RAINFOREST CONVERSION IN CENTRAL SULAWESI, INDONESIA: RECENT DEVELOPMENT AND CONSEQUENCES FOR RIVER DISCHARGE AND WATER RESOURCES

An integrated remote sensing and hydrological modelling approach

With 5 figures and 3 tables

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Keywords: Tropical deforestation, water resources, hydrological modelling, remote sensing, Indonesia

Regenwaldrodung, Wasserressourcen, hydrologische Modellierung, Fernerkundung, Indonesien

Zusammenfassung: Tropenwaldabholzung in Zentral-Sulawesi: neueste Entwicklungen und Auswirkungen auf die Wasserressourcen

Die Vegetationsbedeckung bestimmt maßgeblich die aktuelle Verdunstungsrate humider tropischer Flusseinzugsgebiete. Daher haben Entscheidungen über Landnutzungsänderungen einen wesentlichen Einfluss auf den Wasserhaushalt von tropischen Flusseinzugsgebieten. Im vorliegenden Beitrag werden mit integrierten Fernerkundungs- und hydrologischen Modellierungsansätzen die Auswirkungen von Landnutzungsänderungen auf die Abflussvariabilität in einem mesoskaligen tropischen Flusseinzugsgebiet in Zentral-Sulawesi, Indonesien analysiert. Zunächst wurden mit Hilfe einer change-detection Analyse von Landsat/ETM+-Satellitenbildern die Landnutzungsänderungen des Gumbasa River-Flusseinzugsgebietes in Zentral-Sulawesi quantifiziert. Nach der erfolgreichen Kalibrierung und Validierung des prozess-basierten hydrologischen Modells WASIM-ETH mit der aktuellen satellitenbildgestützten Landnutzungsklassifikation wurde ein historisches satellitenbildgestützes Landnutzungsszenario für das Flusseinzugsgebiet angewendet. Die Ergebnisse des hydrologischen Modellierungsszenarios zeigen einen engen Zusammenhang zwischen Abholzungsraten und zunehmender Abflussvariabilität. Insbesondere für den Hochwasserabfluss zeigt sich ein stark zunehmender Trend.

Summary: The present land cover of humid tropical catchment areas mainly regulates the flow of vapour to the atmosphere. Therefore land use decisions play an important role for the water balance of a tropical catchment. Studies that relate land cover changes with river discharge changes for humid tropical catchment areas at the mesoscale level are rare. This article applies an integrated remote sensing and hydrological modelling approach to analyse the impact of land cover changes on the water resources of a mesoscale humid tropical catchment. First, a change detection analysis of Landsat/ETM+ satellite images was carried out to quantify land cover changes of the mesoscale Gumbasa River catchment in Central Sulawesi, Indonesia. Thereafter the distributed hydrological model WASIM-ETH was calibrated and validated for the current Landsat/ETM+ scene. The historical Landsat/ETM+ scene was integrated for the hydrological model application as a historical land cover scenario. Further hypothetical total-change scenarios were carried out. The results of the hydrological model scenario application clearly demonstrate a strong relationship between deforestation rates and increasing discharge variability. Especially a significant increase of high water discharges was simulated for the applied scenarios. With regard to the high deforestation rates of the research catchment, one can expect further changes of the water balance.

1 Introduction

Land use decisions always imply a decision about water resources (FALKENMARK a. ROCKSTRÖM 2004). In humid tropical areas at continental edge or island location especially the green water flow (FAO 1995, 1997) represented by the evapotranspiration of the vegetation is a significant component of the water balance (BRUIJNZEEL 2000). Therefore the present land use that mainly regulates the flow of vapour to the atmosphere plays an important role for the water balance of a catchment. With respect to the overall degrading consequences of increasing discharge variability, like low flow or flash floods, it is crucial for the water resource management to predict potential consequences of land cover changes in space and time. Studies that relate changes in land cover with changes in river discharge of tropical catchments are abundant especially on a small scale (< 1 km^2) (COSTA et al. 2003). However, to investigate the impact of land cover changes on the water resources, a mesoscale catchment unit represents an ideal research scale. The global and local scale, which is used in many other hydrological studies (GÜNTNER 2002; DÖLL et al. 2003; GODSEY et al. 2004; FLEISCHBEIN et al. 2005; Kleinhans 2004) is far from the regional reality (Falkenmark a. Rockström 2004) where decisions on water resource management are developed and implemented. The Archipelago of Indonesia has an annual forest cover change of –1.2% (Brazil –0.4%), which indicates a dramatic deforestation rate (FAO 2003). The island of Sulawesi still has a total forest cover of 48% (Holmes 2000). But the natural resource tropical rainforest of Sulawesi is constantly threatened by the development of new agricultural land and illegal logging activities. With a population growth of 66% over the past two decades around the area of Central Sulawesi (Maertens et al. 2004) massive land cover transformations have changed and are currently changing the land cover pattern of the island. Thus these land cover transformations will also alter the hydrological regime of the corresponding catchment areas and finally the water resources of the region.

2 *Study area*

The Gumbasa River catchment (Fig. 1) is a sub-basin of the Palu River catchment (2,694 km^2), which is located in Central Sulawesi, Indonesia (1°S, 120°E). The Gumbasa River catchment has a total drainage area of 1,275 km^2 and is characterized by a topography ranging from 99 m a.s.l. to 2,491 m a.s.l. The catchment has

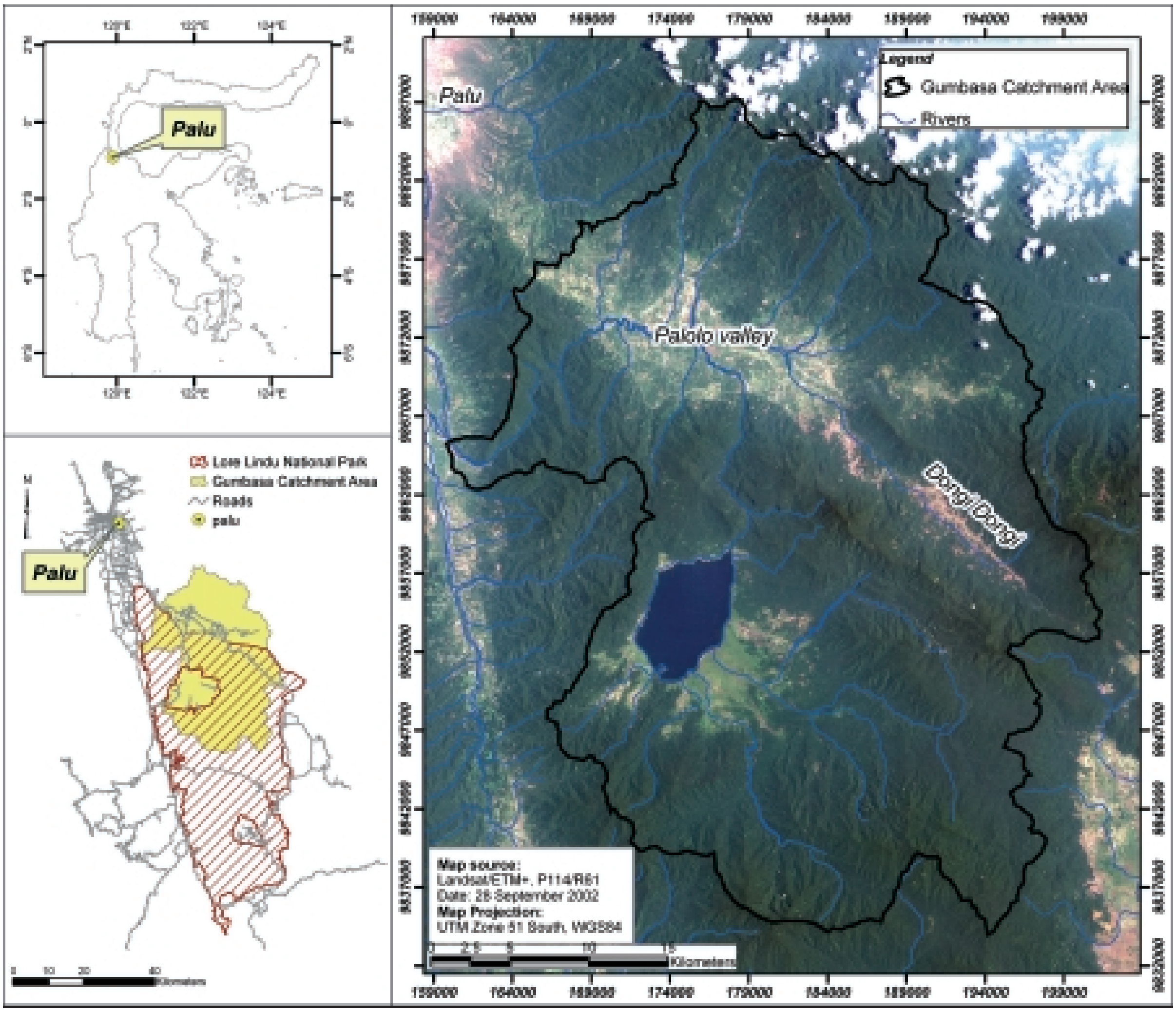

Fig.1: Overview of the project area in Central Sulawesi, Indonesia (left) and the Gumbasa River catchment (right)
Das Gumbasa River-Einzugsgebiet in Zentral-Sulawesi, Indonesien

a gross annual areal precipitation of 2,000 mm y^{-1} and a mean annual discharge of 22.1 $m^2 s^{-1}$. The seasonal hydrological regime of the catchment is described by two peaks and strongly corresponds with the bimodal monsoonal pattern of the yearly precipitation distribution of Central Sulawesi. Like other river basins located in monsoon regions the Gumbasa River also shows a great variation of seasonal and annual flow (OYEBANDE a. BALEK 1987).

3 *Material and methods*

3.1 *Hydrological model application and catchment instrumentation*

In order to study the impact of forest conversion on the water balance of the Gumbasa River catchment we applied the Water Flow and Balance Simulation Model WASIM-ETH (SCHULLA a. JASPER 1999). WASIM-ETH is a process-based fully distributed catchment model. The spatial resolution is given by a grid and the time resolution can vary from minutes to days. The main processes of water flux, storage and the phase transition of water are simulated by physically-based simplified process descriptions (SCHULLA 1997). The meteorological input data of the model are interpolated for each grid cell and are followed by the simulation of the main hydrological processes like evapotranspiration, interception, infiltration and the separation of discharge into direct flow, interflow and base flow. These calculations are modularly built and can be adapted to the physical characteristic of the catchments area. For the set up of the Gumbasa River catchment a 500 m x 500 m raster spatial, and a daily temporal resolution was chosen. As spatial input data WASIM-ETH requires a Digital Terrain model, a land cover map and a soil map (Fig. 2). All spatial data is required in a raster data format (grid) with unique spatial resolution and extension. Starting from the primary grid of the topography secondary grids were generated with a topography analysis program. In order to obtain a feasible temporal data set of meteorological forcing and hydrological calibration data for the performance of a distributed hydrological model the catchment was equipped with four automatic stage recorders and eight automatic climate stations monitoring precipitation, temperature and humidity. Additionally five automatic climate stations measure the complete meteorological parameters including wind speed and global radiation. We measured hydrological and meteorological data for the period Sept. 2002 – Sept. 2004. For the calibration (01.09.2002–31.08.2003) and validation (01.09.2003–31.08.2004) of the hydrological model WASIM-ETH we chose the land cover classification of the Landsat/ETM+ scene from 2002. Each land cover type refers to corresponding physical vegetation parameters like stomata resistance, Leaf Area Index (LAI), albedo, vegetation height, rooting depth and vegetation cover. The parameterization of the vegetation physical properties was mainly derived from a global vegetation guide by MATTHEWS (1983), single studies (MO et al. 2004; DIJK a. BRUIJNZEEL 2001; KÖRNER 1994) and local studies (BOHMANN 2004; FALK 2004) which were conducted within the research area. Figure 3 displays the observed versus the simulated discharge and the simulated baseflow for the Danau Lindu sub-catchment for the calibration period. The model efficiency of the calibration period (R^2=0.83) and the validation period (R^2=0.74) for the entire Gumbasa River catchment reached satisfying results in order to use the hydrological model as a scenario tool. We simulated a land-use history scenario with the Landsat/ETM land cover classification of 2001 as input land cover grid for the analysis of the impact of observed land cover changes from 2001 till 2002 within the Gumbasa River catchment. Furthermore we applied a total change scenario, which assumed that all forest up to 1,200 m a.s.l. is converted in a first conversion phase into annual crops such as maize or dry rice and within a second step into perennial crops. Cacao is a cash crop in Central Sulawesi and therefore is most likely to be planted as perennial crop. In Central Sulawesi the cacao plant can be cultivated up to an elevation of 1,200 m a.s.l., since up to this elevation the temperature does not drop beneath 16 °C at night (REHM 1989). For both scenarios the physical vegetation parameters were altered according to the applied land cover type. The soil physical properties were kept constant, because the changes of soil physical parameters induced by land cover changes were not investigated for the Gumbasa River catchment. The main land cover changes were detected within the Dongi-Dongi sub-catchment, therefore this sub-catchment was also delineated as a sub-catchment of the hydrological model.

3.2 *Remote sensing data analysis of land cover and land cover change*

Several efforts have been undertaken during the past years to map the forest cover in the tropics and monitor changes of tropical land cover and deforestation at the regional level (ALVES et al. 2003; CASTRO et al. 2003; ERASMI et al. 2004; LU et al. 2004). The spatially explicit analysis of land cover and land cover change within the project area is a prerequisite for the initialisation and validation of the forest conversion scenarios that were applied within this study. The land cover assessment for the Gumbasa watershed was based on a data set of two Landsat/ETM+ satellite images, taken on 24 August 2001 and 28 September 2002 (Path 114/Row 61). The geometric and radiometric calibration of the satellite images included the following processing steps:

– geocoding and co-registration of the 2001 image based on the Landsat/ETM+ image of September 2002 (cartographic reference system: UTM Zone 51 South, WGS84)

– top of atmosphere (TOA) reflectance computation and atmospheric correction based on the COST algorithm (CHAVEZ 1996)

– normalization of topographically induced distortions using the adjusted stratified Minneart model

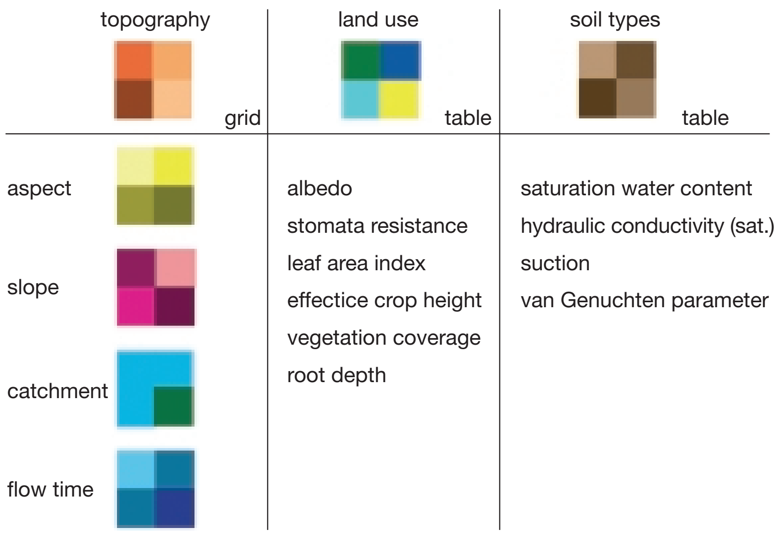

Fig. 2: Spatially explicit data for the hydrological model WASIM-ETH (after NIEHOFF 2001)
Räumliche Datengrundlage für das hydrologische Modell WASIM-ETH (nach NIEHOFF 2001)

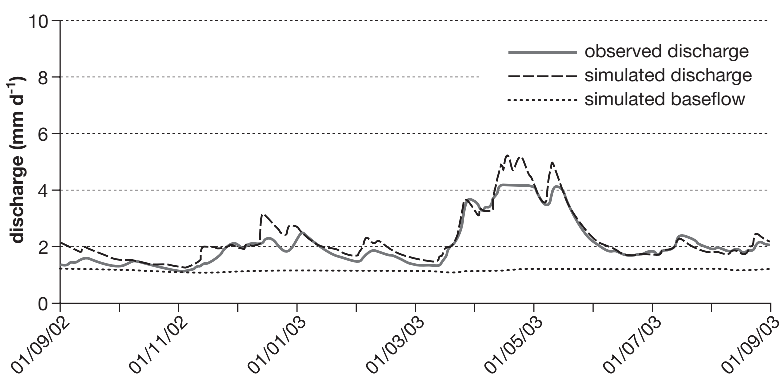

Fig. 3: Results of the calibration of the Danau Lindu subcatchment (daily resolution, 01 Sept. 2002 to 31 Aug. 2003): comparison between observed and simulated discharge (R^2=0.83) and simulated baseflow

Ergebnisse der Kalibrierung für das Danau Lindu-Teileinzugsgebiet (tägliche Auflösung, 01.09.2002 bis 31.08.2003): Vergleich zwischen beobachtetem und simuliertem Abfluss (R^2=0.83) sowie simuliertem Basisabfluss

(MINNAERT 1941) which includes a pre-stratification of the image data according to image based structural surface characteristics (TWELE a. ERASMI 2005)

– object based image classification (eCognition V.30)

– accuracy assessment of the land cover maps based on a random sample of control points and ground truth data from field surveys, higher level classifications as well as visual interpretation of ancillary data sources.

The overall weighted producer's accuracy is 74.4% for 2001 and 71.5% for 2002, respectively. The assessment is based on eight land cover classes and a further separation of the montane forest into two elevation classes based on a digital elevation model. Finally, the change detection analysis was performed using an object-based post-classification comparison approach and confusion matrix analysis.

4 Results and discussion

4.1 Change detection analysis

In 2001, 83.4% of the total area of the Gumbasa catchment were covered by forest. 72.7% of the catchment are classified as closed forest, whereof 61% (44.4% of the total area) are above 1,200 m a.s.l. (upper montane rainforest) and lower montane closed rainforest comprise 39% (28.3% of the total area) respectively. Forest areas with less than 65% crown cover (open forest) can be mainly found below 1,200 m a.s.l. (9.7%). Recently cleared areas with remnants of medium to high vegetation are classified as "open shrubland" and include 2.3% of the project area. The non-forest areas within the catchment are characterized by

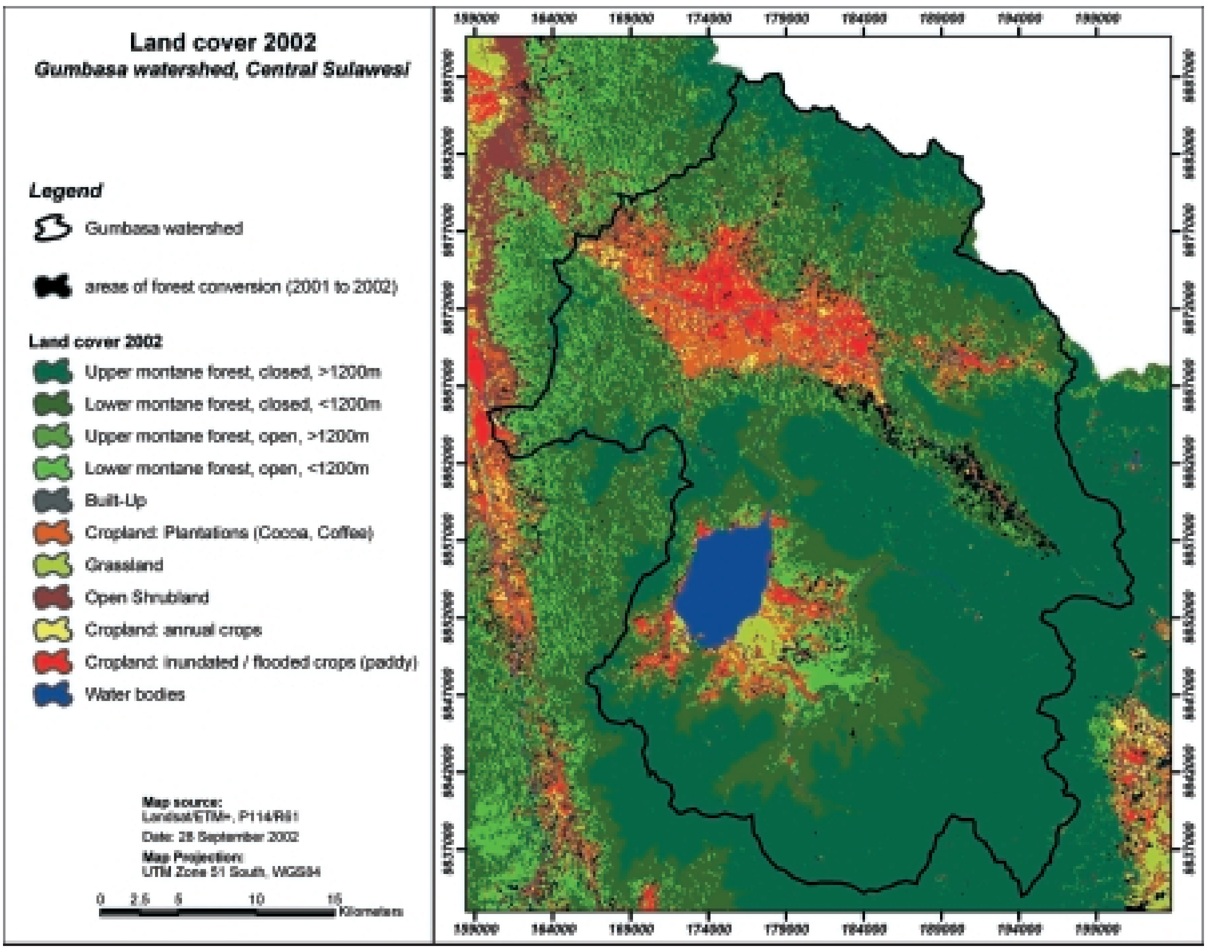

Fig. 4: Land cover 2002, Gumbasa River catchment, Central Sulawesi, Indonesia
Landnutzung 2002, Gumbasa River Einzugsgebiet, Zentral-Sulawesi, Indonesien

Table 1: Statistics of land cover and land cover change Gumbasa River catchment (2001 and 2002)
Landnutzung und Landnutzungsänderungen im Gumbasa River-Einzugsgebiet für die Jahre 2001 und 2002

	Area 2001		Area 2002		Change	
Land cover	(ha)	(% of total)	(ha)	(% of total)	(ha)	(% of class)
Upper montane rainforest, closed (>1,200 m)	57,738	44.4	57,573	44.2	–164	–0.3
Lower montane rainforest, closed (<1,200 m)	36,842	28.3	32,531	25.0	–4,311	–11.7
Upper montane rainforest, open (>1,200 m)	1,396	1.1	1,421	1.1	26	1.8
Lower montane rainforest, open (<1,200 m)	12,580	9.7	15,795	12.1	3,215	25.6
Cropland: perennial crops	7,219	5.5	7,462	5.7	243	3.4
Cropland: annual crops	1,396	1.1	1,284	1.0	–112	–8.0
Grassland	1,740	1.3	2,054	1.6	314	18.0
Open medium to high shrubland	2,984	2.3	4,438	3.4	1,454	48.7
Cropland: inundated / flooded crops (paddy)	4,205	3.2	3,541	2.7	–664	–15.8
Water bodies	4,024	3.1	4,023	3.1	–1	0.0
Total area	130,123	100	130,123	99.9		

Table 2: Statistics of land cover and land cover change Dongi-Dongi sub-catchment (2001 and 2002)
Landnutzung und Landnutzungsänderungen im Dongi-Dongi River-Teileinzugsgebiet für die Jahre 2001 und 2002

	Area 2001		Area 2002		Change	
Land cover	(ha)	(% of total)	(ha)	(% of total)	(ha)	(% of class)
Upper montane rainforest, closed (>1,200 m)	9,489	70.8	9,311	69.5	–179	–1.9
Lower montane rainforest, closed (<1,200 m)	2,927	21.8	1,688	12.6	–1,239	–42.3
Upper montane rainforest, open (>1,200 m)	164	1.2	308	2.3	144	88.1
Lower montane rainforest, open (<1,200 m)	5,96	4.4	956	7.1	360	60.5
Cropland: perennial crops	115	0.9	32	0.2	–82	–71.8
Cropland: annual crops	11	0.1	241	1.8	230	2044.0
Grassland	32	0.2	372	2.8	340	1063.7
Open medium to high shrubland	24	0.2	450	3.4	426	1801.1
Cropland: inundated / flooded crops (paddy)	1	0.0	1	0.0	0	0.0
Water bodies	42	0.3	41	0.3	0	–0.9
Total area	13,401	100	13,401	100		

cropland whereas perennial crops (cacao plantations) and paddy rice constitute the dominant cropping systems. The arable land is mainly situated within the plain of the Palolo valley. During August 2001 and September 2002, some significant changes in the landscape of the Gumbasa watershed occurred. These changes are mainly related to the intensification of forest degradation and conversion activities at the rainforest margin in the Palolo valley and in the Dongi-Dongi region (see Fig. 4). Since the rainforest margin within the project area is mostly situated below 1,200 m, the forest conversion effects only the lower montane rainforest. Table 1 documents the dimensions of land cover change and the major conversion activities. Within the observation period of 13 month, 4,311 ha (–11.7%) of lower montane closed forest has been affected. The forest change is characterized either by forest degradation processes (selective logging) which lead to a decrease in canopy closure (3,215 ha) or by clear cut logging which result in a conversion of forest areas into fallow land and a complete loss of flora and fauna within the previous natural forest. Concerning the land cover statistics, the clear-cut logging activities result in an increase of grassland (+18%) and open shrubland (+48.7%) areas. The increase of cropland and grassland is also a consequence of the conversion of former paddy rice fields into fallow land or cacao plantations. Table 2 summarises the change statistics for the Dongi-Dongi sub-catchment which comprises the hot spot area for forest conversion activities within the Gumbasa River catchment.

4.2 Impact of forest conversion on the water balance

The comparison of the simulated yearly water balance for the year 2002 with respect to the year 2001 and the applied land cover scenarios gives a general first overview about the impact of land cover change on the hydrological performance of the observed watershed. Table 3 compares the changes induced by land cover change for the total Gumbasa River catchment and the Dongi-Dongi sub-catchment respectively of the following water balance components: areal precipitation (P), evapotranspiration (ETR) and total discharge (Q). With respect to the actual land cover changes from 2001 to 2002 the effect on the yearly simulated water balance is rather insignificant. The hydrological model calculated a 0.2% of the total water balance decrease of total yearly discharge for the Gumbasa River catchment. Within the Dongi-Dongi catchment, where the predominant quota of land cover changes took place between the year 2001 and 2002 the yearly drop of total run-off amounts to 1.8% of the total water balance. The annual crop scenario with an increase of 11.4% of the yearly total run-off for the Gumbasa River catchment and the perennial crop scenario with a rise of 5.8% of the yearly total discharge of the Dongi-Dongi sub-catchment indicate a great increase of the yearly total discharge with cumulative deforestation rates. All changes of the total discharge were induced by an alteration of the yearly evapotranspiration rate, due to a decline of LAI, root depth, vegetation height and stomata conductance. Less water is evaporated by interception and hence throughfall increases and more water can infiltrate into the soil. The reduction of the evapotranspiration causes the soil to be wetter and therefore more responsive to rainfall (Bruijnzeel 2004). The graduated impact of annual and perennial crop scenario is related to the more similar physical vegetation parameters of the cacao tree in comparison to the broadleaf evergreen forest of the catchment. Comparing the forest cover changes with total annual discharge changes for the year 2001 and the two land cover scenarios, the simulation results demonstrate a non-linear relationship between forest cover change and changes of the yearly total run-off. Regarding the crop scenarios the Dongi-Dongi sub-catchment does not experience such great forest conversion (–14.9%) as the total Gumbasa River catchment (–37.1%). This difference explains the relative lower rise of total discharge. For a detailed analysis of the implications of the actual deforestation rate between the year 2001 and 2002, and furthermore the deforestation scenarios, a closer investigation of the yearly temporal run-off variability is essential. In order to evaluate the impact of forest conversion on the temporal discharge variability monthly low (MNQ), mean (MQ) and high water (MHQ) discharges were calculated for the Gumbasa River catchment (Fig. 5). The diagram of the monthly variation of the low water discharges (MNQ) demonstrates a moderate monthly rise for both deforestation scenarios and a slight decrease for the year 2001. The impact of for-

Table 3: Total yearly simulated water balance and actual forest cover for the Gumbasa River catchment and the Dongi-Dongi sub-catchment for 2002 and 2001, compared to an annual crop scenario, where up to an elevation of 1,200 m a.s.l. all forest is altered into annual crops like e.g. maize and to a perennial crop scenario where up to an elevation of 1,200 m a.s.l. all forest is converted into perennial crops like cacao; Δ represents the changes of precipitation, evapotranspiration and total discharge in percent proportional to the total water balance

Jährlicher simulierter Wasserhaushalt und Waldbedeckung des Gumbasa River-Einzugsgebietes für 2002 und 2001 verglichen mit zwei landwirtschaftlichen Landnutzungsszenarios, bei denen bis zu einer geodätischen Höhe von 1.200 m ü.M. die Waldflächen ausschließlich in annuelle Kulturen wie z.B. Mais oder in Dauerkulturen wie z.B. Kakao umgewandelt werden; Δ bezieht sich auf die prozentualen Veränderungen des Niederschlages, der Evapotranspiration und des Gesamtabflusses in Bezug auf den gesamten Wasserhaushalt

		Areal precipitation			Evapotranspiration			Total discharge			Forest cover		
	catchment	P (mm)	ETR (mm)	WB (%)	Δ (%)	WB (%)	ETR (mm)	Q (mm)	WB (%)	Δ (%)	(ha)	of total (%)	Δ (%)
Land cover 2002	Gumbasa	1,994	1,521	76.3	–	100	1,521	547	27.4	–	107,320	82.4	–
	Dongi-Dongi	2,215	1,169	52.7	–	100	1,169	1,066	48.1	–	12,263	91.5	–
Land cover 2001	Gumbasa	1,994	1,523	76.4	+ 0.1	100	1,523	542	27.2	– 0.2	108,558	83.4	+ 1.0
	Dongi-Dongi	2,215	1,215	54.8	+ 2.1	100	1,215	1,025	46.3	– 1.8	13,176	98.3	+ 6.8
Annual crop scenario	Gumbasa	1,994	1,260	63.2	–13.1	100	1,260	774	38.8	+11.4	58,994	45.3	–37.1
	Dongi-Dongi	2,215	1,082	48.8	– 3.9	100	1,082	1,148	51.8	+ 3.7	10,267	76.61	–14.9
Perennial crop scenario	Gumbasa	1,994	1,378	69.1	– 7.2	100	1,378	662	33.2	+ 5.8	58,994	45.3	–37.1
	Dongi-Dongi	2,215	1,137	51.3	– 1.4	100	1,137	1,093	49.3	+ 1.2	10,267	76.61	–14.9

est conversion increases for the monthly mean discharge (MQ) and is most significant for the monthly high water discharges (MHQ). The results imply that deforestation has a more important impact on the high water discharges than on the low water discharges.

5 Conclusions

The simulation results of the impact of forest conversion on the water balance of a mesoscale tropical catchment agree with the findings of experimental

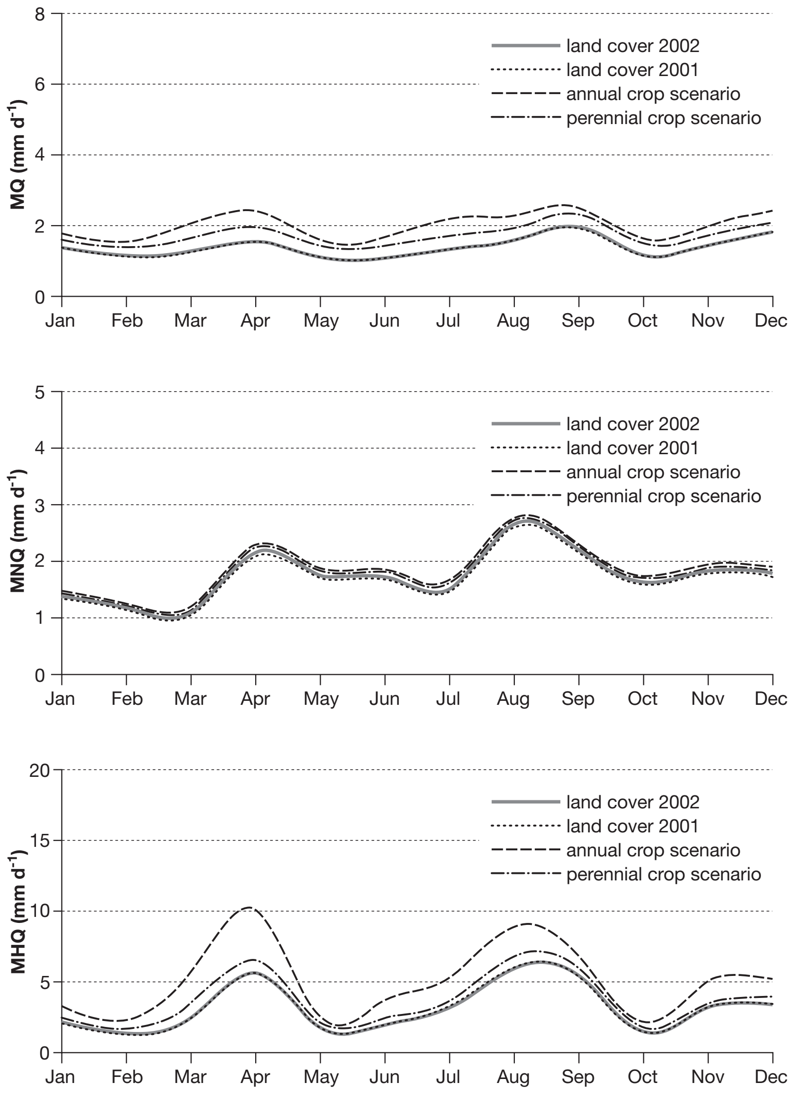

Fig. 5: Monthly low (MNQ), mean (MQ) and high water (MHQ) discharges for the Gumbasa River catchment for the land cover of the year 2001, 2002 and annual crop scenario, where up to an elevation of 1,200 m a.s.l. all forest is altered into annual crops like e.g. maize and a perennial crop scenario where up to an elevation of 1,200 m a.s.l. all forest is converted into perennial crops like cacao

Monatlicher Niedrigwasser- (MNQ), Mittelwasser- (MQ) und Hochwasserabfluss (MHQ) des Gumbasa Rivers für die Landnutzung 2001 sowie 2002 und einem landwirtschaftlichen Landnutzungsszenario, bei dem bis zu einer geodätischen Höhe von 1.200 m ü.M. die gesamten Waldflächen in annuelle Kulturen wie z.B. Mais oder Dauerkulturen wie z.B. Kakao umgewandelt werden paired catchment studies, which describe an increase of peak flows after forest removal (BONELL a. BALEK 1993; CHANDLER a. WALTER 1998). Furthermore we showed the varying impact of agricultural practice after forest removal on the water balance. Cacao plantations have a more moderate impact on the water balance of a catchment than annual crops like maize. Interpreting the simulation results of the dry season flow (low water discharges) special caution is needed, because numerous studies of smaller tropical catchments produced higher baseflow after forest removal, whereas other studies report a decreased baseflow. Regarding these contradictory catchment study results, BRUIJNZEEL (2004) raised the discussion about the "low flow problem". Whether the baseflow is raised or reduced after forest removal is strongly connected to the degree of surface disturbance. COSTA (2005) argues that as a result of the decreased hydraulic conductivity due to soil consolidation less water can infiltrate, which again leads to an increased direct discharge and actually leads to a decrease of the low water discharge. The "low flow problem" indicates that information on land cover change describing the alteration of physical vegetation properties derived from Landsat/ETM+ satellite images can be sufficiently used to simulate alterations of the water balance with the help of a hydrological model. However, data on changes of the soil physical properties after forest removal is lacking. Integrating soil physical alterations due to forest removal for hydrological model simulations would considerably clarify the simulation correctness for the low water discharges. Further, it would also improve the simulation of the mean and high water discharges. Therefore it is most likely that within this study the hydrological model underestimates the increase of total discharge due to forest conversion. We can conclude that green water flow plays a significant role within tropical catchments. Most of the alterations of the water balance due to forest conversion can be explained by changes of the green water flow. However, alterations of the soil physical properties due to forest conversion also play a significant role to describe the hydrological response of a catchment. Besides monitoring of alterations of physical vegetation parameters, there is urgent need of research within tropical catchment areas to describe the corresponding changes of the soil physical parameters.

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