Analysis of basin response resulting from climate change and mitigation measures

ERIK P. QUERNER
Alterra, PO Box 47, 6700 AA Wageningen, The Netherlands
e-mail: e.p.querner@alterra.wag-ur.nl

Abstract The very wet conditions of recent years in Europe have made it clear that measures will have to be taken in this century to prevent flooding. Therefore this study analyses the changes in peak discharge resulting from climate change and the efficiency of mitigation measures. A scenario study was set up, using the SIMPRO model, to simulate shallow groundwater flow locally and water flow in a network of water courses regionally. The climate scenarios represented the period 2050–2100, which is expected to be warmer and wetter. Three mitigation measures to reduce these peak flows were studied. The discharge analysis was done for five regions of The Netherlands, ranging in size from 25 to 142 km^2. The results suggest that climate change would increase peak discharges by 10–30%. Of the three mitigation measures analysed, reducing peak discharges by gates or culverts was found to be very effective; it could cancel out the effect of climate change.

Key words drainage basin; climate change; mitigation measure; rainfall; evapotranspiration; groundwater; surface water; modelling; scenario

INTRODUCTION

The very wet conditions of recent years in Europe have made it clear that measures will have to be taken in this century to prevent flooding. The anticipated climate change will have a crucial effect on the functioning of surface water systems. The question is how to manage the increased peak discharges and/or the increased hydrological risk. This paper reports on a project carried out as part of the Dutch national study "Water Management in the Twenty-first Century" to predict the changes in peak discharge resulting from climate change and to assess the efficiency of mitigation measures.

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 following the drainage of peat bogs and their conversion to farmland means that more than half the country is now below sea level (the lowlying 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 water courses is needed to drain the land.

The design of drainage systems in The Netherlands is often based on discharge rates calculated with analytical prediction models. These models predict the discharge from an area, without considering typical local conditions, such as storage of water in the ground or in the open channels, which may differ from generalized or average conditions. To overcome the shortcomings of empirical or analytical methods, an integrated surface and groundwater model, SIMPRO, is used to estimate peak discharges. This relatively simple one-dimensional saturated–unsaturated groundwater model estimates the flow to the surface water system given the conditions prevailing within the area. Using variables such as minimum and maximum water levels over the year, it is possible to calculate whether the criteria, that ensure that surface water levels remain low enough to prevent flooding are met.

The climate change expected will involve more rainfall and thus higher discharges. There are various technical measures that could be applied to reduce the peak discharges. One traditional measure is to increase the discharge capacity of the water courses. Other measures could be the temporary storage of water in designated areas, the retention of water in the basin, and the control of the water level. How effective these measures are depends on the local hydrology and topography. To elucidate this, the impact of climate change and of mitigation measures are calculated in five regions across The Netherlands. In this paper an outline of the modelling approach is given and the variation in peak discharge calculated for the five regions.

SCENARIO APPROACH

A scenario study was set up to quantify the effects of climate change and of mitigation measures using the modelling approach. The change in drainage and discharge in a region to be modelled were used as indicators of these effects. The discharge calculated for the present situation was used as a reference. The climate scenario represented the period 2050–2100, which is expected to be warmer and wetter than the twentieth century and will result in higher peak flows. The mitigation measures were those thought to have the potential to reduce these peak flows to manageable volumes.

Fifty years of meteorological data on a daily basis (1950–1999) were selected for the simulations. During this period the average annual rainfall was 811 mm, high intensity rainfall events of 30–40 mm day^{-1} occurred 34 times, events of 40–50 mm day^{-1} occurred 6 times and events of 50–60 mm day^{-1} occurred 3 times.

The discharges were analysed in terms of frequency of exceedance, i.e. the peak discharges occurring from once per year to the maximum peak within the 50 years of the simulation period. The analyses were conducted for the climate change scenario and the mitigation measures and results are presented relative to the discharge in the present situation.

THE COMBINED SURFACE AND GROUNDWATER FLOW MODEL SIMPRO

The SIMPRO model simulates the local shallow groundwater flow and the regional flow of water in a network of water courses. Being physically based it can be used in situations with changing hydrological conditions. For a detailed description of the model see Querner (1986, 1993). A detailed discussion on performance of such a combined model is given in Querner (1997).

Surface water flow

The surface water system in The Netherlands is often a dense network of engineered water courses. It is not feasible to explicitly account for all these water courses in a regional simulation model, yet the water levels in the smaller water courses are important for estimating the amount of drainage or subsurface irrigation, and the water flow in the major water courses is important for the flow routing. Therefore in SIMPRO the major water courses are modelled explicitly as a network of sections; the other water courses are treated as reservoirs and connected to this network. The model is based on the St Venant equation (Chow, 1959). Because the change in flow rate is relatively small, gravitational forces can be neglected, so that a simple computational scheme suffices without strict limitations on the time step to be used. The model includes special structures such as weirs, pumps, culverts, gates and inlets, necessary for the modelling of all water movements within a certain region. The time step can, in principle, be chosen freely, but for numerical stability it is limited by factors such as section length, change in flow rate, channel geometry, etc. In practice the maximum time step is about 2 h.

Unsaturated zone

The unsaturated zone is represented by means of two reservoirs, one for the root zone and one for the underlying soil (Fig. 1). If the equilibrium moisture storage for the root zone is exceeded, the excess water will percolate towards the saturated zone. If the moisture storage is less than the equilibrium moisture storage, then water will flow upwards from the saturated zone. The height of the phreatic surface is calculated from the water balance of the subsoil below the root zone, using a storage coefficient that is dependent on the depth to the groundwater. The unsaturated zone is modelled one-

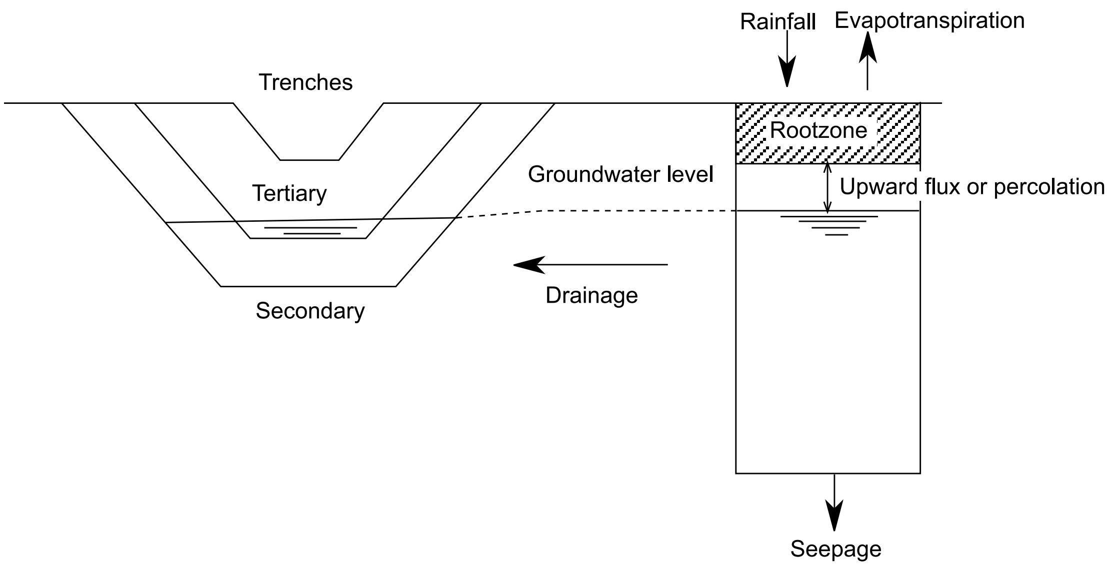

Fig. 1 Schematization of water flows in the SIMPRO model. The main feature of this model is the integration of groundwater and surface water (Querner, 1986).

dimensionally per sub-region and land-use type. Evapotranspiration is a function of the crop and moisture content in the root zone. The measured values for net precipitation and potential evapotranspiration for a reference crop and woodland are used as input. The potential evapotranspiration for other crops or vegetation types are derived in the model from the values for the reference crop by converting with known crop factors.

Saturated zone and drainage

The saturated zone has interactions with the unsaturated zone and the surface water, while there may be leakage or seepage over the lower boundary (Fig. 1). Water courses affect the interaction between surface water and groundwater. In the model, three drainage subsystems are used to simulate the drainage (Fig. 1). It is assumed that these subsystems (ditches, tertiary water courses and secondary water courses) are distributed evenly over a sub-region. The interaction between surface and groundwater is calculated for each drainage subsystem, using a drainage resistance and the difference in level between groundwater and surface water (Ernst, 1978). All drainage water from a sub-region of the groundwater system is allocated to a nodal point of the surface water network.

Linkage of groundwater–surface water modules

As the groundwater part reacts much more slowly to changes than the surface water part, both parts have their own time step. The result is that the surface water module performs several time steps during one time step of the groundwater module. The groundwater level is assumed to remain constant during that time and the flow between groundwater and surface water is accumulated using the updated surface water level. The next time the groundwater module is called up, the accumulated drainage or subsurface irrigation is used to calculate a new groundwater level.

ANALYSIS OF DISCHARGES BY SIMPRO

Study areas and schematization

The discharge analysis was carried out in five regions of The Netherlands, ranging in size from 25 to 142 km^2 (Fig. 2) and representing the country's major landscape areas. They were selected because modelling studies had been carried out on them previously, so data availability was not a problem. The output of the model has been verified for the study areas and results compared well with observed data. Typical characteristics of the five regions are given in Table 1 (Grontmij, 2000). Drentse Aa and Baakse Beek are higher-lying areas, indicated by a higher range of elevation in the region (Table 1).

For the SIMPRO model the surface water and groundwater needs to be schematized for surface water in sections with nodes on either side and for

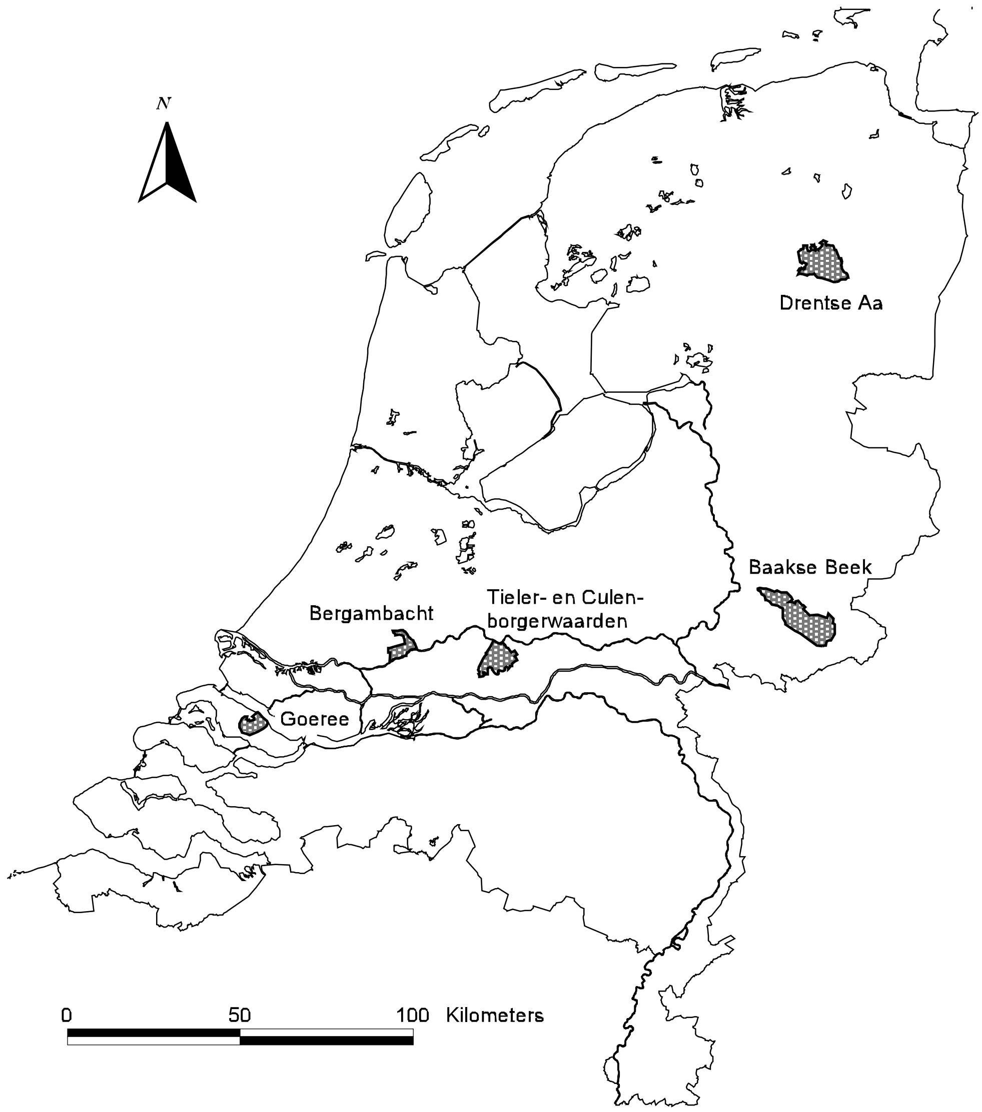

Fig. 2 The five areas in The Netherlands used to estimate the discharge characteristics (typical characteristics of the regions are given in Table 1).

Table 1 Typical characteristics of the five regions used for the discharge analysis (the location of the regions is given in Fig. 2).

Name of region	Area (km^2)	Soil type	Range of elevation in the region (m)
Drentse Aa	105	Sand and boulder clay	7
Baakse Beek	142	Sand	20
Tieler- en Culenborger-waarden	62	River clay	1.8
Bergambacht	25	Peat	0.4
Goeree	44	Marine clay	0.4

groundwater in sub-regions. For example, for the Drentse Aa region the surface water was discretized in 44 nodes and 43 sections, and 39 sub-regions were considered for the groundwater.

Climate change

Climatologists anticipate that the climate in 2050–2100 will be warmer and wetter. It has been estimated that the average temperature will rise in the order of 2–4°C (Table 2). For a temperature rise of 2°C the average annual rainfall will increase by 6% (by 2% in summer and by 12% in winter) and the annual evapotranspiration will increase by 8% (Grontmij, 2000). It is further expected that the high rainfall events (>10 mm day^{-1} in winter and >20 mm day^{-1} in summer) will increase by 20%. Based on these expected changes the 50 years of meteorological data (1950–2000) were transformed into a new series applicable for the 2050–2100 period.

Table 2 Anticipated increased rainfall and evapotranspiration for a rise in temperature of 2°C and 4°C (Grontmij, 2000).

	Rise in temperature: 2°C	4°C
Yearly rainfall	+6%	+12%
Total summer rainfall	+2%	+4%
Total winter rainfall	+12%	+25%
High rainfall events*	+20%	+40%
Increased evapotranspiration	+8%	+16%

* Events >20 mm day^{-1} in summer and >10 mm day^{-1} in winter.

Mitigation measures

The expected climate change will bring about increased peak discharges and therefore mitigation measures were defined that would reduce these peak discharges to acceptable volumes. The following measures were analysed:

(a) *Increase in area of open water*. Currently, about 1–2% of the areas is open water. The mitigation measure assumes that the percentage is increased five times in all areas, except for the Bergambacht area, which currently has 15% of open water, and for which, therefore, the percentage of open water was doubled.

(b) *Increase in flow resistance*. The flow resistance (Manning *n*) was assumed to be 0.033 in the reference situation and for the mitigation measure it was doubled. This measure can be achieved by reducing maintenance (weed control) and by re-engineering the water courses, so that meandering could start.

(c) *Restrict peak discharges by sluice gates or culverts with a fixed dimension*. 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 water level upstream was allowed to rise by a maximum of 0.1 m compared to the reference situation. This criterion was used in order to prevent too wet conditions. The measure was applied in only 50% of each of the five areas.

The measures described above could have beneficial or adverse impacts on, for example, agriculture or urban areas. For agriculture, changes in groundwater levels could be more favourable for crop production, but could also be negative by creating too wet or too dry conditions. These effects were not considered in the analysis.

RESULTS

Running the model for the present situation in the five regions gave discharges between 6 and 10 mm day^{-1} for an occurrence interval of once a year and discharges between 11 and 15 mm day^{-1} for the maximum peak within the 50 years of simulation. Table 3 gives the results for discharges occurring once a year and are given as a percentage increase or decrease from the present situation.

For the different landscapes it appeared that a rise in temperature of 2°C would increase peak discharge between 7% and 19% (Table 3). For all the regions except the Drentse Aa, increasing the high intensity rainfall events by 20% in winter, resulted in an attenuation of runoff and in increasing the peak discharges by only about 10%. The Drentse Aa region, which has sandy soils and boulder clay at shallow depth, coupled with a large (for The Netherlands) range in elevation over the region (Table 1), showed a more direct response to increases of rainfall. A rise in temperature of 4°C gives increased peak discharges between 19% and 33%.

Increasing the open water resulted in peak flows falling by about 3–11%. This measure was more effective in the two lower-lying areas (Table 3). An increased flow resistance had about the same effect on peak discharges as the increase in open water. Reducing peak discharges by gates or culverts was a very effective measure. If applied to only 50% of the area, it could reduce the peak flows by 7–19%, which is of the same order as the increase in peak flows brought about by a temperature rise of 2°C.

Table 3 Change in discharge (%) relative to the present situation, for climate change and for the three mitigation measures (peak discharges occurring once a year).

Name of region	Climate change: 2°C	4°C	Increase in open water	Increase in flow resistance	Restricting peaks
Drentse Aa	19	33	–3	–3	–16
Baakse Beek	7	19	–7	–8	–7
Tieler- en Culenb.	12	25	–5	–15	–15
Bergambacht	11	22	–6	–12	–19
Goeree	10	21	–11	–7	–9

CONCLUSIONS

The climate in Europe is expected to become warmer and wetter during the next century. When temperature rises two degrees, the peak flows from regional water systems will increase by 10–20%. When temperature rises 4°C the peak discharges will increase by 20–30%. Therefore the anticipated climate change results in more frequent flooding and mitigation measures are necessary to cope with the hydrological risk.

The simulations show that increasing the area of open water will not substantially reduce the higher peak flows expected as a result of climate change. However, this measure would increase the water storage capacity in the basin. In extreme situations, when the discharge exceeds the outlet capacity of the basin, a greater storage capacity will result in fewer higher levels of surface water. An increased flow resistance would have about the same effect on peak discharges as the increase in open water. Reducing peak discharges by gates or culverts would be very effective and could cancel out the effect of climate change if it were applied to 50% of the basin area.

This study shows that to adequately simulate the effect of climate change and mitigation measures the model must be comprehensive and integrate surface water and groundwater, because these measures have a great effect on surface water levels and on shallow groundwater conditions. Because the amount of seepage or leakage in the model is used as a boundary condition, in its present form the model can only be applied to situations in which manipulations of water levels have no major influence on the regional groundwater flow. Based on the experience gained in the five regions, the modelling approach can be applied easily in other regions with different climate or hydrological conditions.

The analyses have been carried out for shallow groundwater conditions in The Netherlands and for different landscapes. The differences in the results between the three landscapes were not great. The results, therefore, will be applicable to similar meteorological and groundwater conditions in other parts of the world.

REFERENCES

Chow, V. T. (1959) *Open Channel Hydraulics*. McGraw-Hill, New York.

Ernst, L. F. (1978) Drainage of undulating sandy soils with high groundwater tables. *J. Hydrol.* **39**, 1–50.

Grontmij (2000) *Karakteristieke Respons van Regionale Systemen* (Basin response for regional water systems). Houten, Grontmij and Alterra, The Netherlands.

Querner, E. P. (1986) An integrated surface and groundwater flow model for the design and operation of drainage systems. In: *Hydraulic Design in Water Resources Engineering* (Proc. Int. Conf.), 101–108. Land Drainage, Southampton, UK.

Querner, E. P. (1993) Aquatic weed control within an integrated water management framework. PhD Thesis, Wageningen Agricultural University, also *DLO Winand Staring Centre Report 67, Wageningen*.

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