QUANTIFYING WETLAND HYDROLOGICAL FUNCTIONS: SOME EXAMPLES OF INNOVATIVE METHODS USING WATER TABLE INFORMATION

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Abstract: This presentation at the 1st WETHYDRO workshop (12–14 June 2003, Gonadz, Poland), briefly summarized the authors' findings in two areas of 'wetland hydrology' where improvements are possible:

1) better quantification is needed of hydrological functions that wetlands can present to water management, and

2) better use of wetland characteristics in data collection and modeling can make such quantification easier.

While some water balance components, notably discharges, are very hard to measure in wetlands, others can actually be determined easier than in other environments. The key characteristic of most wetlands, their high and often uniform water tables, allows direct calculation of changes in storage and therefore of actual evapotranspiration, discharges and recharge rates. This advantage, that is not often used in studies of wetland hydrology, is demonstrated for Sarawak peatswamps.

INTRODUCTION

A hydrological wetland *function* can be defined loosely as 'a service to society with a certain value' – this function results from a hydrological *process*, but it is not the same: e.g. all natural floodplains will flood during high water (a process), but this may or may not be valued by society.

In recent decades, wetlands have been become valued especially for their natural richness and ecological importance. The main focus of 'wetland hydrology' is therefore generally on water fluxes *within* wetlands, that support their ecological functioning. Such studies rarely focus on the full water balance over longer periods,

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or on the effect of water storage on river flows. While this approach answers questions that are important to natural sciences and nature conservation, it often does not answer questions that are relevant to water management. Most remaining large wetlands are in parts of the world (e.g. the tropics) where economic benefits, rather than ecological considerations, are most important to policy makers and the general population. Hence, the best arguments for wetland conservation may be economic, not least the functions that wetlands perform within river basins.

HYDROLOGICAL FUNCTIONS REQUIRING QUANTIFICATION

The hydrological functions of wetlands are associated with their capacity to retain and release water in a specific way:

1. they can **reduce flood peaks** by storing water,
2. they can **contribute to baseflows** in rivers by slowly releasing the stored water (especially in the case of peatlands),
3. they can act as a **filter or sink**, retaining sediments, nutrients or pollutants, and
4. they can enhance **groundwater recharge**.

Wetland hydrology is as varied as that of other environments and most wetlands at best perform only one or a few of these functions. Storage during floods may or may not result in a degree of flood attenuation during extreme events that is significant in flood risk management. Not all wetlands can be expected to contribute to baseflows to a degree that benefits water supply managers (as is shown in this paper); the same is true for the 'sink' function. Wetlands that are in depressions, or underlain by impermeable sediments, are unlikely to allow groundwater recharge. Therefore, it is important to quantify specific functions for specific wetlands – not only for the benefit of water managers but also because the argument for wetland conservation can actually be weakened by inaccurate claims on functions, certainly if these lead to disappointments at a later stage. While this is not a new insight, such a 'function quantification' approach is still not followed in most studies. A recent overview of knowledge on wetland functions (on the website http://www.lk.iwmi.org/ehdb/wetland/index.asp), clearly shows that most knowledge not at the 'function level' but at the 'process level' that is not directly useful in policy making and practical management.

This paper

To answer questions on the hydrological role of wetlands in river basins, detailed quantification of the hydrological processes within wetlands is not always needed. In cases where quantification of the quantity and timing of inflows and outflows of the wetland as a whole is sufficient, and time and budget for monitoring and research are limited, the wetland itself may often be considered a 'grey box' (in hydrological model terms). In such cases, techniques are required that allow quantification of the hydrological functioning of the wetland as a whole, rather than of the functioning of each of its components. This short paper does not aim to provide a full account of such techniques, but briefly presents a few recent findings by the author, that are published more extensively elsewhere.

ADVANTAGES AND DISADVANTAGES TO WATER BALANCE STUDIES IN WETLANDS

As for non-wetland catchments, the water balance for wetlands can be written as:

$$P=ET+QS+QG+\Delta S$$

where P=rainfall, ET=evapotranspiration, QS=net surface water discharge, QG is net groundwater seepage, and ΔS=change in catchment storage, including groundwater storage.

Wetlands differ from other catchments in the accuracy with which most of these components can be determined. A major reason that 'full' hydrological studies in large wetlands are still rare, is that they pose specific difficulties to monitoring. These disadvantages are:

- Most natural, large wetlands are sparsely populated. Few permanent monitoring stations (rainfall, weather, discharge) exist in such wetlands, hydrological data are therefore also sparse.
- Such wetlands are often also inaccessible. Even periodic visits are labour-intensive, so automatic monitoring (using dataloggers) is required. The technology for this is only recently becoming affordable and widely available.
- Most wetlands are flat, and (sub-)basins can often not be delineated accurately with only topographic data (even if these are available, which is usually not the case); it is therefore not clear to what area the water balance applies.
- As water tables are often above the soil surface, flow is often diffuse and not contained to a few (main) channels; discharges are hard to measure.
- In the common case of backwatered or tidal wetlands, rating curves can not be established and discharges can not be determined from water level information but must be measured directly and continuously.

However, hydrological studies in wetlands also have a major advantage that becomes clear when monitoring options are compared with those in non-wetlands:

- In most hydrological studies, rainfall, discharge and catchment area can be determined directly and with relatively high accuracy. Evapotranspiration, on the other hand, is usually determined indirectly from meteorological data or by difference (between P and Q). Changes in catchment storage (mostly groundwater storage) are also usually determined by difference as they can rarely be monitored directly.
- The situation in wetlands is often the opposite: discharge and catchment area are very difficult to measure (and only with a considerable error margin) while evapotranspiration, recharge and changes in actual catchment storage can be determined directly and accurately from water table information, with simple techniques and a limited monitoring program.

The analysis of fluctuations in water levels is a widely applied component in studies of wetland hydrology. In peat bogs and floodplains it has been used for the determination of evapotranspiration, soil moisture retention characteristics and groundwater seepage rates (e.g. Dolan *et al.*, 1984; Laine, 1984; Hooijer, 1996). The applicability of these methods is unique to wetlands because some unusual assumptions can be made:

- Due to the limited depth of the unsaturated zone (generally less than 0.3 m), there is very little delay in the response of the water table to changes in storage. Water table fluctuations can therefore be linked directly to individual rainfall- and evaporation events.
- Due to the high rates of capillary rise in peat soils it may be assumed that moisture content in the unsaturated zone remains close to field capacity (except during extreme drought events); changes in storage are therefore proportional to changes in water level. Based on this principle, it is possible to determine vegetation transpiration plus surface evaporation rates (*Et*), groundwater seepage rates (*G*) and the storage coefficient of the soil (*Sf*) from a single diurnal water table record. The principle of this approach is demonstrated in Figure 2C.
- Due to the relative geological, topographical and botanical uniformity within peatswamps, hydrological characteristics such as water table fluctuations are also quite uniform, as illustrated in Figures 2A and 2B. Point data on hydrological characteristics can therefore often be applied to an entire catchment area – such simple extrapolation is rarely possible in non-wetland areas.

AN EXAMPLE OF A FULL WATER BALANCE THROUGH WATER TABLE STUDIES IN SARAWAK PEATSWAMPS

In the Jemoreng study catchment in Sarawak (Malaysia), water level data were used successfully to determine and model most water balance components (apart from rainfall interception) independently (Hooijer and Sivapalan, 1995; Hooijer *et al*., 1997; Wong *et al*., 1997; Hooijer, in press). The aim was to determine minimum water yields from peatswamp catchments, an important factor for water resources management in the region. The study was carried out by the Centre for Water Research (University of Western Australia) together with Montgomery Watson Australia, to enable the Sarawak Water Resources Council to develop a Sarawak Water Resources Master Plan. Similar research approaches were followed in other studies by the author in Ireland and the Danube Delta – these studies were reported in Hooijer (1996) and WL | Delft Hydraulics (2002).

Catchment boundary delineation

The normally relatively simple task of defining catchment boundaries is challenging in peatswamps, as in most wetlands. Not only is it difficult to define the water divide when surface gradients are generally under 0.5 m/km, but even the concept of a single constant catchment area does not fully apply here. Catchment boundaries

may shift rapidly with extreme rainfall events, they will change gradually as the swamp develops, and they can also change progressively due to peat subsidence caused by drainage – even when drainage activities take place well away from the catchment boundaries. Moreover, even relatively minor artificial depressions like logging tracks are likely to lead water across the natural catchment boundaries. Remote sensing data can still rarely be used for digital elevation model generation in these low-gradient areas with a dense forest canopy. Therefore, determination of the catchment area requires either highly accurate (and recent) topographic data, or an estimate based on the water balance. For the 'water balance method', rainfall records and discharge records are required.
For the Jemoreng catchment, both methods were used, allowing assessment of the accuracy of the water balance method:

- The catchment boundaries were first determined through elevation measurements at over 300 points (using laser instruments) at 0.5 km intervals along 14 transects through the swamps (1 km apart, parallel to transect 6; Figure 1). Water level readings in 55 wells were used to confirm that the shape of the groundwater body coincided with that of the peat surface (Figure 2A). As the catchment boundaries are located on the flat summit of the peat domes they could only be delineated with a margin of uncertainty – the minimum catchment area was determined at 123 km^2, the maximum area at 136 km^2.
- The minimum estimate was confirmed by water balance modelling (see model discussion below), which **confirms that the water balance method can indeed provide an accurate estimate of a wetland catchment area.**

Evapotranspiration

The following methodology was followed to determine actual evapotranspiration through water table records:

1. Actual evapotranspiration (*Et*, i.e. tree water uptake plus soil evaporation but excluding rainfall interception) rates were determined from analysis of a continuous record of the position of the groundwater table in a representative part of the forest (monitored at station C, Figure 1), using the basic equation ***Et* = *ΔL(Et)* *Sf**. The diurnal drawdown of the water table (*ΔL*, Figure 2C) is largely caused by loss of water through evapotranspiration, which can be determined accurately if the drawdown due to groundwater seepage (*ΔLG*) and the storage coefficient (*Sf*) of the peat soil are known. The latter variables can be determined from the same water table record: groundwater seepage from the drawdown between midnight and 6:00 am (when *Et* can be assumed to be negligible) and *Sf* from the water table response during intense rainfall events (Figure 2C). This method has been used successfully in several other wetland types (e.g. Dolan *et al.*, 1984; Laine, 1984; Hooijer, 1996). Groundwater seepage was found to be negligible (< 0.1 mm/d) when the groundwater table was more than 0.1 m below the peat surface. An average *Sf* value of 0.71 was found at depths less that 0.1 m (the upper peat layer), while a value of 0.29 applied at greater depths. Using these results, E_t was then determined as: E_t=

*ΔL*0.29* for rainless days when the water table was at least 0.1 m below the surface (cf. Figure 2C).

2. Penman potential evapotranspiration (*PET*) was determined using hourly records of temperature, humidity, wind speed and radiation.
3. ***PET* and *Et* (excluding rainfall interception) proved to be highly correlated and very close**: *Et=1.05*ET*. Using this relation, a record of daily actual evapotranspiration was generated, using a literature value of 14% for rainfall interception.

Changes in catchment storage

In peatswamps, unlike any other environment apart from lakes, it is possible to obtain a record of changes in catchment water storage from a few, or even a single, water level record. Water storage is a function of water level; therefore, if the storage coefficient of the peat (*Sf*) is known and a water level record representative for the entire catchment is available, it is possible to determine a record of daily water storage changes for the entire catchment.

Figure 2B shows that the average of the water level fluctuations in 13 wells (2-weekly manual measurements) along transect 6 ($L_{transect}$) was almost identical to water levels at water level monitoring station C alone (see Figure 1), where a pressure transducer was placed for permanent automatic measurements. A close relation was also found between the water level and station C and average water levels for 44 wells (irregular measurements), distributed over the entire catchment. A slightly modified water level as measured at station C is therefore considered representative for the catchment ($L_{catchment}=0.035+1.026*L_{station}$; r^2=0.99). **Changes in catchment water storage can thus be calculated from water level fluctuations monitored at a single site**, using an *Sf* of 0.71 just below the surface and of 0.29 at greater depths (see above).

Stream discharge measurements

Two major difficulties meant that unconventional techniques were needed to be able to monitor discharges from the catchment:

- Because water levels are controlled by *backwater effects and tidal influence*, conventional rating curve methods (assuming a unique relation between discharge and water level) could not be applied. Flow velocities were therefore measured permanently using ‘acoustic Doppler flow profiling sensors’. Combined with water level data from ‘pressure transducer’ sensors, this yielded a highly accurate record of discharges in the main channel. Two separate discharge monitoring stations were installed, data from the one more upstream were used in cases where the downstream one suffered too much from tidal effects.
- As in many wetlands, however, much of the peatswamp catchment *outflow passes outside of the main channel*. The higher the discharge, the larger the fraction of flow that leaves the catchment through inundated riparian zones of hundreds of metres wide. Therefore, the highest stream discharge that could be measured accurately was only about one-third of the highest daily peak outflow

during the study period (as simulated using the water balance model; Figure 3), and the discharge record does not include peak events.

These flow monitoring techniques are too labour-intensive and costly for most studies. However, the fact that measured discharge record fitted well with the modeled results (Figure 3) confirms that **it is possible to predict wetland discharges from the water level record**, and that model calibration with actual discharge is not always necessary.

Wetland water balance model calibrated with water level information

A water balance model was developed that could be calibrated using either water level and discharge information, or both. The model served two purposes: A) it helped understand the relation between water levels and flow mechanisms within the swamps (a research purpose), and B) it could simulate long-term flow extremes (a water resources management purpose). This conceptual, non-distributed, reservoir model operates at a daily timestep. Inputs to the model are rainfall and evapoptranspiration, outputs are discharges and water levels. Model stores represent actual peatswamp water stores, and model fluxes represent actual runoff mechanisms (Hooijer *et al.*, 1997). Further details on the model are presented in Hooijer and Sivapalan (1995), Hooijer *et al*. (1997), Phillips *et al.* (1997) and Hooijer (in press).

Essential to the modelling approach is the use of water level as the state variable on which all discharges depend. The difference with most other reservoir models is the possibility to calibrate it by optimizing modelled versus observed catchment water levels, and thus optimizing actual changes in water storage. This ensures that model simulations represent the hydrological conditions in the catchment more accurately than would be the case when only discharge data were used for optimization. Thus, the predictive value of simulations for extreme conditions, which may not be encountered during the calibration period, will also be higher.

The output of a water balance model is only meaningful if the catchment area is known. The difficulties encountered in delineating catchment areas in peatswamps have been mentioned above. Fortunately, it proved possible to estimate the catchment area from model results, by fitting simulated long-term discharges to observed totals. It was found that the catchment area derived using this method was 119 km^2, which is very close to the ‘minimum area’ of 123 km^2 delineated from topographic information (see above).

The water balance model was calibrated using 1 year of discharge and water level data for the Jemoreng catchment (note that discharge data were not available for 14.9% of the time, when discharges were high). Figure 3 shows that good fits between simulated and observed data were obtained both for discharges and for catchment water levels, with the coefficient of determination for discharges R^2_Q of 0.91 and for water levels R^2_L of 0.83.

Result: quantification of the 'baseflow maintenance function' of peatswamps

In terms of water resources management, the most important output of the water balance model was the prediction of 25-year minimum discharges from the Jemoreng catchment and 9 other coastal peatswamp catchments (where similar data were collected at a lower level of accuracy). The results were used to determine which peatswamp areas should be protected for water supply purposes, and to calculate the dimensions of water storage facilities needed to maintain water supply during dry periods, when water yields from the peatswamps would be insufficient.

Because of this focus on low flows, the stores and fluxes that generate baseflow were thoroughly calibrated and carefully chosen to represent actual hydrological processes. Model results show that the **discharge from the peatswamps is largely controlled by storage in flooded areas** along streams draining the peatswamp. This result was confirmed by field observations. Due to the low gradients and high surface resistance, the floodwaters are released only slowly from the open water storage, accounting for the 'sluggish' storm flow response that is sometimes attributed to retention on the peat surface or in the peat dome itself (the 'peatswamp sponge' concept). Once this surface storage is depleted, baseflows are maintained by groundwater flow from the peat domes to the main channels.

In many years, the water table in the Jemoreng catchment can drop to around 0.5 metres, and the 'specific yield' can fall to around 0.2 mm/d. In fact, baseflows are likely to have ceased at two occasions in a 38-year modelling period, when the peatswamp water table dropped to 0.7 m below the peat surface. Thus, the catchment is actually not a very good 'baseflow generator' from a water supply perspective, but these dry periods are usually not very long, and a water supply reservoir to overcome them was feasible in this case.

Comparison of the model results for the 10 peatswamps showed a significant variation in the amount of baseflow in dry periods. This variation could be explained largely by the type of substrate: peatswamps underlain by permeable sediments (sand) yielded much higher baseflows than those underlain by clay, (such as the Jemoreng catchment discussed above), and were therefore more suitable from a water supply perspective. Thus, the reputation of peatswamps for maintaining minimum river flows by producing steady baseflows was confirmed to some extent, but it should be noted that this is due as much to the characteristics of the substrate as to the presence of a 'peat sponge' above it.

CONCLUSIONS

Three main conclusions can be drawn from the above:

1. It was shown that it is possible to develop, run and calibrate a water balance model that can be used for quantifying wetland functions, using mainly water level information. This approach is thought to be useful not only for other large wetland areas where 'normal' types of hydrological information (discharge,

catchment area) are scarce or absent, but also for wetlands where such data area available but current models are not sufficiently able to quantify hydrological wetland functions.

2. The common description of peatswamps as a 'sponge' is not very accurate from a hydrological perspective. The typical slow response to rainfall is due to slow release of water from open water storage along the channels – the storage at surface of the peat dome itself is depleted within weeks in dry periods. Once the open water storage is emptied, baseflow is maintained by groundwater flows from the peat, but this is often at a low rate because of the very low gradients, the absence of an aquifer under the peat (in many cases), and the rather low permeability of the peat itself (note that this permeability can vary a lot within and between peatswamps). It can be concluded that peatswamps may act as 'sponges' when it rains, soaking up water, but are developed perfectly to maintain this water as much as possible during dry periods: unlike a sponge, peatswamps limit water release as much as possible. This is not surprising in fact, because this water retention capacity is a condition for accumulation of organic material in the first place.
3. Not all peatswamps therefore maintain significant river baseflows during droughts, outflows can occasionally cease completely. However, some peatswamps that are underlain by more permeable sediments do produce significant baseflows. Also, in the coastal areas of Sarawak the peatswamps, even the ones that produce low baseflows, are the main source of fresh water and responsible for preventing salt water intrusion deep inland. Therefore, peatswamp conservation can certainly be important to water resources management, but not in all cases. If baseflow maintenance is indeed the goal of peatswamp management, the hydrology of individual swamps must be quantified. Of course, there are many other arguments for peatswamp conservation, and in some cases these will be stronger than the value of the hydrological functions.

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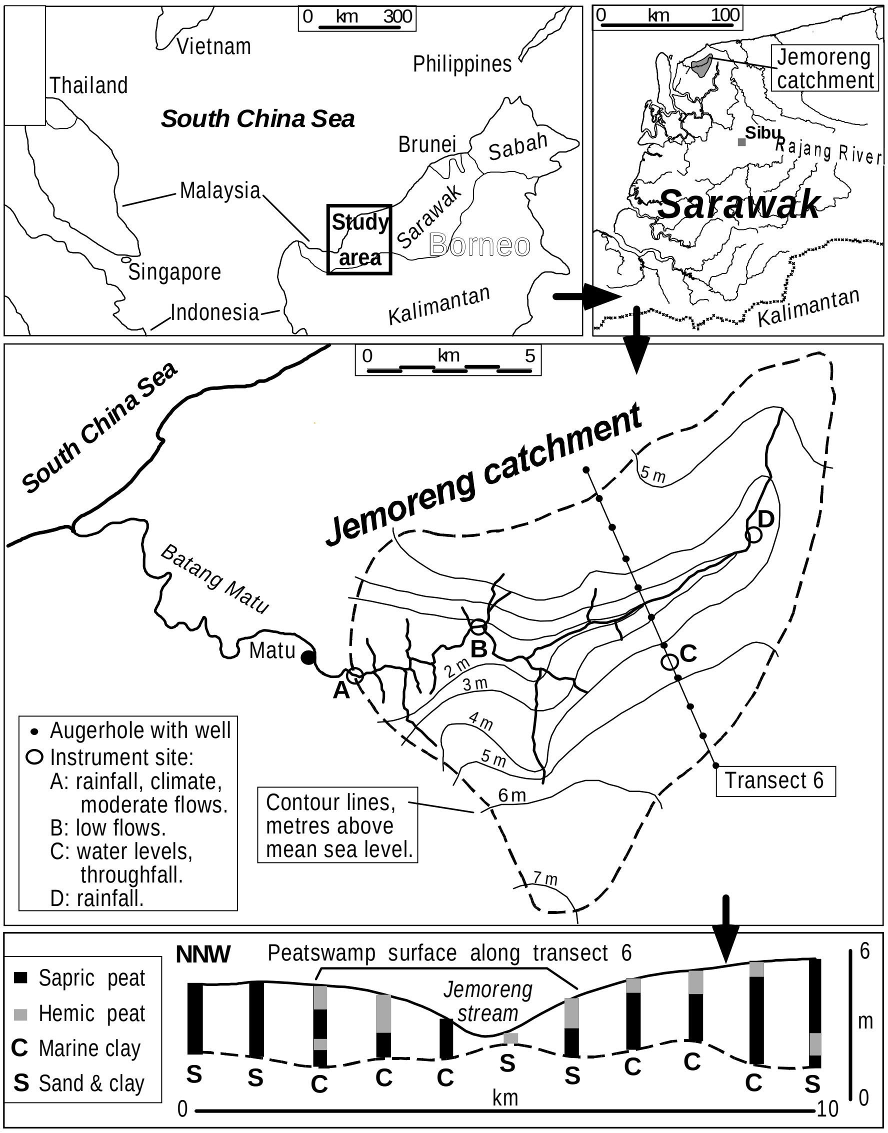

Figure 1. Location, topography and geology of the Jemoreng peatswamp study catchment.

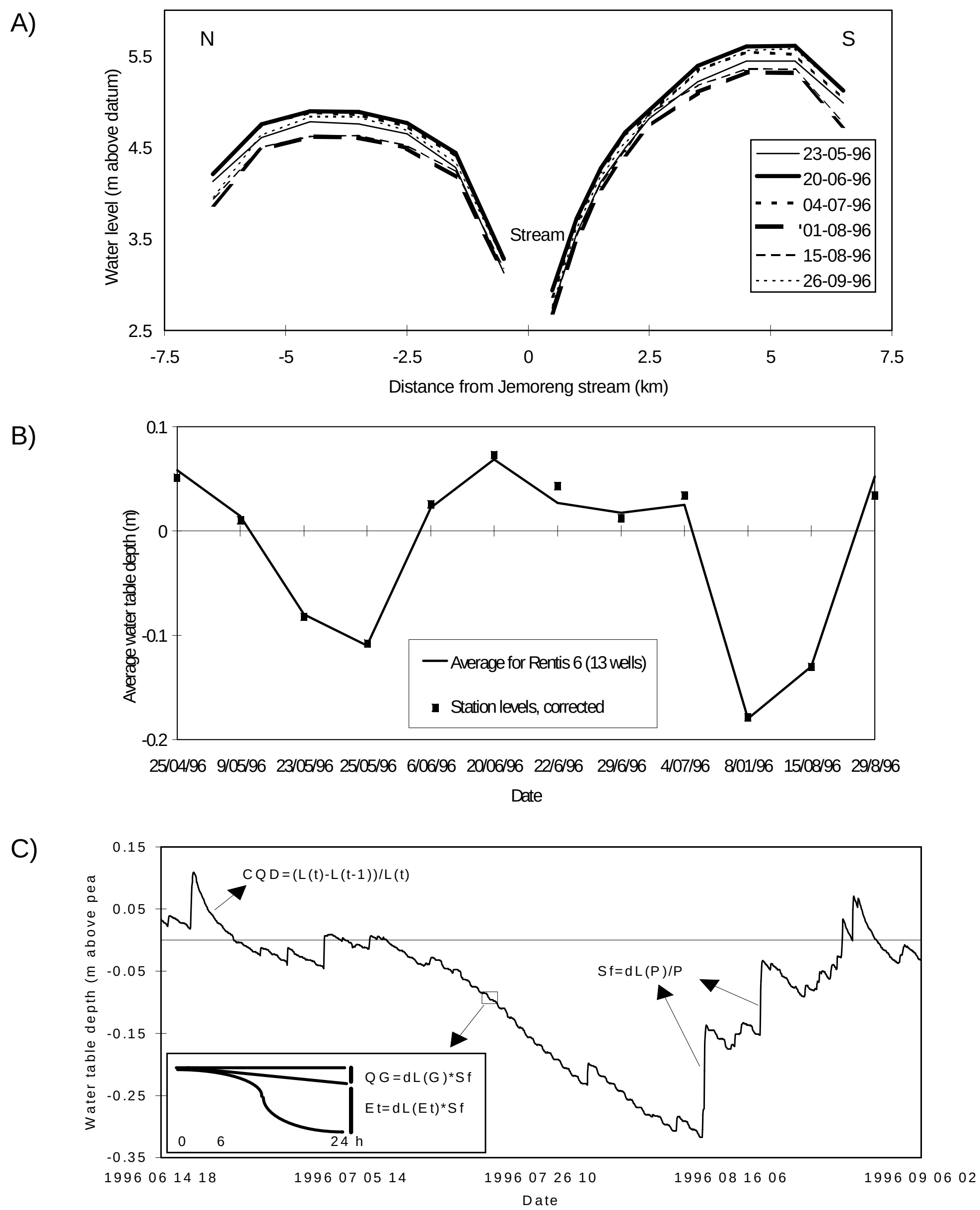

Figure 2. Temporal fluctuations and spatial uniformity in water table levels in the Jemoreng peatswamp..

A. Typical fluctuation pattern of the water table in the Jemoreng peatswamp, along transect 6 (Figure 1). Note that water levels usually fluctuate uniformly, and by less then 0.3 m above or below the peat surface (approximately the water level at 23-05-96).

B. Average water levels (manually monitored) for all 13 wells along the same transect 6, compared to those in a single well (water level monitoring station C; Figure 1). Note the very small difference between the two, confirming the high degree of spatial uniformity in water level fluctuations.

C. Water table fluctuations at water table monitoring station C in the Jemoreng catchment were used to determine the following:

- The storage coefficient (*Sf*) is determined from the rapid response of the groundwater table to rainfall.
- Rates of groundwater seepage (*QG*) and evapotranspiration (E_t) are determined from diurnal fluctuations in periods without rainfall.
- The fraction of water standing in depressions on the surface that is discharged by surface runoff is determined from the daily drawdown rate of the water level when it is above the peat surface (corrected for drawdown due to evapotranspiration).

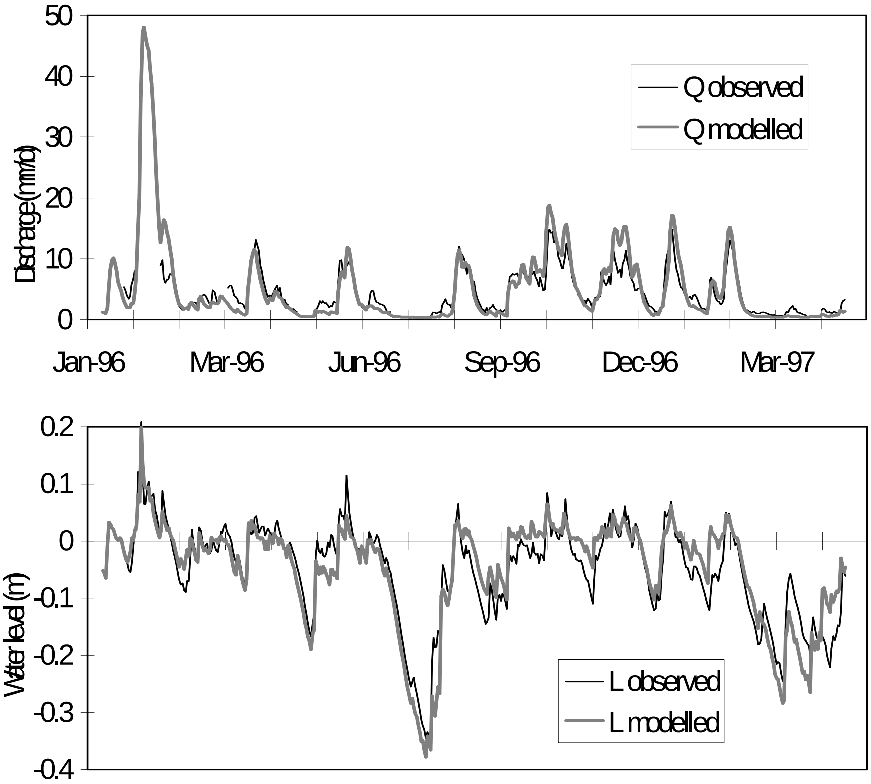

Figure 3. Modelled and observed discharges (Q) and water levels (L) for the Jemoreng catchment.