Integrated catchment modelling: an application to Molenbeek catchment, Belgium

M. Radwan, P. Willems, A. El-Sadek and J. Berlamont
Hydraulics Laboratory, Department of Civil Engineering,
Faculty of Engineering, K.U.Leuven, Belgium

Abstract

Hydrological, hydrodynamic and water quality models are often used to simulate surface water in a correct way to be a good basis for decisions regarding the development and management of water resources. Molenbeek is one of the main tributaries of the River Dender basin (Belgium). The hydraulic model is implemented by using the MIKE 11 software of the Danish Hydraulic Institute (DHI). It is a very detailed physically-based model: measured cross-sections are inserted at least every 40m and all significant structures (bridges, weirs, culverts and control structures) are considered. A simplification to the detailed model is performed to overcome the difficulties of running the model with higher time step (because of numerical instability problems). The simplified model is calibrated to the detailed one to make sure that it has a comparable performance accuracy. In this way, also an accurate and fast model for Molenbeek brook is implemented. The hydrodynamic model is linked with a hydrological model, which was calibrated and validated on the basis of new concepts. In addition, water quality modules (advection-dispersion and water quality) are applied to the river. Therefore, it was important to study the activities (agricultural, domestic, and industrial) that influence the river water and their quality. Model calibration was performed on the basis of available measured flow and water quality data.

Keywords: *rainfall-runoff, hydrodynamic, water quality, modelling, calibration.*

Introduction

In recent years, water resources studies have become increasingly concerned with aspects of water resources. A mathematical simulation model can be considered a major tool for the efficient management of receiving waters. With such a model, a river or watercourse can be simulated to analyse its

observed state. The different physical processes, which underlie the observations, can be identified, making the understanding of the observation possible. A mathematical model also allows the identification of the most efficient measures for the improvement of the observed surface water state (Willems et al. 2000).
The water quality of the receiving waters has decreased a lot all over the world for a few decades now. The data flow through measuring systems makes quantification of this decline possible. To solve the problem, water management authorities and environmental protection agencies all over the world are developing management plans for the water quality of the receiving waters. In these water management plans severer standards for the discharge of polluted water and for dumping pollutants on permeable surfaces are defined. Moreover, a lot of money is invested in water collection and treatment infrastructure (Willems et al. 1996). In this study both aspects of water quantity (hydrological and hydrodynamic modelling) and water quality (advection-dispersion and water quality modelling) are considered.

Hydrological modelling

NAM is an abbreviation meaning precipitation-runoff-model. The Hydrological Section of the Institute of Hydrodynamics and Hydrological Engineering has developed this modelling system at the Technical University of Denmark. In this study it is implemented and evaluated for Molenbeek subcatchment of the river Dender watershed in Belgium. The river Dender is located in the Flemish region of Belgium to the west of Brussels. It is a tributary of the river Scheldt and rises in the Walloon region of Belgium of total catchment area of 1384 km2. The Flemish part of the Dender catchment area is divided into 12 hydrographic subcatchments (zones) and Molenbeek is one of them as shown in Figure 1.

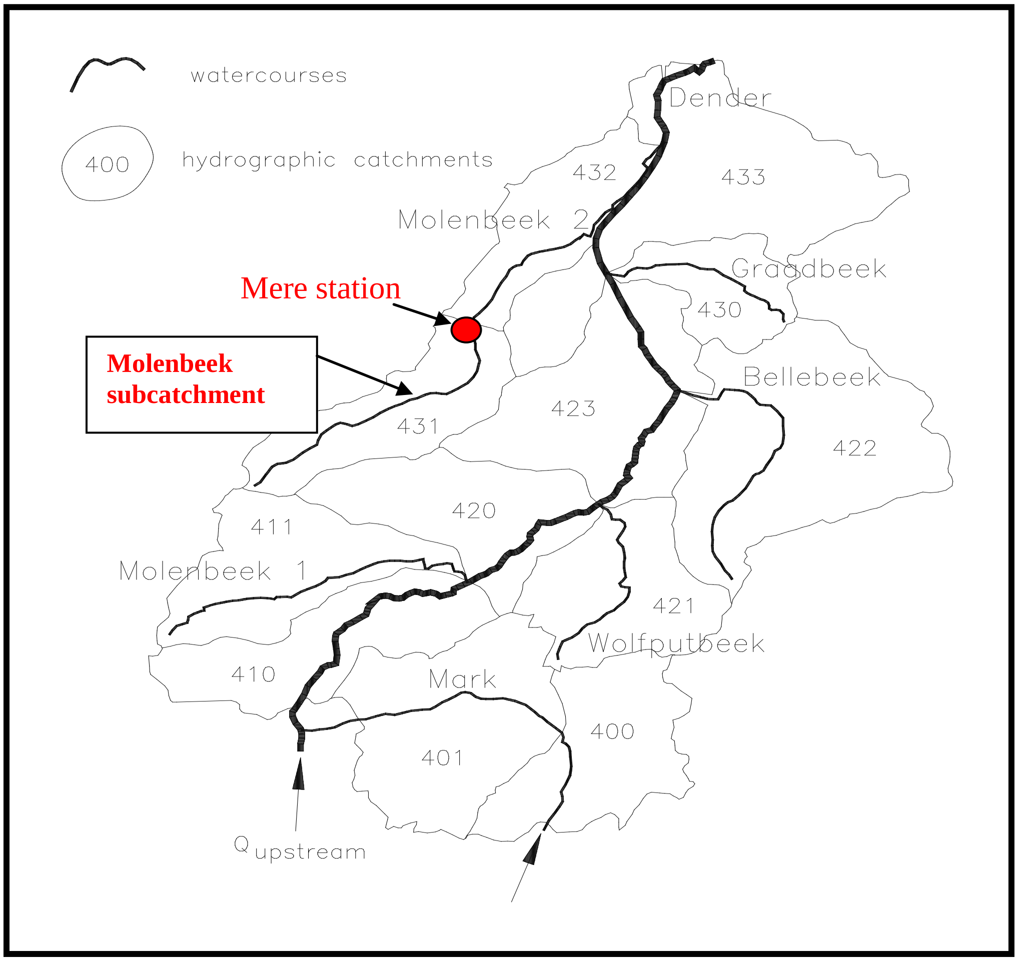

Figure 1. Plan view of the river Dender basin, together with the location Molenbeek subcatchment and discharge measuring (Mere) station.

Calibration methodology

Model calibration is done for two different parameter groups: first the parameters of the routing models (the recession constants or time constants for baseflow, interflow and overland flow). Secondly the water balance parameters (maximum water content in the lower zone storage, maximum water content in the surface storage, and overland flow runoff coefficient. A recursive digital filter is applied (Willems, 1999) to separate total flow to three different subflows: baseflow (groundwater runoff), interflow (sub-surface runoff), and overland flow (surface runoff). The working-principle of the filter can be explained physically as the routing of the high frequency (or quick) subflows through a linear reservoir, with the reservoir constant equal to the recession constant of the signal that is filtered. In this reservoir routing, the routed signal is considered equal to the filtered subflow as it has the same qualitative behaviour in recession periods. The subflows with the largest recession constants are separated first. In this way, baseflow is first separated from total rainfall-runoff discharges, secondly interflow is separated from total discharges of surface runoff and interflow. Finally, the total flow filtered series is the sum of the three filtered subflows. For each filtered subflow, the recession constant is estimated as the average value of the inverse slope of the linear path in the recession periods of a Log (Q) – time graph

After calibration of the recession constants, the water balance parameters are calibrated by trial and error. The procedure is repeated till the maximization of the agreement between the measured and modelled peak discharges and total volumes is achieved. During the calibration procedure of the water balance parameters, the models are evaluated in three steps:

(1) Evaluation of water balance (comparison of simulated and observed runoff volumes).
(2) Evaluation of peak flows and low flows (comparison of hydrograph maxima and minima for the different individual rain storms).
(3) Evaluation of long-term statistics. The observed and simulated discharge values in the full time series are plotted after ranking them in a ascending order.

After calibration, model validation of overall agreement of hydrograph shape is done by directly comparing the simulated and measured time series (Figure 2).

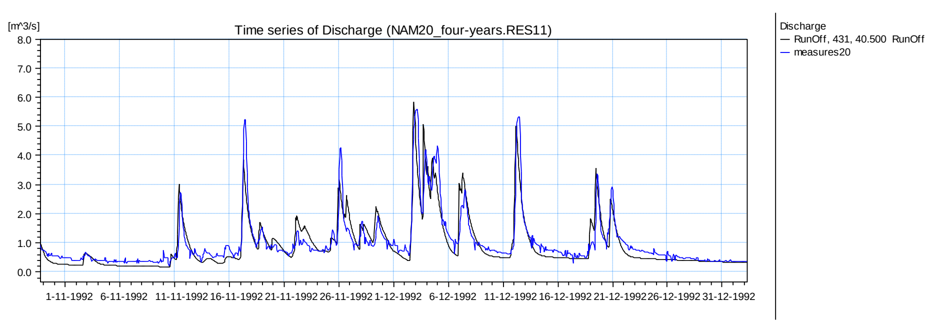

Figure 2. Comparison between measured and simulated discharge series (for a validation period in 1992).

Hydrodynamic modelling

The MIKE 11 hydrodynamic module is a modelling system for the hydrodynamical computation of unsteady flows in rivers by solving the basic hydrodynamic equations in an implicit finite difference scheme (DHI, 1993). The system has been used in numerous engineering studies around the world. For the Molenbeek case study, a full hydrodynamic MIKE 11 model was implemented.

Model Implementation: The total length of the Molenbeek brook is 23043m. For the first 5650m no detailed data about cross-sections and hydraulic structures are available, but for the next 17393m, detailed data about cross sections and all significant hydraulic structures are available. There are 440 cross sections inserted along a distance of 17393m. In this way, the variation in channel shape along the model branches can be described adequately. In total 16 bridges, 16 weirs, 6 culverts and 6 control structures over a distance of 17.393 km are considered. The 6 control structures are present at different locations along the brook to regulate water levels to prevent areas from flooding problems. Those control structures were also modelled. For the first 5 structures, this could be done easily by regulating the constant upstream water levels. But for one weir (structure no.6), the regulation was more complex. The crest level of the structure was regulated on the basis of both up-and downstream water levels. Regulation priorities between upstream and downstream are given below. The highest priority is given last:

(1) For normal conditions, upstream water level should be regulated at 18.9m
(2) If ($h_{upstream}$ < 21.5m) and ($h_{downstream}$ < 19.15m) are true, then downstream water level should be regulated at 19.03m
(3) Downstream water level should be less than 19.15m ($h_{downstream}$ < 19.15m)
(4) Upstream water level should be less than 21.5m ($h_{upstream}$ < 21.5m)

These regulations for control structure no. 6 are working as follows: for normal conditions the water level upstream is regulated at 18.9m. Once the water level is increasing up to 19.03m (the first critical level), crest level should be increased to maintain downstream regulation (to avoid downstream flooding). Whenever the discharge is increasing more, the crest level is increasing to have a downstream level less than 19.15m. If the upstream water level increases up to 21.5m and the downstream level is still lower than 19.15m, there is no problem. But once the upstream level reaches 21.5m (the critical level for upstream flooding), the priority regulation is switched to the upstream level to avoid upstream areas to be flooded by decreasing the crest level of the structure.

Model simulation

Simulations are performed for this detailed model. In the calculation, a distance between computational grid points of 500m is used, and hourly averaged rainfall-runoff input discharges are considered. Due to the very detailed description, a long calculation time is needed: 25 min. on a Pentium processor with 130 MHz speed and 32 Mbyte RAM to simulate 1 day (hydrodynamically).

Model simplification

Due to the big calculation time of the detailed model and difficulties to run the simulation for long periods, also a simplified model has been developed for the Molenbeek brook. The simplification has been achieved by eliminating a large number of cross-sections and by grouping the hydraulic structures. The calibration of the simplified model to the detailed one is done by comparing the Q-H relationships up stream of each group (Figure 3). For group 3, the results are presented in Figure 4. Also at the discharge measuring station (Mere station) a comparison with the measured Q-H relationship is performed (Figure 5).

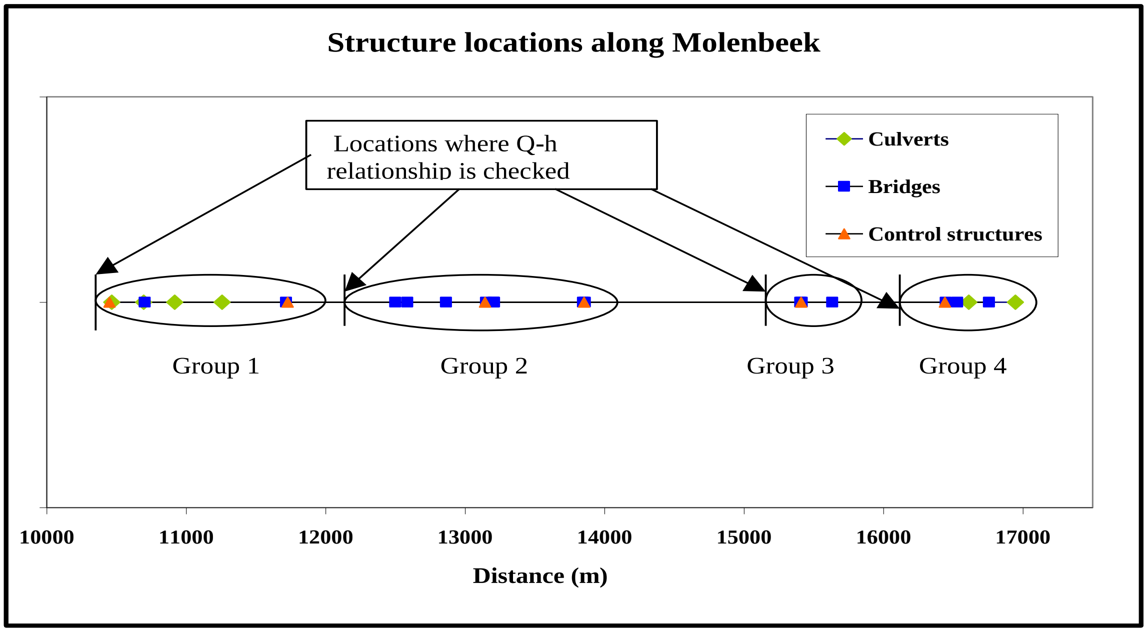

Figure 3 Structure locations along Molenbeek brook

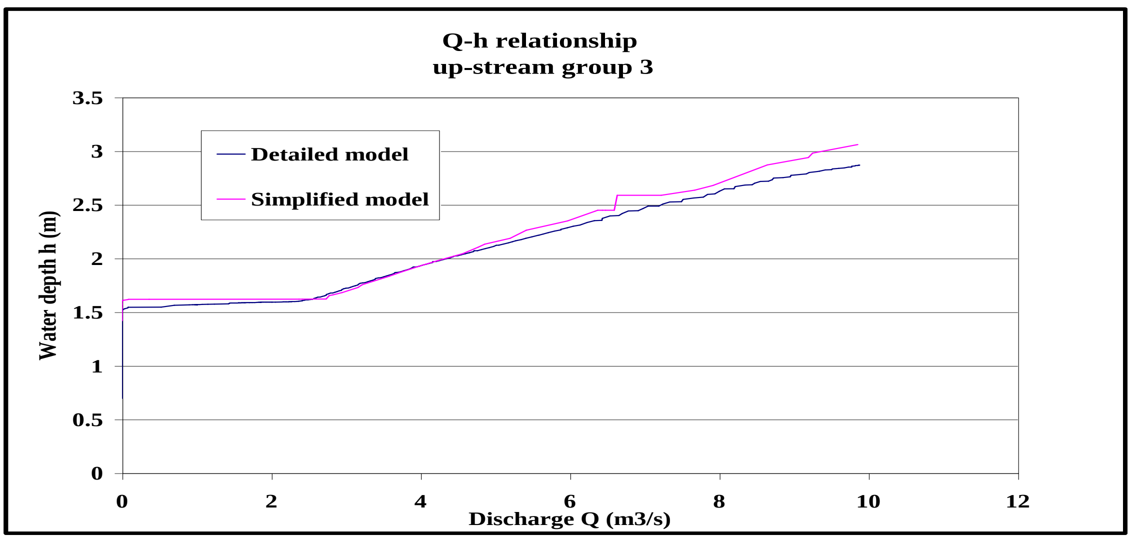

Figure 4 Comparison of the Q-H relationship up stream of structure group 3

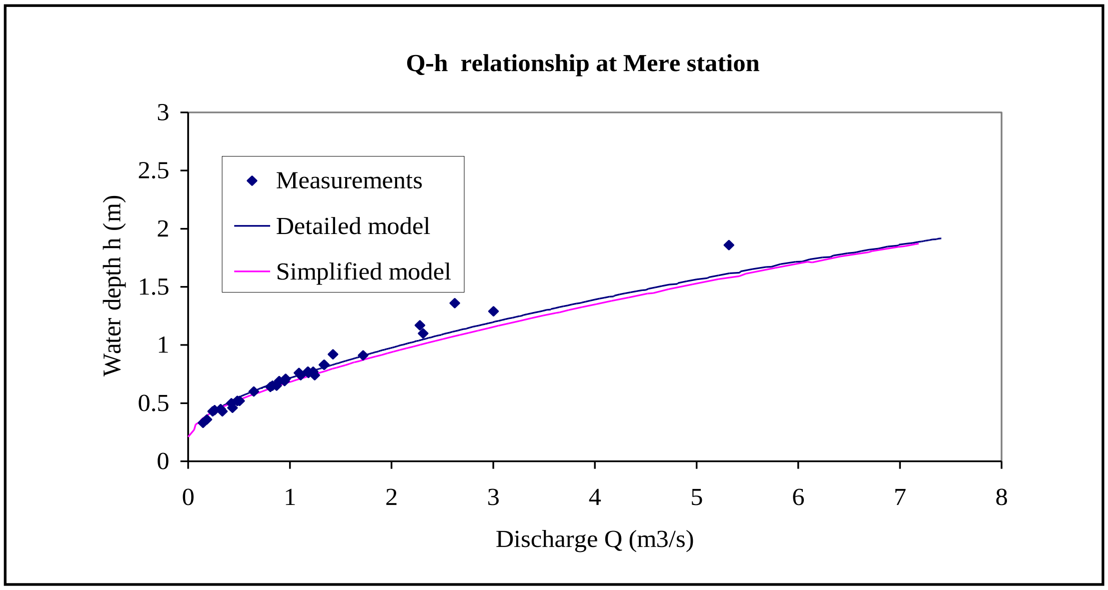

Figure 5 Comparison of Q-H relationship at Mere station

The comparison of the simulation results and the measured Q-h relationship at Mere station show that the dynamics of the system are well represented at lower discharge values (< 2 m^3/s) but with higher discharge values (>2m^3/s) it is underestimated. This is might be explained by some missing data (e.g. culvert under a big highway, local narrowing of the brook) downstream of Mere station. Additional data, which will become available later, and a parallel modelling application with a comparable model (implementation of the ISIS modelling package, HR Wallingford) by a consulting agency in charge of the Flemish authority AMINAL will make this more clear.

Water quality modelling

With the increase in water consumption to satisfy the different demands, the quantities of waste waters to be disposed are increasing rapidly. The continued release of the waste waters has had serious impact on the water quality of the river. Concentrations of dissolved oxygen (DO), biochemical oxygen demand (BOD), ammonium (NH4) and nitrate (NO3) are calculated in MIKE 11 by taking into consideration advection, dispersion and the most important biological, chemical and physical processes.

Sources of pollution

Along the Molenbeek brook, the major sources of pollution are agricultural drainage, industrial and domestic waste water.

Agricultural leaching pollution

Agricultural activities in the catchment are about 76 % of the total area. To estimate nitrate leaching, a DRAINMOD-N (Brevé et al., 1997) model is used.

The DRAINMOD (Skaggs, 1997) model is used to simulate the performance of drainage and related water table management systems. DRAINMOD-N is an add module to DRAINMOD for simulating the nitrogen dynamics in artificially drained soils. Nitrate-nitrogen (NO_3-N) is the main N considered. The model is a quasi two-dimensional model because the nitrogen movement component considers only vertical transport in the unsaturated zone and both vertical and lateral transport in the saturated zone. The controlling processes considered by the model are rainfall deposition, fertiliser dissolution, net mineralisation of organic nitrogen, denitrifcation, plant uptake, and surface runoff and subsurface drainage losses. A detailed description of each functional relationship and a model application in the Netherlands and Flanders is given by El-Sadek et al. (1999&2000).

The climates, soil, crop and crop management data, required as input for the water and nitrate transport modelling, were collected. The distribution over the catchment of the model input and simulation results were presented graphically using GIS (El-Sadek et al. 2000). Combination of soil type and the main agricultural land units resulted in 32 scenarios, being the result of eight soil types and four main field crops. The soil-land use map was overlaid by the parcel map and for each parcel the climate, soil, crop conditions and nitrogen application depth were determined and used as input for DRAINMOD model. The leaching period from 1 January 1990 to 31 December 1993 ($0 < t < 1461$ day) was simulated using the measured NO3-N concentrations on 16 December 1989 as initial condition (El-Sadek et al. 2000). The simulation results are used as input for Mike11.

Industrial wastewater

The industrial wastes are considered as one of the main sources of water pollution, because of their toxic chemicals and organic loading. In the studied catchment there is one factory located at 10.990 km. The pollution load for different water quality parameters was estimated on the basis of measurements of the Flemish Environmental Agency.

Domestic wastewater

Along the Molenbeek brook there are 21 sewerage outlet pipes which receive domestic wastes. For each point the total number of population discharging to it is calculated and then the concentration of rough effluent was evaluated by assuming concentrations of BOD and ammonia equal to 54 and 10 g/capita day

Simulation results

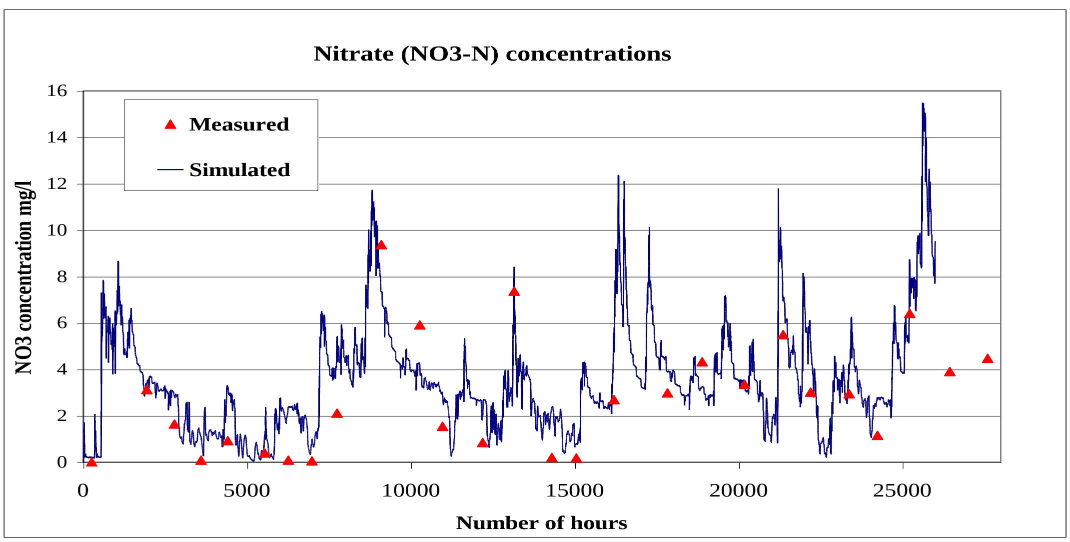

Figure 7 Simulated NO3-N concentrations against measurements

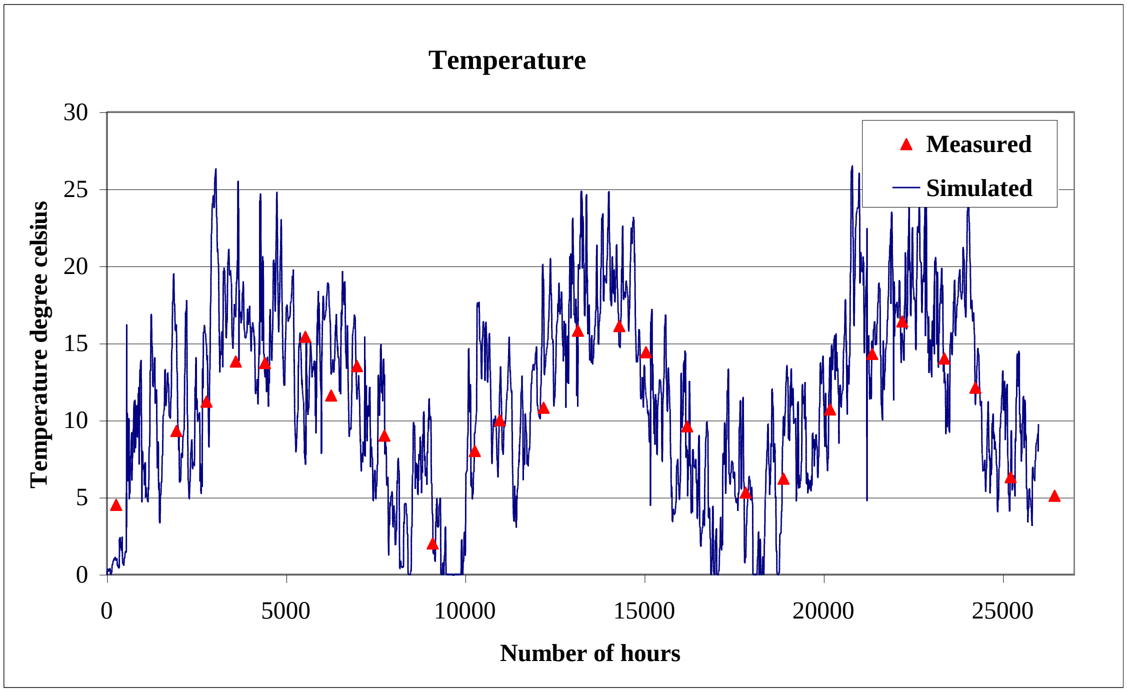

Figure 8 Simulated temperature against measurements

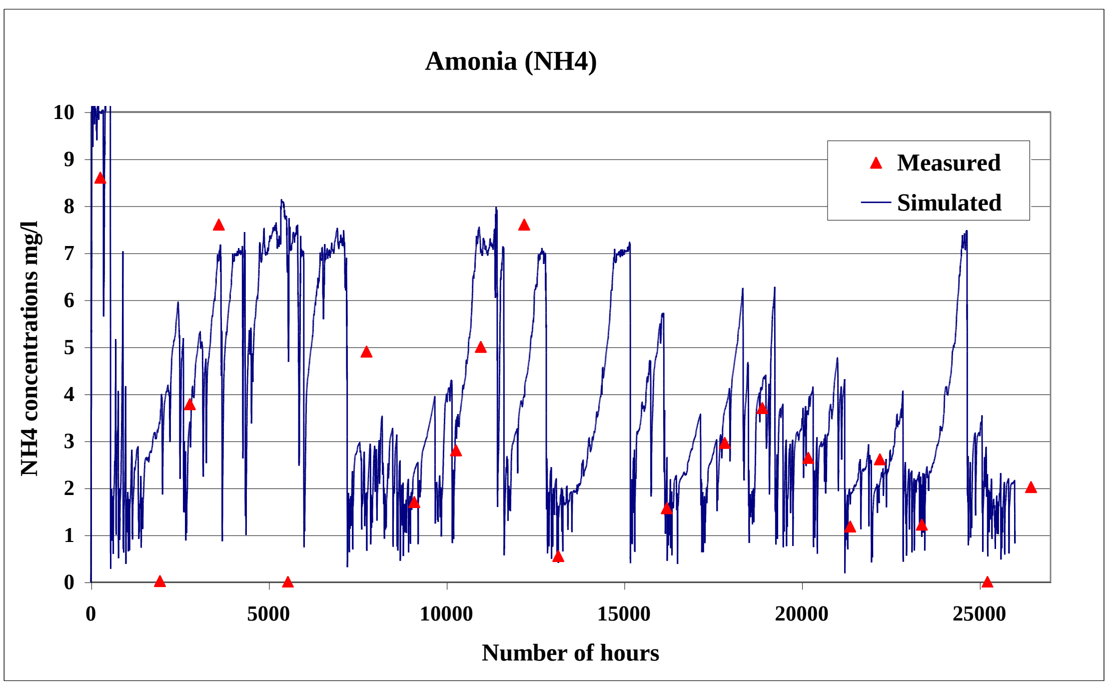

Figure 9 Simulated NH4 concentrations against the measurements

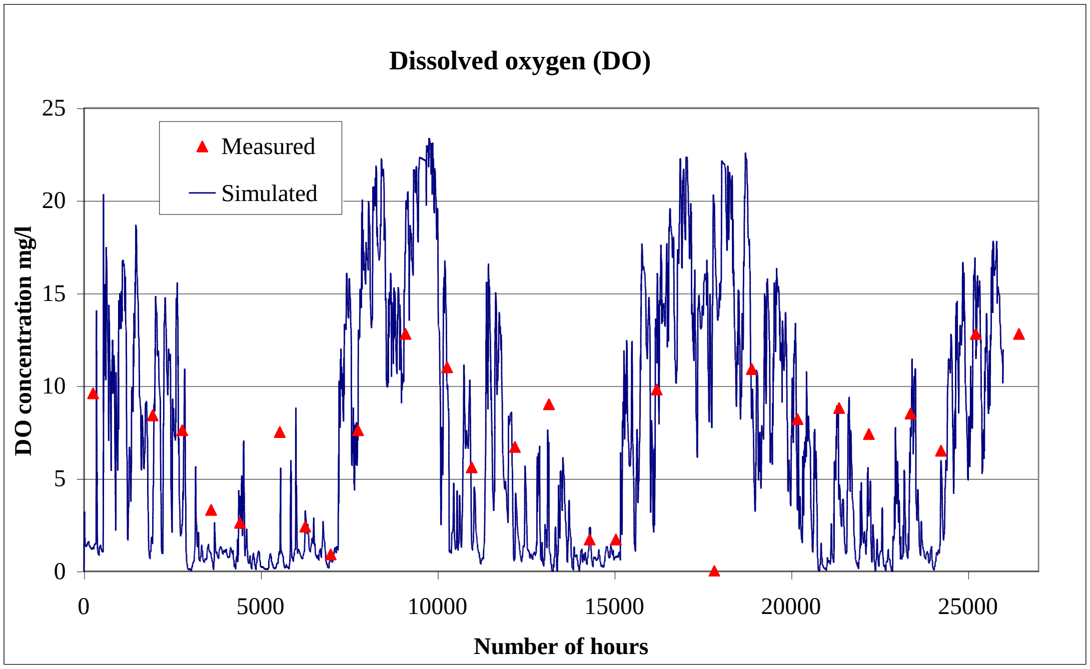

Figure 10 Simulated DO concentrations against measurements

The model was simulated over a period of four years. Observed flows, rain and temperature data for the period 1990 to 1993 were hereby used. The calculations were performed on an hourly basis. From the simulation results, it can be seen that the general performance of the model was satisfactory

Conclusion

Molenbeek is one of the main tributaries of the River Dender basin (Belgium). A hydraulic model is implemented by using the MIKE 11 software of the Danish Hydraulic Institute (DHI). It is a very detailed physically-based model: measured cross-sections are inserted at least every 40m and all significant structures (bridges, weirs, culverts and control structures) are considered. The detailed model was also simplified to overcome the difficulties of running the model with higher time step (because of numerical instability problems). The simplified model is calibrated to the detailed one to make sure that it has comparable performance accuracy. In this way, also an accurate and fast model for Molenbeek brook is implemented. The hydrodynamic model is linked with a hydrological model, which was calibrated and validated in a step-wise way. In addition, water quality modules (advection-dispersion and water quality) are applied to the river. Therefore, it was important to study the activities (agricultural, domestic, and industrial) that influence the river water and their quality. The model was calibrated on the basis of available measured flow and water quality data. The comparison between simulation results and measurements show that the general performance of the implemented hydrological, hydrodynamic and water quality models for Molenbeek brook is satisfactory. Therefore, it can be concluded that surface water quantity and quality can be simulated in an accurate way to be a good basis for decisions regarding the development and management of the brook.

Acknowledgements

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References

Breve, M., Skaggs, R., Kandil, H., Parsons, J., and Gilliam, J., 1992. DRAINMOD-N, a nitrogen model for artificially drained soils. Proceedings of the Sixth International Drainage Symposium, ASAE, St. Joseph, MI 49085-9659, 327-344.

Breve, M., Skaggs, R., Kandil, H., Parsons, J., and Gilliam, J., 1997. DRAINMOD-N, a nitrogen model for artificially drained soils. Trans. ASAE, 40 (4), 1067-1075.

Danish Hydraulic Institute (DHI), 1993. MIKE11, A microcomputer-based modelling system for rivers and channels, User & reference manual, Version 3.1, DHI, Horsholm, Denmark.

Devantier, B.A. & Felman, A.D 1993. Review of GIS application in hydrological modelling. Journal of Water Research Planning and Management 2,119.

El-sadek, A., De vos, J., Ducheyne, S., and Feyen, J., 1999. Analysis of the nitrate leaching to surface waters using a simplified and detailed model approach. Proceeding of the Int. Workshop on Modelling transport processes in soils, EurAgEng's IG on Soil and Water, Leuven, Belgium, 24-26 Nov., 569-579.

El-sadek, A., Willems, P., Christiaens, K., Casteels, C., Ducheyne, S., and Feyen, F., 2000 Modeling of the nitrogen balance at regional scale using a quasi- two dimensional mechanistic model in combination with GIS.

Accepted for the Micro 2000 Congress, 22-27 October, Cape Town, South Africa
Jones, J., 1997. Global hydrology, Addison Wesley Longman Limited, England
Nathan, R. & McMahon, T., 1990. Evaluation of automated techniques for base flow and recession analyses, Water Resources Research, Vol. 26 No. 7, p. 1465-1473.
Nienhuis, P., Leuven, R. and Ragas, A. 1998. New concepts for sustainable management of river basins, Leiden, The Netherlands.
Radwan, M. Willems, P. and Berlamont, J. 1999. Rainfall-runoff modelling as part of integrated watershed management, International Workshop on Modelling transport processes in soils, EurAgEng's IG on Soil and Water, Leuven, Belgium, 24-26 Nov., p. 755-764.
Refsgaard, J. & Knudsen,J., 1996. Operational validation and intercomparison of different to get rid of these random fluctuation types of hydrological models, Water Resources Research Vol. 32, No. 7, p. 2189-2202.
Skaggs, R.W., 1997. Methods for design and evaluation of drainage water management systems for soils with high water tables, DRAINMOD. North Carolina State University, Raleigh, North Carolina, USA.
Viessman, Jr. & G. Lewis, 1996. Introduction to hydrology, Fourth edition, Harper Collins College Publishers, New York, NY 10022, USA.
Voet M., 1991. Frequency analysis of high water discharges in the liminigraphic network of the Flemish Authority for land and water (in dutch). Report, Ministry of the Flemish Community, Flemish Authority for Land Management (Vlaamse Landmaatschappij), 138p.
Willems, P., Huysentruyt, H., and Berlamont, J., 1996. A water quality model as a management tool, Proceedings WEF conference on Urban Wet Weather Pollution, Quebec.
Willems, P., 1999. Probabilistic lumped conceptual modelling of rainfall-runoff from watersheds, Report, hydraulics laboratory, Katholieke Universitiet Leuven, Belgium.
Willems, P., 1999. Transparent physically-based calibration and optimal case-specific construction of a lumped conceptual rainfall-runoff model for watersheds, submitted to Water Resources Research.
Willems, P., Looveren, R., Sas, M., Boglitti, C., and Berlamont, J., 2000 Practical comparison of the modelling systems MIKE 11 and ISIS for hydrodynamic modelling in the Flemish river Dijle catchment, submitted to hydroinformatics 2000, Iowa.