Assessing the water balance of tropical peatlands by using the inverse groundwater modelling approach

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Summary

The understanding and proper management of the groundwater system are key factors for sustainable land development and effective soil and nature conservation in tropical peatlands. To assess the water balance in tropical peat swamps, a methodology based on a groundwater-balance approach was developed. Two groundwater modelling packages, MODFLOW and SIMGRO, were applied to quantify the groundwater recharge by assessing the water balance in three peat swamps in South-east Asia. As water flows in tropical peatlands are extremely difficult to measure, the models were calibrated using rainfall and groundwater levels. This inverse modelling approach required fewer data than the traditional water-balance method.

Key index words: hydrology, tropical peatland, hydrology, water balance, groundwater modelling

Introduction

To be able to feed the growing world population and to banish hunger, food production needs to be doubled in the next 25 years. In South-east Asia, where fertile land has become scarce, agriculture development more and more focuses on marginal soils such as peatlands, acid sulphate soils, and steep land. Peatlands in South-east Asia cover about 27.1 Mha, or about 10% of the total land area (Hooijer *et al.*, 2006). These peatlands, which are waterlogged most of the year, are dome-shaped. Both the Indonesian and Malaysian Governments have identified their coastal peat swamps as major regions for agricultural development. These lowland peat swamps are purely rain-fed and waterlogged most times of the year (Ritzema and Wösten, 2002). Drainage is needed to make these waterlogged lands suitable for agriculture or other land uses. The resulting subsidence process threatens the sustainable use of the fragile ecosystems (Rieley *et al.*, 2002). Many development projects on tropical peatlands have failed through a lack of understanding of the natural functions of these complex ecosystems. It will only be successful if the principles and practices of sustainable 'wise use', especially with respect to hydrology and water management are taken into account (Rieley and Page, 2005).

The understanding and proper management of the groundwater system are key factors for sustainable land development and effective soil and nature conservation in tropical peatlands. The tropical peatlands in Indonesia and Malaysia are, generally, characterised by elevated rainfall figures, which largely exceed the potential evapotranspiration. The infiltration capacity of the peat soils, together with the transmissivity, do not permit the discharge of all excess precipitation and large volumes of water are, therefore, discharged by surface runoff (including interflow) and surface water courses. Only a small portion of the precipitation excess recharges the groundwater. The groundwater recharge pattern, the geometry and the hydraulic properties of the soils determine the groundwater regime of the peatlands. Any land development may impact on the groundwater regime, which may then trigger a number of derivative impacts, such as soil subsidence and environmental degradation. It is, therefore, imperative to analyse and assess the groundwater system in any peatland development or conservation scenario.

The form of a peat dome can be considered to reflect the form of a saturated water mound (Ingram, 1982). As groundwater flows in tropical peatlands are extremely difficult to measure, the models are calibrated using rainfall and groundwater levels. This inverse modelling approach required fewer data than the traditional water-balance method (Boonstra and Bhutta, 1996).

Materials and methods

A wide variety of groundwater models are presently available. In the ongoing research on peatlands in Malaysia and Indonesia two groundwater modelling packages are being applied, MODFLOW and SIMGRO. The hydrological model SIMGRO (SIMulation of GROundwater and surface water levels) is a distributed physically-based model that simulates regional saturated groundwater flow, unsaturated flow, actual evopotranspiration, irrigation, stream flow, groundwater and surface water levels, and groundwater abstraction (Querner, 1997; Van Walsum, 2004). The model is used within the GIS environment Arcview (user interface ALTERRAQUA). This allows the use of digital geographical information, such as soils, maps, land use, water courses, etc., that can be converted in to input data. Further use is the graphical presentation and analysis of results and/or specific input parameters. MODFLOW is a (pseudo-)3D groundwater modelling package, developed by the U.S. Geological Survey, which is nowadays one of the most widely used packages. The model is based on the *finite-difference* calculation technique and is capable to simulate the effects of wells, rivers, drains, and other groundwater recharge (or discharge) functions (www.modflow.com). A major challenge in using the groundwater models in the tropical peat swamps of South-east Asia is that there is generally a lack of (reliable) data sets, especially long-term data records. For this research, the PWWIN 5.0-79 simulation package was selected because it offers good pre- and post-processing options, requires not too much input data, is well documented and can easily be extended with additional modules (Ritzema *et al.*, 2003).

MODFLOW was used to simulate the groundwater flow in the Balingian area, a tropical peat dome of about 10,000 ha in the Central Region of Sarawak, Malaysia (3° 00' N, 112° 36' E). The Government of Sarawak (Malaysia) has identified the populated coastal zone of Sarawak as a major region for agricultural development. In total, 2 million hectares of coastal lowlands will be developed for oil palm, forest plantation, sago, aquaculture, paddy, and miscellaneous crops including vegetables (Ritzema *et al.*, 2003). It is estimated that between 300,000 and 535,000 hectares of the proposed agricultural area is on peat, located mainly in the Central Region. The land use in the Balingian area is characterised by a smallholder sub-sector, mainly sago, subsistence padi, coconut and peri-urban horticulture, and a large-scale oil palm plantations. Besides the agricultural land-use, some parts of the dome are still in their natural state, e.g. tropical peat forest (Ritzema *et al.*, 2004).

SIMGRO was used to model the Air Hitam Laut (meaning 'Black Water flowing to the Sea') catchment area, located in the eastern lowlands of Jambi Province, Sumatra Indonesia (1^0 42' - 2^0 05'S, 103^0 52' - 104^0 34' E). The central part of this catchment (220 000 ha) is occupied by Berak National Park, which is under treat due to illegal logging and the conversion into oil palm plantations and agricultural lands of the surrounding areas (Wösten *et al.*, 2006). SIMGRO was also used to study the catchment of Sungai (=river) Sabangau in Central Kalimantan, Indonesia (2° 15' - 3° 06'S, 113° 33' - 114° 01' E). This area consists of both the relatively intact Sabangau catchment, the last remaining, large continuous area (13,000 km2) of dense peat swamp forest in Borneo and the degraded Block C of the former Mega Rice Project (Wösten *et al.*, 2006; Wösten *et al.*, in press) Wösten *et al.*, in press).

Two conflicting conceptualizations of peatland hydrology currently exists: 'shallow-flow' and 'groundwater flow' hypotheses (Reeve *et al.*, 2000). The shallow flow model assumes mainly flow through the uppermost layer (acrotelm) and neglects vertical flow. In the groundwater flow models this vertical flow is more important. In the simulations, the peat domes were schematised as a one-layered, unconfined aquifer with the mineral subsoil as the bottom boundary. The mineral subsoil was considered to be impervious. The top boundary was the soil elevation of the peat layer, which in the waterlogged peat soils, is also the elevation of the groundwater level. The hydraulic conductivity is an important parameter in peat land hydrology. Ingram (1982) assumed a uniform hydraulic conductivity throughout the profile, but others argue that the hydraulic conductivity decreases with depth (see e.g. Amstrong, 1995).

Results

For Balingian, the model was calibrated using the recharge as input and the elevation of the groundwater table as output (Grobbe, 2003). The hydraulic conductivity of the peat domes is high, but varies considerably with the type of peat and the degree of humification (Wösten and Ritzema, 2001). For the model simulation, the horizontal hydraulic conductivity in the peat layer was assumed at 30 m/d, based on long-duration pumping test data (Ong and Yogeswaran, 1992). Using these hydraulic conductivity values the simulated groundwater levels were far too high. A sensitivity analysis conducted for the horizontal hydraulic conductivity showed that the hydraulic conductivity had to be increased to unrealistic high values (> 180 m/d) to obtain acceptable groundwater levels, thus the value of the hydraulic conductivity was left unchanged. Subsequently, a value of the recharge was determined using the inverse modelling package PEST, which is part of the PMWIN programme. Results indicate that the total amount of recharge, i.e. around 40 mm/year or about 1% of the total rainfall, is considerably lower than found in previous studies (around 220 mm/year or 6% of the total rainfall, (SWRC, 1997), but more in agreement with results found in European peat domes (Van der Schaaf, 1999). Sensitivity analysis of the horizontal hydraulic conductivity shows that the assumed value (30 m/d) is quite realistic.

The hydrology of the Air Hitam Laut and the Sebangau watersheds were modelled with the SIMGRO. To use SIMGRO, a Digital Elevation Model (DEM) of the peat surface was created using radar imagery (Wösten *et al.*, 2006). The model was calibrated using measured and calculated groundwater levels at representative sites in the watershed, measured and calculated discharge rates in the catchments and calculated and observed flooding patterns as deduced from radar images (Siderius, 2004; Clymans, 2006). An analysis showed that model simulations were not so much affected by hydraulic conductivity, but were very sensitive for precipitation and evapotranspiration, drainage levels and resistance, runoff fractions and storage.

Discussion

The groundwater recharge is difficult to quantify. The direct measurement of groundwater recharge is almost impossible. Water balance studies showed that the groundwater recharge is only a small component compared to evapotranspiration and surface runoff. As a consequence, groundwater recharge can only be determined tentatively through water balances. Existing water balances show that the groundwater recharge amounts to 6% of the precipitation (SWRC, 1997). The groundwater model of the Balingian area, Sarawak, Malaysia, was calibrated with only 1.1 % of the rainfall (representing 41 mm/year) (Grobbe, 2003). This area is characterised by high rainfall figures

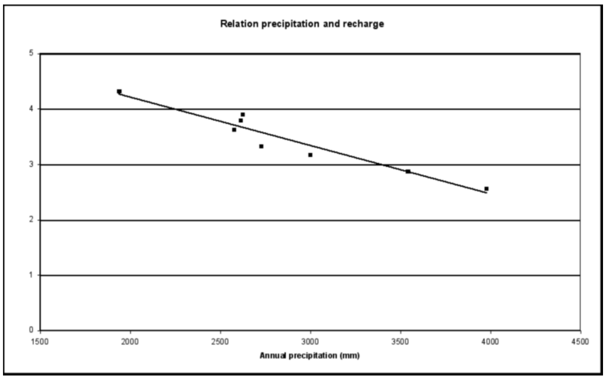

Figure 1. Groundwater recharge Sungai Sebangau catchment (SIMGRO model)

(3700 mm per year). The Balingian model was calibrated for a steady-state situation.

The peatlands of the Sungai Sebangau catchment in Central Kalimantan, Indonesia, were modelled with SIMGRO. A period of almost 9 years was simulated, including 8 entire calendar years (1994-2001). The groundwater recharge was determined for these 8 years. Although that these values should be interpreted with caution (given that in some years a significant change in storage was calculated), indications are that the groundwater recharge is dependent on the precipitation (Fig. 1). The calculated annual groundwater recharge varies from 80 to 100 mm. The figure shows that the groundwater recharge would be approximately 2.5 % in the case of 3700 mm precipitation (such as in Balingian). This value is reasonably in line with the calibrated value of 1.1 % (with the MODFLOW model).

The water balances of the unsaturated zone, as calculated by SIMGRO (Sungai Sebangau catchment), show that the interception and surface runoff are minor in comparison with the evapotranspiration and percolation term. The 30-days moving averages of daily water balances (Fig. 2A) and the quarterly water balances (Fig. 2B) shows that almost all precipitation excess percolates into the soil (n.b. this is not the groundwater recharge). These graphs were also generated for 5 representative sub-catchments as well as 5 representative nodal points, all showing the same pattern. The modelling of the unsaturated zone, therefore, does not give much additional information. This may be different when simulations with deeper groundwater are conducted (e.g. scenario simulations).

The water balances of the saturated zone, as calculated by SIMGRO (Sungai Sebangau catchment), show that most of the percolated water is discharged by the surface water system (3 different surface water systems were defined). The 30-days moving averages of daily water balances (Fig. 3) shows that almost all percolation from the unsaturated zone is discharged by the surface water system and that only a minor quantity recharges the groundwater (n.b. this is the leakage term).

Conclusion

Two groundwater modelling packages, MODFLOW and SIMGRO, were applied to quantify the groundwater recharge by assessing the water balance in three peat swamps in South-east Asia. Although actual field data were scarce, the initial results are rather promising: the models were calibrated by simulating groundwater table fluctuations based on actual rainfall data. Inverse modelling was used to access the recharge to the groundwater. The simulations showed that the model were not so much affected by hydraulic conductivity, but were very sensitive for precipitation and evaotranspiration, drainage levels and resistance, runoff fractions and storage. Although the hydraulic conductivity is high, the gradients in hydraulic head are small and thus also the groundwater flows. Thus fluctuations in the watertable are mainly influenced by processes in the unsaturated zone. Both models need accurate data on the elevation, a more accurate DEM will improve outcomes. A major difference between the two models is the groundwater recharge from precipitation. In MODFLOW this value is principally determined by model calibration. In SIMGRO the unsaturated zone is simulated through a reservoir model of the root zone. The capillary flux from the groundwater to the root zone is dependent of the groundwater depth. SIMGRO, therefore, requires daily values of the rainfall and evapotranspiration. The model also requires the soil physical properties (calculate capillary fluxes and the storage coefficient). With this information, SIMGRO *calculates* the groundwater recharge. In MODFLOW the interaction between the groundwater and surface water is described by two recharge/discharge relations: (i) rivers (both recharge and discharge of groundwater are possible), and (ii) drains (only groundwater discharge). The water levels (drain levels) are constant during each 'stress period', i.e. the water levels are not influenced by groundwater inflow or outflow into/from the

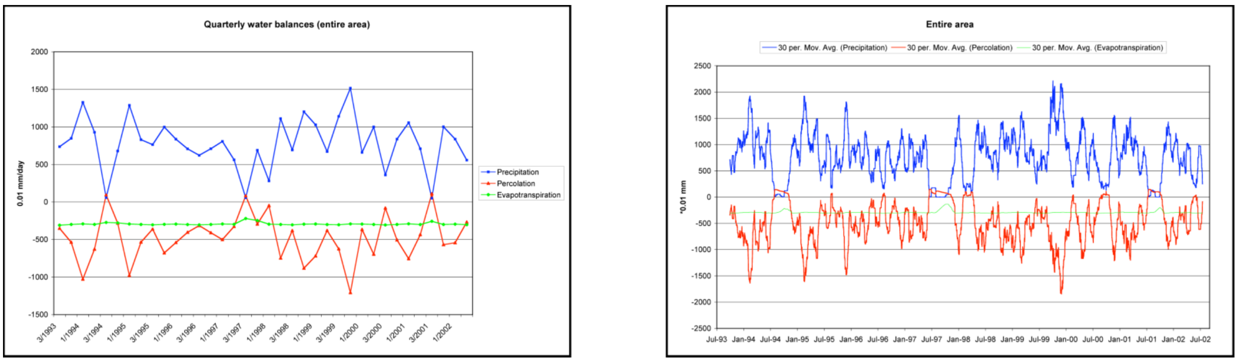

Figure 2. Daily (A) and Quarterly (B) water balances of the unsaturated zone

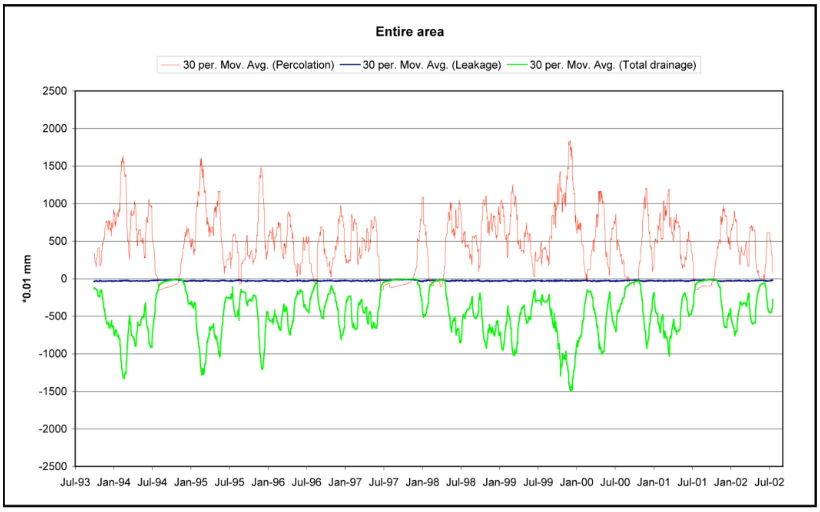

Figure 3. Water balances saturated zone (entire area).

surface water system. In SIMGRO the surface water system is integrated with the groundwater model. Five different surface water systems can be described. The surface water level is calculated by the model.

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