Supporting natural resources management in Tasmania through spatially distributed solute modelling with JAMS/J2000-S

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EXTENDED ABSTRACT

To support natural resource management in Tasmania it is important to improve understanding of the coupled hydrologic and nutrient cycle. Of special interests are the detection of diffuse sources, their nutrient specific turnover processes, the relative importance of specific pathways and their connectivity under variable climatic conditions.

The assessment of these processes are especially demanding as in the Tasmanian environments the nutrients levels for freshwater systems are low, e.g. in comparison to European or North-American conditions. Thus evidence has been given that even low nutrient enrichments substantially influence aquatic health by altering the composition of aquatic communities in some parts of Tasmania.

Modelling low nutrient levels for freshwater systems requires deterministic and process-oriented physically-based model components with carefully parameterization as small changes in the modelling output will significantly influence the accuracy of the model results. Therefore an accurate description of the underlain system, input factors and depended variables for water and nutrients turnover is essential. The process-based and fully spatially distributed model JAMS/J2000-S, recently developed at the FSU Jena in Germany was applied in a Tasmanian test catchment (Duck) to cope with the above considerations.

The modelling therefore had the objective to represent dominant processes and pathways occurring in different landscape partitions by

(i) Proofing the applicability of the JAMS/J2000-S model for low nutrient levels.

(ii) Locating source areas contributing high inputs of nitrogen to the Duck River taken its contrasting hydrological and land use systems into account.

(iii) Developing conceptual knowledge for the Duck catchment on spatio-temporal dominant processes controlling water and nutrient releases to guide decision making in natural resource management.

Accuracy indices to quantify the dynamics and percent bias for volume quantification were explored to evaluate model performance. The model was used to estimate the contribution of agriculture inputs to the total load of measured nutrient at the outlet of the Duck basin. It showed good agreement between simulated and measured loads. The application demonstrates the ability to improve the process knowledge of nutrient impacts on freshwater systems at the scale of implementation.

Future investigation will focus on how such a process-oriented distributed model can be

(i) Enhanced by data driven model development and

(ii) Used to develop adaptive land use management strategies for better planning on resource conditions targets.

1. INTRODUCTION

In response to the Tasmanian Government's Natural Resource Management Framework and its enabling legislation (Tasmanian Natural Resource Management Act 2002), three regional bodies have been accredited to manage natural resources in Tasmania. One of the key roles of the natural resource management (NRM) in Tasmania includes the management of water quality and quantity based on a 'whole catchment approach'. Water quality problems have been reported throughout the state related to nutrient enrichment, salinity and erosion problems, mainly caused by agricultural practises (DPIWE, 2003). To improve these conditions, the resource management and planning system includes several stages of activities:

- Describing and assessment of current conditions of disturbance characters for impaired rivers and estuaries to determine the cause-effects on catchment health and economic issues.
- Setting resource conditions targets (RCTs) to scale water quality objectives, e.g. setting targets for improvements the impacts on freshwater and estuarine systems within a give time scale and budget.
- Development of appropriate tools and mechanism to implement on-ground management actions (e.g. initiating incentives like whole farm planning for integrated best management farming practices).
- Establishing a monitoring and review cycle which allows measuring the progress towards the RCTs by carefully selected indicators.

To date a lack of understanding is recognised on how some of these impacted catchments in Tasmania are functioning. To support the natural resource management planning stage a conceptual knowledge is needed for the

- Detection of source location contributing to water quality problems in streams and estuaries
- Assessment of spatio-temporal conditions and processes to be responsible for high releases of impairing constituents.
- Envisage and a priori estimate when the success of RCTs can be expected.

Here a case study from the North-Western parts of Tasmania, the Duck catchment was selected. It is one of the most impacted catchments of Tasmania in respect to nutrients (DPIWE, 2003).

2. STUDY AREA

2.1 Physiographic catchment characteristics

The coastal Duck catchment is located in the North-Western part of Tasmania debouching into Duck Bay through Smithton and finally draining into the Bass Strait (Figure 1). It comprises a catchment area in total of approximately 542 km^2. To avoid calibration problems the catchment outlet for this modelling application was set up about 2.8 km towards the inland to avoid influences of the tidal range. The modelling area therefore covers about 369 km^2.

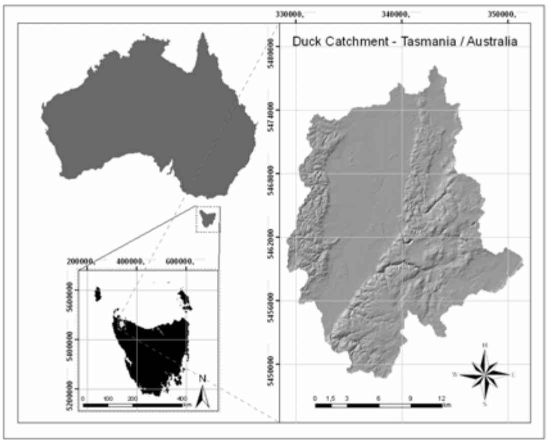

Figure 1: Location of the Duck catchment in Tasmania and entire catchment with the outlet at Scotchtown

The headwater originates in the south-east on rolling low hills, developed on Precambrian mudstones and quartzite. Along the middle and lower reaches on the eastern side of the catchment, a belt of low hills extends formed on sequences of Cambrian greywacke turbidite and basic-intermediate volcanic rocks reflected mainly by tenosols and ferrosols (Richley, 1978). The western margin of this belt is comprised of a clearly defined scarp, which descends 100m to the plains below and was formed on Quaternary sand deposits where dermosols had developed. The mid and lower reaches of the river contain complex alluvial soils (podosols and hydrosols) that are comprised of a mixture of sand and clay with peat present through the deeper drainage lines (DPIWE, 2003). These areas are prone to quick saturation during storm periods and therefore drainage systems have been widely implemented.

The climate is oceanic driven with annual precipitation of approximate 1250 – 1500 mm (Richley, 1978) with a slightly declined in the last years. Rainfall is general higher in the upper reaches due to orographic influences. The highest monthly rainfall occurs in winter, with July and August generally being the wettest months and

February and March the driest through the summer period (DPIWE, 2003). The average monthly maximum temperature is about 21°C occurring during January and February. In contrast the minimum monthly average temperatures are observed in July and August accounting for 6°C (Richley, 1978).

The vegetation and land use varies throughout the catchment according to topography, rainfall and soil type. Upper reaches are covered with forests, partly native vegetation for conservation purpose (15 %). Major landscape modifiers are forestry, particularly clear felling and plantation development (29%). The lower reaches of the catchment had been cleared extensively on alluvial soils for agricultural development such as grazing, particularly of dairy and beef cattle (54%). Many swamps in these areas have been drained and riparian zones are often cleared. Urban areas account for around 1% (Tasmanian Vegetation Mapping Program 2001).

2.2 Water quality in the Duck catchment

Since 1999, monthly water quality data has been sampled for the Duck catchment as a part of the Tasmanian freshwater baseline monitoring program. A data gap occurred between the years 2001-2003. The water quality samples are analyzed for nutrient parameters amongst others, such as total nitrogen and phosphorous, dissolved nitrogen, ammonia, and orthophosphate.

Table 1 provides a summary of descriptive statistical parameters for the nutrient concentrations data of the Duck River. In addition Table 1 shows the reference values of the ANZECC water quality guidelines. These values have been adopted for Tasmanian conditions (ANZECC 2000).

	TP [µg/l]	FRP [µg/l]	TN [µg/l]	NO_x-N [µg/l]	NH4-N [µg/l]
Average	280	111	1300	457	152
Max	2460	918	5300	928	990
Min	18	3	346	74	12
Stdev	0.39	0.17	0.79	-	0.18
CV	1.39	1.56	0.61	-	1.19
ANZECC	13	5	480	190	15

Table 1: Descriptive statistical parameters for N and P species of the Duck catchment (monthly samples from 1999 to 2006)

On average all nutrients exceeded the trigger values for nutrients concentrations of the ANZECC guidelines. The order of magnitude for this divergence differs amongst the nutrients but is strongly observed for ammonia and phosphorous. Minimum values of the nutrients concentrations are generally below the ANZECC guidelines.

In total the high values of the standard deviation and the coefficient of variation (CV) suggests a high variability of the nutrients concentrations. As shown by the discharge-concentration correlation patterns (Figure 2) non-linear relationships are found. Therefore the variability of the concentration levels can not be explained by the flow distribution (Figure 2).

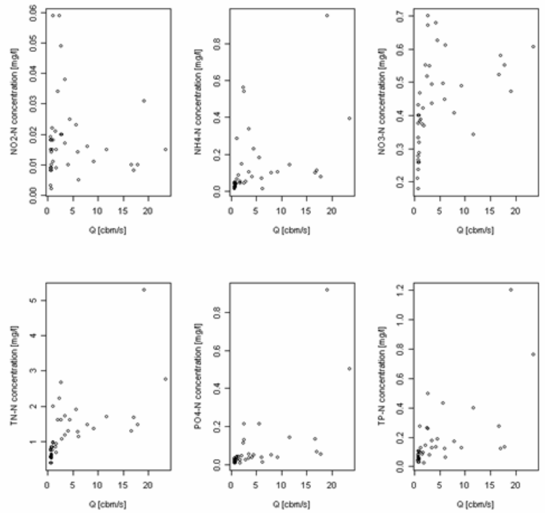

Figure 2: Discharge – nutrient concentration relationship for the Duck catchment (2/2003-12/2006)

In addition the divergence between the total and dissolved nutrients components is relatively high (Table1). About 50% of the total nitrogen load is in dissolved form. Nitrate is usually the dominant constituent followed by ammonia, and then nitrite. On average about 39% of the orthophosphate contributes to the total P. Hence these differences suggest the contribution of organic and/or particulate bounded forms reflecting various sources and possibly different pathways which will be examined by the modelling approach.

3. MODEL APPROACH

To address the scale of implementation for natural resource management the fully spatially distributed model JAMS/J2000-S was used. J2000-S was developed inside the modular oriented framework system JAMS (Kralisch and Krause 2006) in addition to the fully distributed hydrological model J2000 (Krause 2001, Krause et al. 2006). Nitrogen routines have been taken out of SWAT (Arnold 1998). The reasons for this recent development were the semi distributed character of SWAT and the stronger process oriented representation of the hydrological cycle in J2000 (Bende-Michl et al., 2006). With J2000-S it is now possible to simulate water and nutrient transport processes in a river basin fully distributed in high quality (Fink et al., 2007).

The hydrological part of J2000-S comprises methods for input data regionalisation, radiation calculation, and calculation of potential evapotranspiration according to Penman-Monteith. The hydrological processes which are considered are interception, snow accumulation and ablation, horizontal differentiated soil-water balance, ground-water balance, runoff generation by explicitly computed lateral flows and flood routing in the catchment's river network (Krause et al. 2006).

The nutrient transport routines converted mainly from SWAT into JAMS. Compliant process components were methods for computing soil temperature, crop growth and nitrogen turnover.

Soil temperature is an important constraint for nitrogen turnover as it influences the bio-chemical processes in the soil. Soil temperature is calculated depending on air temperature and global radiation with empirical equations (Neitsch et al., 2002, Williams et al., 1984) and is damped compared to air temperature because of aboveground biomass, snow cover, soil matrix and soil water. The damping increases with soil depth down to the lower border of the simulation domain for which the average annual air temperature is assumed to be representative.

The crop growth process component allows modelling of potential and actual crop growth in several steps. First the potential crop growth is simulated by describing the daily leaf area development curve, light interception, and the conversion of intercepted light into biomass given the plant species-specific radiation use efficiency. Moreover, calculated total biomass is differentiated into the root development (below) and above ground biomass, each simulating the N-uptake, both residues and yield. The potential crop growth is reduced by modelling water, temperature and soil nitrogen stress factors to determine the actual crop growth and to reduce the actual soil NO_3 pool by the amount of the plant's N uptake.

For the modelling of nitrogen dynamics in the soil horizons five different nitrogen pools, the nitrate, the ammonium, the stable organic, the active organic and the plant residue pool are utilised. In the centre of the calculation is the nitrate pool as shown in Figure 3. Turnover dynamics are influenced by the soil temperature (red arrows) and the soil moisture (blue arrows).

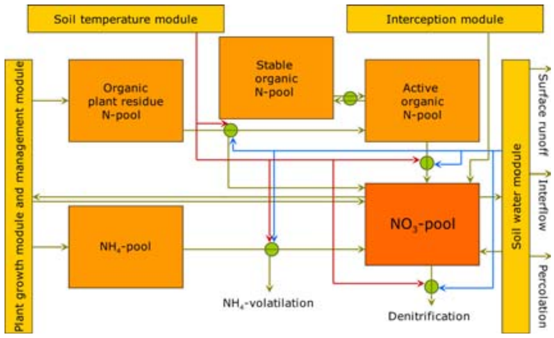

Figure 3: N-pools of the soil nitrogen component and their interactions with other components

Since JAMS/J2000-S requires spatially distributed modelling entities, the 'Hydrological Response Units' (HRU) concept (Flügel 1995) was adapted for this study. As defined by Flügel (1995), HRUs are distributed, heterogeneously structured model entities representing specific landscape units of similar response in terms of their hydrological process dynamics. Termed as 'Chemical hydrological response units (CHRUs) this approach has been extended for hydrochemical applications, e.g. nitrate studies (Bende-Michl 1997). Criteria that are used for definition of the homogeneity are based on the hydrological system analysis of the basin of interest. RUs are delineated by overlaying GIS data layer such as land use, soils, geology and topography which were identified as being important for hydrological process dynamics. To allow water and solute transport modelling between RUs, are routed based on digital relief analyses (Staudenrausch 2001).

4. JAMS/J2000-S MODEL APPLICATION

Data input and preprocessing

Climate data were provided for 14 climate stations from the Australian Bureau of Meteorology (BOM) including daily time series of precipitation, temperature, sunshine duration, evapotranspiration, relative humidity and atmospheric pressure for the period of 1966 – 2006. Hydro-meteorological records were checked and statistically corrected based on regression analyses between station data by the BOM. Continuously river runoff data have been downloaded by the 'Water Information System Tasmania (WIST)' including time series from 1966 to 2006 in 15 min intervals. The WIST also contains water quality records from the baseline water quality monitoring program of Tasmania. It includes monthly analyses, partly bi-annual analyses since 1999 for the catchment outlet (Scotchtown). Digital data have been implemented in a GIS database and have been processed using ArcInfo and ArcMap. A DEM with a spatial resolution of 25m was supplied by the Department of Primary Industries and Water (DPIW). A correction of the DEM was processed through the GIS fill & sink function before generating the relief analysis.

The digital spatial soil information was provided by the Australian Soil Resources Information System database (ASRIS). Initially, soil types were reclassified to address the needs for the delineation of Hydrological Response Units (HRU). Thus, Kandosol, Dermosol, Ferrosol, Podosol, Rudosol, Hydrosol and Tenosol were identified as representative soil classes having similar hydrological properties like pore volume, field capacity, texture, hydraulic conductivity and the bulk density.

Geological digital data (ANZLIC) also were reclassified to seven classes (sediments, alluvium, colluvium, Rocky Cape group, and coastal dunes, Togari group and mafic volcanic) showing significant differences in hydrologic storage capacity and texture (fractured, porous, conductivity).

Seven main land use classes were considered reflecting various land use management systems and different potential sources such as leaching of N from cleared land, fertiliser run-off and agricultural effluents in contrast to pristine areas. Conservation areas, production forest and plantation have therefore been distinguished as well as grazing on modified pastures, irrigated areas, rural areas and water bodies.

HRU delineation

For the Duck River a GIS-based analysis of DEM was undertaken. The flow accumulation and the flow direction functionality were used as a base for delineating catchments boundaries, subcatchments, the Duck river network and assigned nodes. First order topographic parameters (slope, curvature and aspect) were generated to represent geomorphic landscape features. Thereafter the derived layers from the DEM analysis were combined and overlayed with the classified land use, soil and geology information. To reduce the number off small scale landscape units a threshold filter of 0.01 ha was used based on the longest adjacent neighborhood. The last step comprised the assignment of the topology routing scheme link the landscape units for the Duck catchment. As a result 6431 units have been delineated as for the modelling base of the Duck River.

Modelling results

The model simulation period was set up for a time series from 1995-2007. The overall goodness-of-fit for discharge accounts for r^2=0.78 which is also represented by a satisfying reproduction of the observed runoff as shown by Figure 4. The average long-term observed volumetric discharge accounts for 5.7 cbm/s for a period of 35 years 1966-2001 (DPIW 2003). In contrast the simulated discharge volume is 4.9 m^3/s but flow has been decrease since the year of 2000.

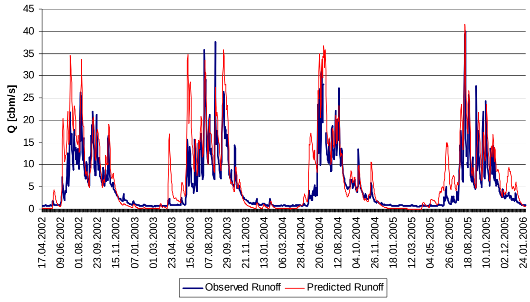

Figure 4: Observed and predicted runoff for the Duck Catchment (Year 2002-2005)

The overall root mean square error (RMSE) is 4.4 and is reflecting that certain situations are not covered by the simulated discharge. As shown in Figure 4 an overestimation of the simulated hydrograph is observed at the beginning of autumn (March-May). It covers a period of significant increase of rainfall. As this dynamic is observed in each year of simulation it is therefore likely that the incoming rainfall in this time is used for farm dam refilling after the summer period. Annual licensed water allocations are 13.26 ML, linked to 62% of the total water allocation as on-farm storages (DPIW 2003).

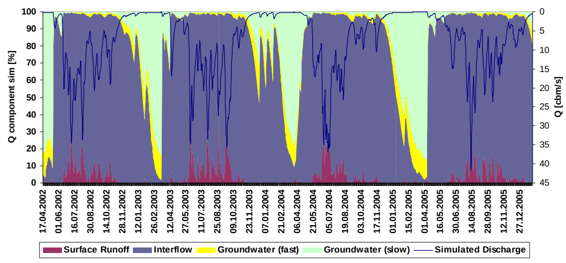

Figure 6: Simulated discharge and relative contribution of flow components for the Duck catchment (Year 2002-2006)

The simulated flows components are showing are distinct pattern (Figure 6). During periods of high flows the discharge is mainly covered by the contribution of interflow (mauve area), and to a lesser extends by surface runoff (purple area). In contrast baseflow conditions are dominated by fast and slow groundwater components (yellow and light blue areas).

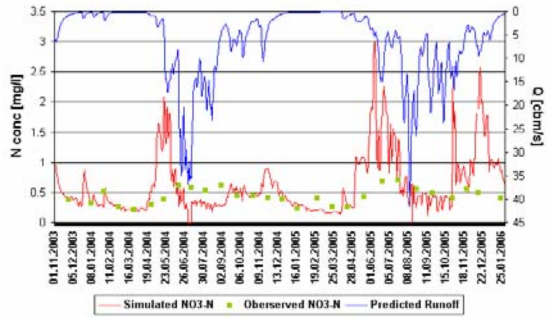

Figure 7: Observed and predicted N-concentration as well as simulated discharge for the Duck catchment (Year 2003-2005)

Figure 7 shows the simulated and observed N concentrations (2003-2005). A correlation coefficient of 0.34 was achieved for this period. Thus it has to be noted that N concentration levels fit well the observed low ranges of nitrogen. In general the nitrogen concentration peaks with the rising hydrograph and declines under recession conditions. Both periods at the beginning of winter overestimate the N concentration by a factor up to 6 (0.5 mg N/l to 3.0 mg N/l). But again this period mismatches the observed hydrologic dynamics as well.

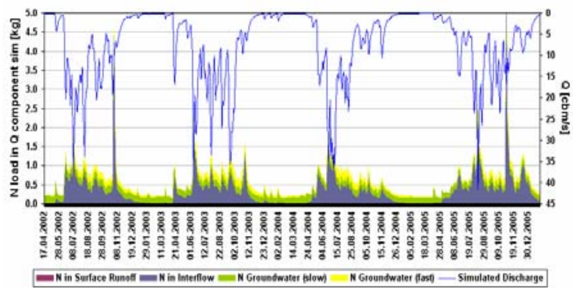

Figure 8: Simulated N loads by flow components for the Duck catchment (2003-2006)

The contributions of N loads vary strongly with hydrologic conditions (Figure 8). High flow periods are coupled with high release of nutrients. This is mainly covered by interflow (mauve area) immediately being activated with rainfall events. Fast groundwater flows comprise additional N loads and develop further during high flow conditions (yellow area). In contrast a remarkable N load is carried by the slow groundwater component becoming dominant with lower flow conditions (green area). N loads with surface runoff are negligible thus only being reported for flood events in November 2005. These loads are not uniformly covered over the entire catchment. Thus it has to be remarked that a uniform amount of fertilizer rate was modelled for each of the land use of the entire catchment.

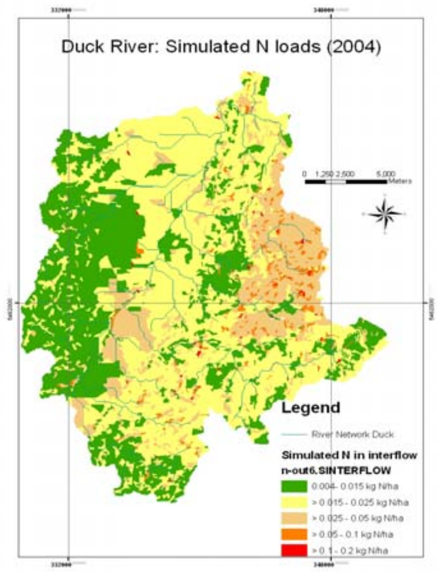

Figure 9: Simulated N loads by interflow and stream network for the Duck catchment (2004)

Figure 9 shows the simulated N loads by the separated response units for the year 2004. Areas showing highest N loads contributed by interflow are located at near stream zones mostly occurring in the hilly parts of the catchment. A remarkable area with high N loads is simulated for the eastern part of the catchment. Hence they are located on high fertile ferrosols with relative high organic C contents. Therefore an intense mineralization rate is calculated. In conjunction with well drained characteristics these soils are responding in high N release in comparison to other landscapes.

5. CONCLUSIONS

The major goal of this investigation was the proof of reliability of the JAMS/ J2000-S model for modelling low nutrient levels for the Duck River test catchment in Tasmania. This goal has been achieved as shown by various results of goodness of fit. Thus it has to be noted that the limited number of observed values for N concentrations is impeding a detailed goodness of fit interpretation. Future investigation will overcome this gap through the measurement of high frequency monitoring nutrient concentrations in the Duck catchment.

Thus there are specific hydrologic conditions which are not covered by the model but are reflecting particular management options (e.g. water allocation) within the catchment. The need for implementing these management options (e.g. representing small local farm dams) will be addressed in future model developments.

The spatial distribution of sources of N loads has been simulated for the scale of implementation which is of major importance for the NRM decisions making process in Tasmania. Within this context a conceptual understanding of major nutrients delivery flow pathways und variable hydrologic conditions has been provided in this study which will support future developments of adaptable management strategies.

ACKNOWLEDGEMENT

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