Estimating The Importance Of Topological Routing For Modelling Water And Nitrogen Transport At Catchment Scale

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Keywords: *Nitrogen transport; Watershed modelling; Water quality; Water management.*

EXTENDED ABSTRACT

The catchment management of reservoirs for drinking water supply not only requires knowledge about the nitrogen discharge of every agricultural field. In order to recommend changes in land use management it is much more important to evaluate its influence to the nitrogen concentration in the reservoir. In order to achieve this the influence of processes that take place during transport must be considered.

The transport of mineral nitrogen is associated with water fluxes in the landscape i.e. transport is closely linked to the discharge components surface runoff, interflow and groundwater flow. In the case of surface runoff and interflow, nutrients are passed to subsequent areas where they can be processed by soil processes and plant uptake. These effects are well investigated mainly for riparian zones but not for the hill slope.

In order to estimate the influence of lateral transport processes we applied the Water and Substance Model (WASMOD) (Reiche 1996), which explicitly simulates routing between single model units down to the receiving stream. We simulated two scenarios for a mesoscale catchment. In the first scenario, the routing was properly simulated by the model. In the second case we cut the routing and directed the discharge directly to the receiving stream.

To evaluate the effects of these two scenarios we compared the modelled runoff and nitrogen load to measured data on the catchment scale. Additionally, we compared the model results to measured soil suction at two hill slope catenas equipped with 48 tensiometers.

The comparison of the modelled scenarios showed that the water and nitrogen loads were affected by the routing in different manners. In the case of water, we found only minor differences between the two versions. In general the results of the version with routing are slightly better. This holds for every considered parameter. For the case with routing the soil moisture is higher than in the case without routing. These higher values fit better to the measured data. In the case of runoff we gain only a small improvement by the use of routing while its dynamic is quite similar.

In the case of nitrogen the results were quite different. In the scenario without routing, the loads were significantly overestimated (by 90 %), whereas in the scenario with routing only a slight overestimation (by 11.9 %) was found. The dynamic of the nitrogen load was slightly improved with routing as well. The reason for this big difference in the nitrogen load is the possible plant uptake in the downstream polygons on one hand. On the other hand, the conditions of the model were generally wetter in the case with routing. This higher wetness led to higher denitrification losses because denitrification takes place under anaerobic conditions which are more frequently found under wet conditions.

These findings show that the consideration of topological routing between the model units is of high importance. This is especially true for nutrient transport models. Therefore, the consideration of watershed management problems that deal with water quality issues strongly requires the use of hydrologic models that are able to simulate topological processes.

1. INTRODUCTION

In regions with little groundwater, reservoirs are a major resource for the supply with drinking water. Before Germany was reunited, reservoirs in the eastern part were built without accounting for the specific land use conditions in the contributing area. Reservoirs were even established in catchments which are mostly used for agriculture. As a consequence, water quality problem result. These can be traced back mainly to two influences: (i) diffuse nutrient leaching from farmland and (ii) settlement waste water that is untreated or clarified inadequately. A reservoir system showing this controverse problem in a typical manner is the Weida-Zeulenroda system located in eastern Thuringia (a federal state of Germany) managed by the Thuringian Water Management (TFW). Two thirds of the catchment of the reservoir is used for intensive agriculture (Arbeitsgemeinschaft Trinkwassertalsperren e.V., 2000).

In order to reduce nitrogen inputs to the reservoirs field-specific measures like fertilizer reduction or catch crops are implemented. These measures must be compensated financially by the TFW. To use the financial means cost effectively it is necessary to know on which fields the nitrogen reducing measures have a high influence on the water quality in the reservoir. To estimate this influence three issues must be considered:

1. the mineral nitrogen excess that leaves the field.

2. the transport of mineral nitrogen from the field to the receiving stream. The transport is associated to the water fluxes in the landscape. Thus the transport is closely linked to the discharge components surface runoff, interflow and groundwater flow (Wilkison et al. 2000). In the case of surface runoff and interflow the nutrients are passed to subsequent areas where it can be processed by soil processes and plant uptake (Menzel and Richter 1999). These effects are well investigated for riparian zones (Correll 1997, Blackwell et al. 1999).

3. transformation processes in the stream.

While the first and the third issues are being considered by many hydrological models, the lateral nitrogen transport is often neglected or described in a very simplified way (e.g. by distance reduction or delay coefficients). Therefore we aimed on analyzing the importance of considering the lateral transport processes in models. To investigate its influence we made experiments with the model WASMOD (Water and Substance Simulation Model, Reiche, 1994/1996) which explicitly simulates routing between single model units down to the receiving stream.

2. STUDY AREA

The catchments of the reservoirs of Weida and Zeulenroda are located in the Thuringian Slate Mountains and include an area of about 163 km² (Figure 1). The altitude in this catchment varies between 315 and 565m above sea level. Located in the rain shadow of the Thuringian Forest Mountains, the annual average precipitation is only approx. 690mm. This portion is divided in approx. 210mm runoff and 480mm evapotranspiration annually. The annual average temperature is also low at approx. 7° C. The geology is dominated by clay shists and eruptive rocks. Most of these rocks have a low permeability. This causes interflow to be the dominant runoff process in the region. The soils developed from this bedrock range from shallow rankers to well developed cambisols and fluvisols in the river valleys. The predominant part of the area is used for agriculture (65.5%) and forestry (29.3%). Settlements and traffic areas have a portion of 5% and water areas cover about 0.2% of the catchment (Flügel and Müschen 2001).

Figure 1. The location of the Weida-Zeulenroda catchment (Kralisch et al. 2003).

3. MEASUERMENT PROGRAM

To study not only the impact of lateral routing at catchment scale but also at the field scale, we instrumented two hill slopes in the study area with equipment for hydrological measurements. The land use of the hill slopes was arable farm land which was the most frequent land use in the catchment. The most frequent soil classes were also covered by the test hill slopes. The shape of one hill slope is shown in Figure 2 the other hill slope had a more convex shape.

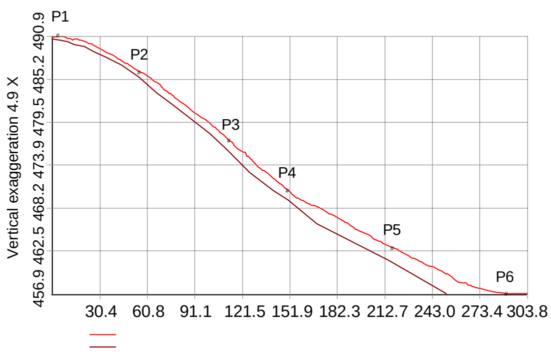

Figure 2. Profile of one of the instrumented hill slopes.

The measurement period was from September 1999 to July 2001. In particular we installed 11 tensiometer stations with up to 5 pressure transducer tensiometers in depths between 15 and 120 cm. At the valley bottom we installed two groundwater gauges. We also established two climate stations to measure precipitation, air temperature, soil temperature, humidity, wind speed and global radiation. All measured data were stored in data loggers at 5 minute intervals. Additionally we undertook field campaigns to characterize the soils and the subsurface. During the soil survey we took samples for soil texture, organic carbon, bulk density, saturated hydraulic conductivity and to determine pF-curves and analysed them in the laboratory. We also studied the structure of the subsurface with seismic refraction (Figure 2). The measured values are used for model parameterization and validation.

4. MODEL VERSIONS

For the modelling of the water and nitrogen dynamics the WASMOD (Water and Substance Simulation Model) model was used. The model structure is designed for plot and catchment scale application. WASMOD simulates the nitrogen discharge as a function of soil, relief, land use and climate data. It describes the considered processes with physically based algorithms. The processes that are described by WASMOD are surface runoff, interflow, infiltration, soil water dynamics, leakage, interception, evapotranspiration, soil temperature nitrogen transport, composition and decomposition of organic substance, plant uptake, phaenology, crop rotation and volatilation. The soil water dynamics is described by the Richard's equation in one dimension. The simulation of nitrogen transport in the soil profile considers advection, dispersion and diffusion. The most important microbiological processes are described by three different organic carbon pools (fresh organic pool, microbiological organic pool and stable organic pool) with different reaction kinetics. The nitrogen dynamics (mineralisation, nitrification, denitrification, plant uptake and vertical transport) are closely linked to the carbon dynamics. WASMOD was used in several studies of water and nutrient dynamic in different scales (e.g. Müller 1987, Reiche 1994, Trepel & Reiche 2002).

An application of WASMOD presumes that GIS-layers of soil, relief, land use, river network, subcatchments and relief units (slopes, sinks and plains) are assembled to smallest common geometries (SCGs). These SCGs result from a polygon overlay union analysis of the GIS-layers mentioned above. The SCGs are not further classified into hydrological response units (HRUs, Flügel, 1996) to preserve the available information. Additionally the HRU concept considering classes of polygons is not suited to model lateral processes between polygons.

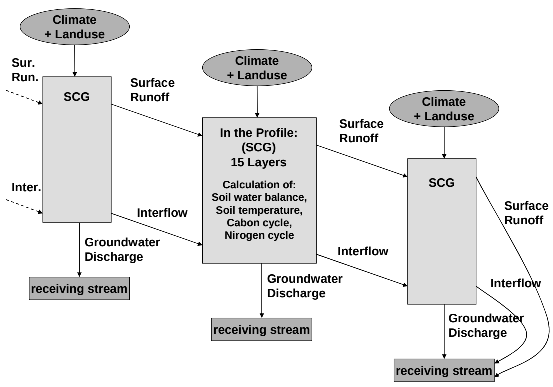

Figure 3. Model routing scheme of WASMOD with lateral transport (Kralisch et al. 2003).

A simplified routing scheme representing the water and substance fluxes in the catchment is shown in Figure 3. The model calculates the water and substance balances in each of the SCGs and routes the fluxes to the next downstream polygon were the calculation starts again. This process ends at the receiving stream where all fluxes are added up.

The sum represents the model output for the whole catchment.

To analyse the influence of the lateral processes the surface runoff and the interflow were cut and routed directly into the receiving stream (Figure 4). The resulting configuration is equivalent to many nutrient transport models like CANDY (Franko et al. 1995), SWAT (Arnold et al. 1998) or RZWQM (Malone et al. 2001), which also do not consider lateral transport between the model units. In the following chapter the calculated scenarios are called “with routing” and “without routing”. In our model application we considered a time period from 1970 to 2000, as temporal resolution we chose daily time steps.

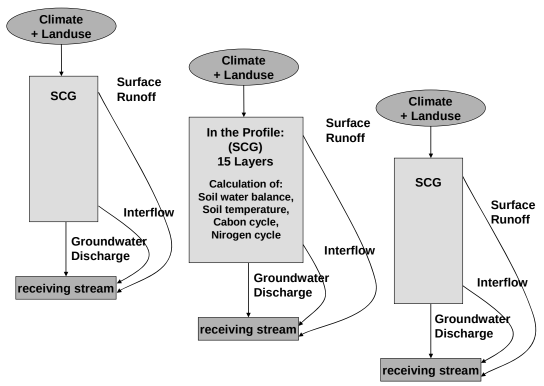

Figure 4. WASMOD model with truncated routing.

5. RESULTS

The results of the model applications for both scenarios were compared with runoff and nitrogen load data from the gauging station Läwitz (catchment size 102 km²) which measures the main inflow to the reservoir Zeulenroda. The instrumented hill slopes are 4 respectively 8 km away from the gauging station. That’s why there is no close correlation between the dynamics of the hill slopes and the gauging station. Figure 5 shows the measured data (blue line) together with the model application results for the scenario with routing (red line) and the scenario without routing (green line). The following figures all have that same colour scheme.

A comparison of the results shows that they are quite similar for both model scenarios. The main difference that can be seen is that the recession curves are less steep with routing. The similarity is also emphasised by statistical parameters like the efficiency R_{eff} from Nash and Sutcliffe (1970). The values for the year 2000 are 0.70 with routing and 0.71 without routing. The mean efficiency from 1997 to 2000 is 0.63 without routing and 0.65 with routing.

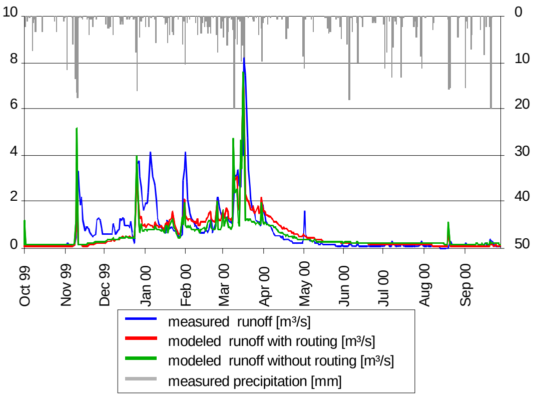

Figure 5. Daily measured and modeled runoff at gauge Läwitz for the year 2000.

Regarding the annual water balance (Figure 6) the curves are rather similar too. The coefficients of determination (R²) for the annual dynamics are a bit lower for the scenario with routing (0.90) than for the one without (0.91). The mean annual derivation shows slightly better results for the scenario with routing (3.95 % to 4.45 %).

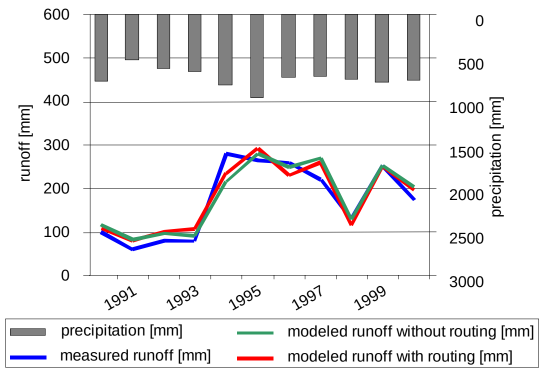

Figure 6. Annual measured and modeled runoff at gauge Läwitz from 1990 - 2000.

We compared the results of both scenarios to the measured values of the instrumented hill slope catenae as well. Examples of the simulation of the soil water dynamics are shown in Figures 7 and 8 where the modelled and measured soil suction is shown. Figure 7 shows an upper hill situation.

The model with routing shows a higher pressure head which means higher soil moisture. These results meet the general expectation that there is more water available with routing. The curves of scenario with routing also fit better to the measurements. The trend that the simulation results fit better with routing also holds for other tensiometer stations form the top to the middle hill position. In the valley, as shown in Figure 8, the results have no general trend. This behaviour is caused by the influence of the near groundwater layer. Also, the deep pressure heads at the beginning of the graph are caused by an erroneous ground water simulation. The groundwater modul of WASMOD strongly relies on the quality of the digital elevation model which had an average error of 4 m elevation that can explain this error. The statistical parameters show almost no difference between the two scenarios. The average correlation coefficient for all treated tensiometers was 0.69 with routing and 0.70 without routing. The standard error was 30 hPa with routing and 29 without routing.

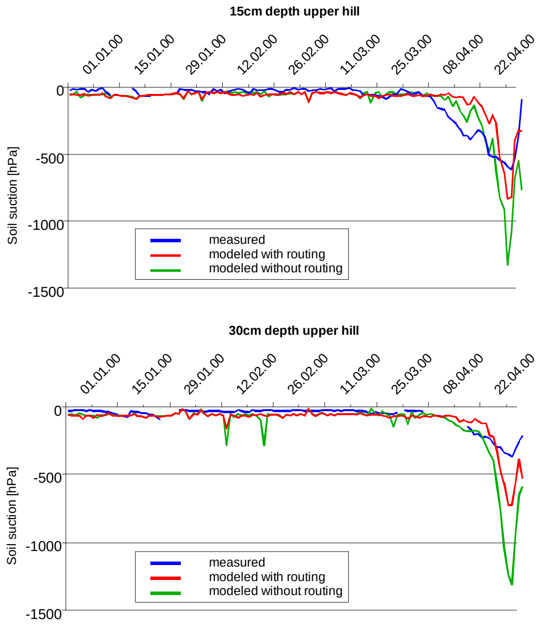

Figure 7. Daily measured and modeled soil suction upper hill in 15 and 30cm depth from January to May 2000.

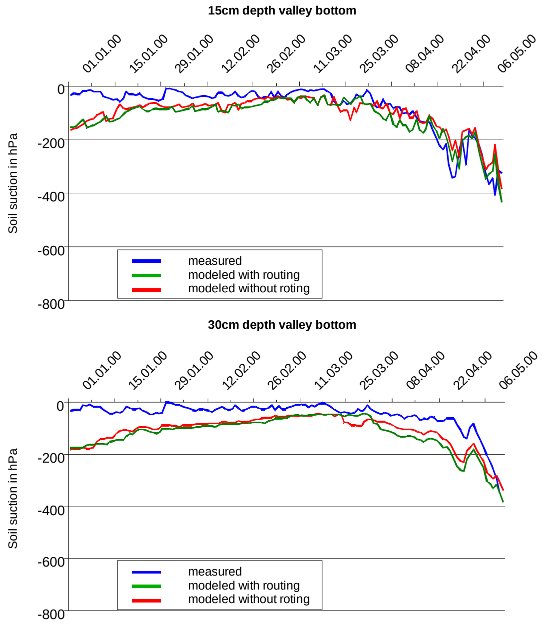

Figure 8. Daily measured and modeled soil suction valley bottom in 15 and 30cm depth from January to May 2000.

In the case of nitrogen load only data of the gauging station were available for a comparison with the simulation results. The results for the year 2000 are shown in Figure 9. It is obvious that both modelled signals are damped strongly compared to the measured one. This damping is caused by to much inertia in the groundwater simulation. The coefficients of determination are 0.65 for the case with routing and 0.62 without routing. The coefficients of determination for the period from 1998 – 2000 was for the case with routing 0.62 and for the one without routing 0.58. This period was used because daily values of nitrogen load were available only in this period.

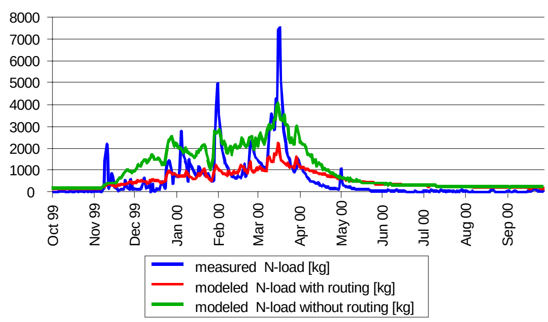

Figure 9. Daily measured and modeled nitrogen loads at gauge Läwitz for the year 2000.

A more important difference between the two scenarios is the annual sum of the nitrogen load as pointed out in Figure 10. The model without routing shows a strong overestimation of the nitrogen load compared to the measured one. Unlike the model with routing, it shows a much better fit to the measured values. The mean annual derivation pointed out this behaviour. The values were 11.8 % with routing and 90 % without routing. The coefficient of determination also shows that the dynamic fits better for the scenario with routing (0.89) than for the scenario without routing (0.85). Since WASMOD does not consider waste water from settlements we added the nitrogen load for 8000 inhabitants (Statistical authorities of the federal states Thuringia and Saxony 2002) to the modelled value. We considered a population equivalent of 13 gN/(d*person) (Witt and Schmoll 1999) and calculated an overall sum of 38 tN/a for the catchment. This amount was added to the model output for every year (Fink 2004).

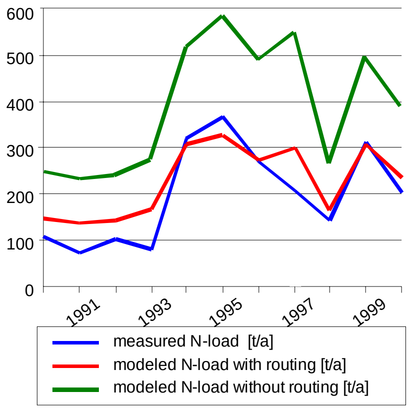

Figure 10. Annual measured and modeled nitrogen load at gauge Läwitz from 1990 - 2000.

The reasons for the distinct differences between the two scenarios are the possible plant uptake in the downstream polygons on the one hand. In the catchment the valleys are normally used as meadows where the fertilization is low. Consequently there is a big potential for plant uptake. On the other hand – as shown above – the conditions of the model with routing are generally wetter. This higher wetness leads to higher denitrification losses because denitrification takes place under anaerobic conditions. These anaerobic conditions can be found more frequently under wet conditions. This effect is also considered by the WASMOD model.

6. CONCLUSIONS

To estimate the importance of routing in water and nitrogen modelling we made experiments with the WASMOD model. We created two model versions, one with consideration of lateral routing processes and one where the routing processes were disabled. We compared the model results with measured values from a gauging station and from pressure transducer tensiometers.

The comparison of the model versions showed that the water and nitrogen loads were affected by the routing in different manners. In the case of water we found only minor differences between the two versions. In general the results of the version with routing are slightly closer to the in-situ measurements. This holds for every considered parameter – runoff dynamic, water balance and soil water dynamic.

The version with routing generally showed higher values of soil moisture which mostly fit better to the measured data. In the case of runoff we gained only small improvements by the use of routing while the dynamic was quite similar. The reason for this behaviour can be found in the short retention time of the surface runoff within the system. Since we considered only daily time steps the surface runoff reached the receiving stream within one time step for both model versions. We expect the version with routing to show more improved results when shorter time steps are considered.

In the case of nitrogen things are different. In the scenario without routing the loads were significantly overestimated (by 90 %), whereas in the scenario with routing only a slight overestimation (by 12 %) could be found. The dynamics of the nitrogen load were slightly improved with routing as well.

These observations show that the consideration of topological routing between the model units is of high importance. This is especially true for nutrient transport models. Therefore, the consideration of watershed management problems that deal with water quality issues strongly requires the use of hydrologic models that are able to simulate topological processes.

7. ACKNOWLEDGMENTS

We would like to thank the Thuringian Water Management (TFW) for funding this project and especially acknowledge the friendly cooperation with our colleagues from the TFW who were involved in this project.

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