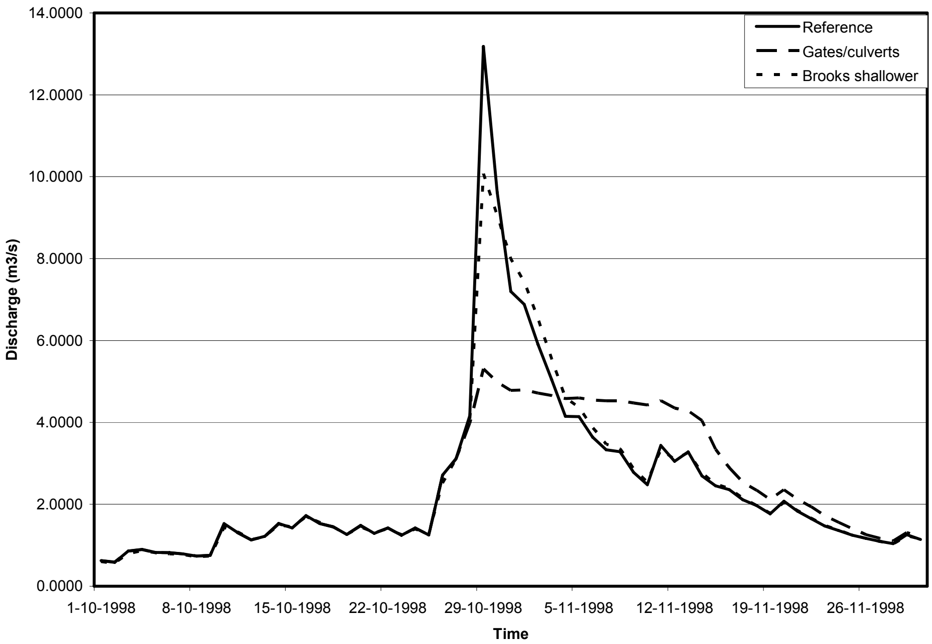

Fig. 3 Discharge for reference situation and the two measures for an extreme wet period in 1998.

means a decrease in peak flow of the order of 25–50%. The large variation depends on local conditions and the number of structures in a stream. Limiting the flow has very little influence on groundwater levels, because the water flow is obstructed only for a number of days or weeks. Local flooding may occur and thus groundwater levels rise. This small and short rise, often in winter time, has no apparent effect on agriculture or nature.

When the stream is made shallower, the reduction of peak discharges is of the order of 5–20% (Table 2). The consequence of this measure is higher water levels in both wet and dry periods. The flow reduction is mainly caused by the water overflowing the river banks and flooding the valley. As a consequence, the groundwater levels adjacent to the stream will be higher. In general the higher levels may have a positive influence on the presence of rare and protected marsh species.

When the above measures are introduced the peak flows will be reduced and discharge is spread over a longer time period. As an example, in Fig. 3 the flow situation is given for October and November 1998, a period with extreme rainfall in the Northern part of The Netherlands. Figure 3 shows the calculated discharge for the present situation and the two measures. In the reference situation the duration of the high flow was about one week, but after flow restriction the maximum flow is much smaller as it is spread over a period of 2.5 weeks (Fig. 3). When the streams are made shallower, the maximum peak reduces, but the flood wave looks very similar to the present situation.

CONCLUSIONS AND DISCUSSION

The physically-based Simgro model was able to simulate streamflow in basins with different land use and climate conditions. The model calibration was limited, but the simulation results show that the model gives satisfactory estimates of the discharges and groundwater levels. The model is therefore an adequate tool to simulate streamflow, and has the potential to assess the impact of measures to reduce flooding.

This study has shown that ecosystems of lowland catchments where the groundwater levels have been lowered by extensive land drainage can be restored by restricting the flow from the upper parts. Holding water in the upstream parts of the basins is feasible. The delay of the peak flow is significant. Limiting the flow by introducing gates or culverts, means a decrease in peak flow in the order of 25–50%. To make the stream shallower results in reduction of peak discharges in the order of 5–20%.

For extreme situations, such as occurred in October 1998, it is also possible to use measures to reduce peak flows that have a recurrence of once in 10 or 50 years. In that way the choice is explicitly to accept local flooding in the upper parts of a catchment where mostly agricultural land is situated, instead of flooding high densely populated areas more downstream.

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REFERENCES

EEA (2001) Sustainable water use in Europe. Part 3: Extreme hydrological events: floods and droughts. *Environmental issue report no. 21*. European Environment Agency, Copenhagen, Denmark.

Querner, E. P. (1997) Description and application of the combined surface and groundwater model MOGROW. *J. Hydrol.* **192**, 158–188.

Rakhorst, M. (2005) Reduction in peak discharges for the Streams in Northwest Drenthe; estimated with the SIMGRO model. MSc Thesis, Wageningen University, Wageningen, The Netherlands (in Dutch).

Querner, E. P. (2002) Analysis of basin response resulting from climate change and mitigation measures. In: *FRIEND 2002–Bridging the Gaps Between Research and Practice* (ed. by H. van Lanen & S. Demuth) (Fourth Int. Conf. on Friend, Cape Town, South Africa, March 2002), 77–84. IAHS Publ. 274. IAHS Press, Wallingford, UK.

Querner E. P., Rakhorst, M., Hermans, A. G. M.& Hoegen, S. (2005) Exploring the possibilities to retain water on the Drents Plateau; Pilot in Northwest Drenthe (in Dutch). *Alterra Report 1240*. Alterra, Wageningen, The Netherlands.

Walsum, P. E. V. van, Veldhuizen, A. A., van Bakel, P. J. T., van der Bolt, F. J. E., Dik, P. E., Groenendijk, P., Querner, E. P.& Smit, M. F. R. (2004) SIMGRO 5.0.1, Theory and model implementation. *Alterra Report 913.1*. Alterra, Wageningen, The Netherlands.