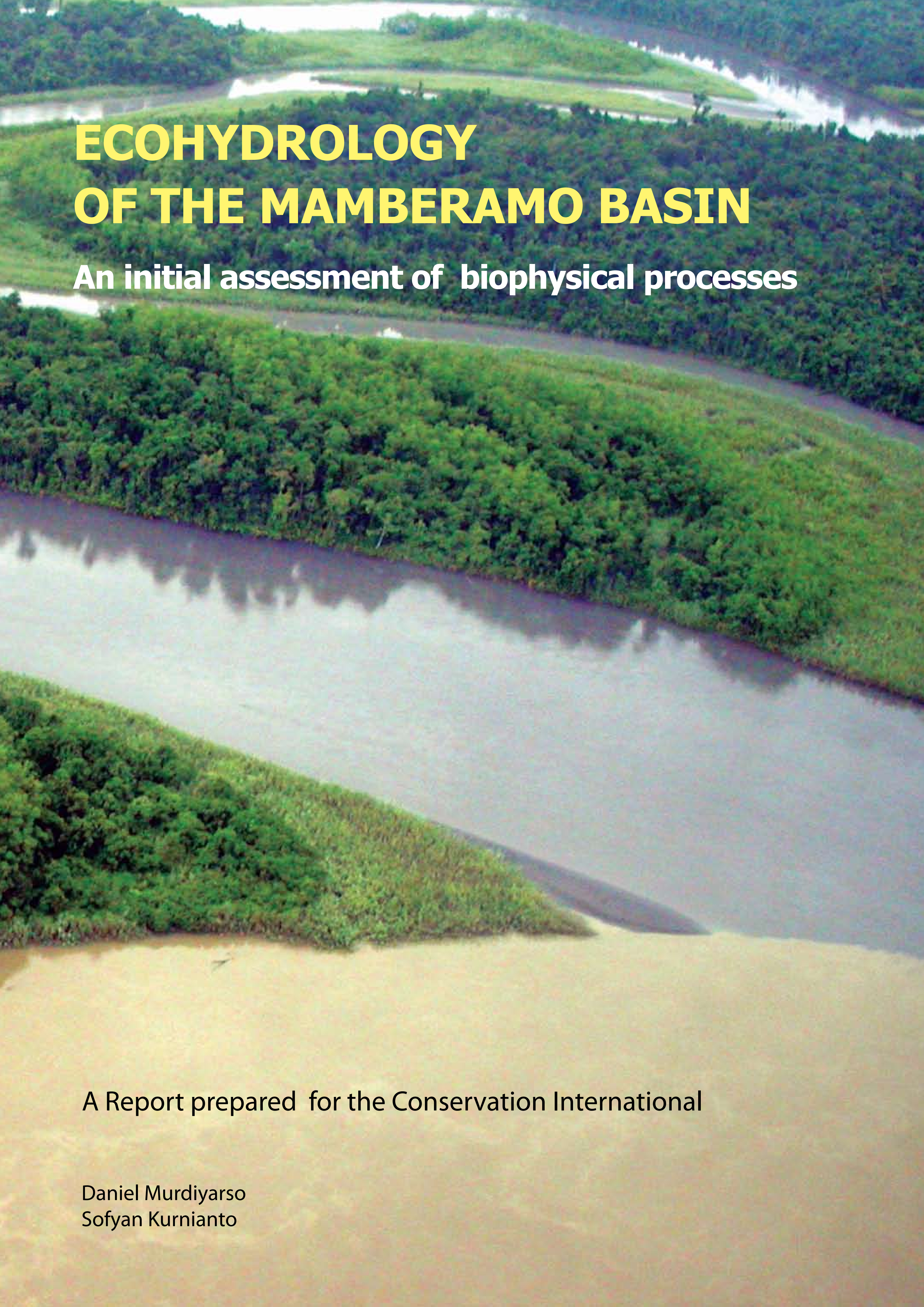

ECOHYDROLOGY OF THE MAMBERAMO BASIN

An initial assessment of biophysical processes

A Report prepared for the Conservation International

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Ecohydrology of the Mamberamo basin: An initial assessment of biophysical processes/by Daniel Murdiyarso and Sofyan Kurnianto. Bogor, Indonesia: Center for International Forestry Research (CIFOR), 2008.

42p.
ISBN: 978-979-14-1262-9

CABI Thesaurus: 1. landscape 2. ecology 3. hydrology 4. biodiversity conservation 5. watersheds 6. climatic change 7. sedimentation 8. livelihoods 9. assessment 10. rapid methods 11. Papua 12. Indonesia

Printed by Subur Printing, Jakarta

Design and layout by Rifky
Photos by Daniel Murdiyarso
Maps by Sofyan Kurnianto

Published by
Center for International Forestry Research
Jalan CIFOR, Situ Gede
Bogor Barat, 16115, Indonesia
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E-mail: cifor@cgiar.org
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1. Introduction

Papua is Indonesia's largest and least populated province. Three million people live in an area of around 42 million hectares, 80 percent of which is still forested (BAPLAN 2002). This is equal to approximately 35 million hectares of original forest cover intact (FWI 2004).

The Mamberamo Biodiversity Conservation Corridor Program of Conservation International (CI) in Papua recognizes that large-scale conservation is essential for the long-term survival of rich biodiversity and that networks of conservation management areas are the most effective strategy for preventing species extinctions in the near-term. The long-term persistence of both threatened species and threatened sites will also depend on the maintenance of critical ecological processes at landscape scale. Landscape scale conservation is especially relevant to the Mamberamo region, which contains a large number of wide-ranging, low-density, threatened species that cannot be effectively conserved and managed at the site scale.

One of the most crucial biophysical processes at landscape scale in the region is ecohydrology. The process is unique since the vast flat region is influenced by and sensitive to a complex process of flooding and sedimentation. Consequently, constant change in river flow directions and establishment of pioneer formation and new habitats results. Moreover, the livelihoods of people as hunters and gatherers are greatly affected.

The threats to such large-scale conservation activities may be driven from the outside rather than the inside since the 8 million hectare Mamberamo Basin is sparsely populated. Natural resources–based development plans including large-scale dam and road constructions, extractive industries (logging and mining concessions), and large-scale plantations will substantially affect the region. These human-induced activities should take into account the environmental and social consequences, which to a large extent are irreversible.

A rapid assessment was carried out in two phases. First came fieldwork consisting of an appraisal of the landscape and the livelihoods of the local people. The two-week work was combined with geopositioning of specific landmarks and soil sampling activities to quantify their physical properties. Second came desk work dealing with modelling exercises to establish the rate factors affecting the ecohydrological performance of the basin in both spatial and temporal terms. The assessment may be considered to represent baseline information before any changes in biophysical and socioeconomic variables occurred. Anticipated biophysical changes were simulated by means of model experimentation, however.

The assessment was initiated by a recognizance survey over the Mamberamo Basin to obtain a general impression of the entire basin. A chartered flight was arranged from Jayapura to Sarmi and then followed by overviews from an elevation of around 1000 feet, which covered most of the basin. It was followed by visits to a number of sites, namely Papasena I, Papasena II, Dabra, and Kwerba (Figure 1) to interact with the community, collect soil samples, and geoposition necessary landmarks and sampling points. Half-day boat trips were needed to move from one location to another after what were on average two-night stays at each location.

Although the visits were not meant to assess community awareness about conservation efforts, it became obvious that the communities were keen to learn the results of any activity carried out by 'outsiders'. This is particularly important as they are highly motivated to enhance their negotiating capacity regarding their resources and livelihoods. The objective of this assessment is to determine

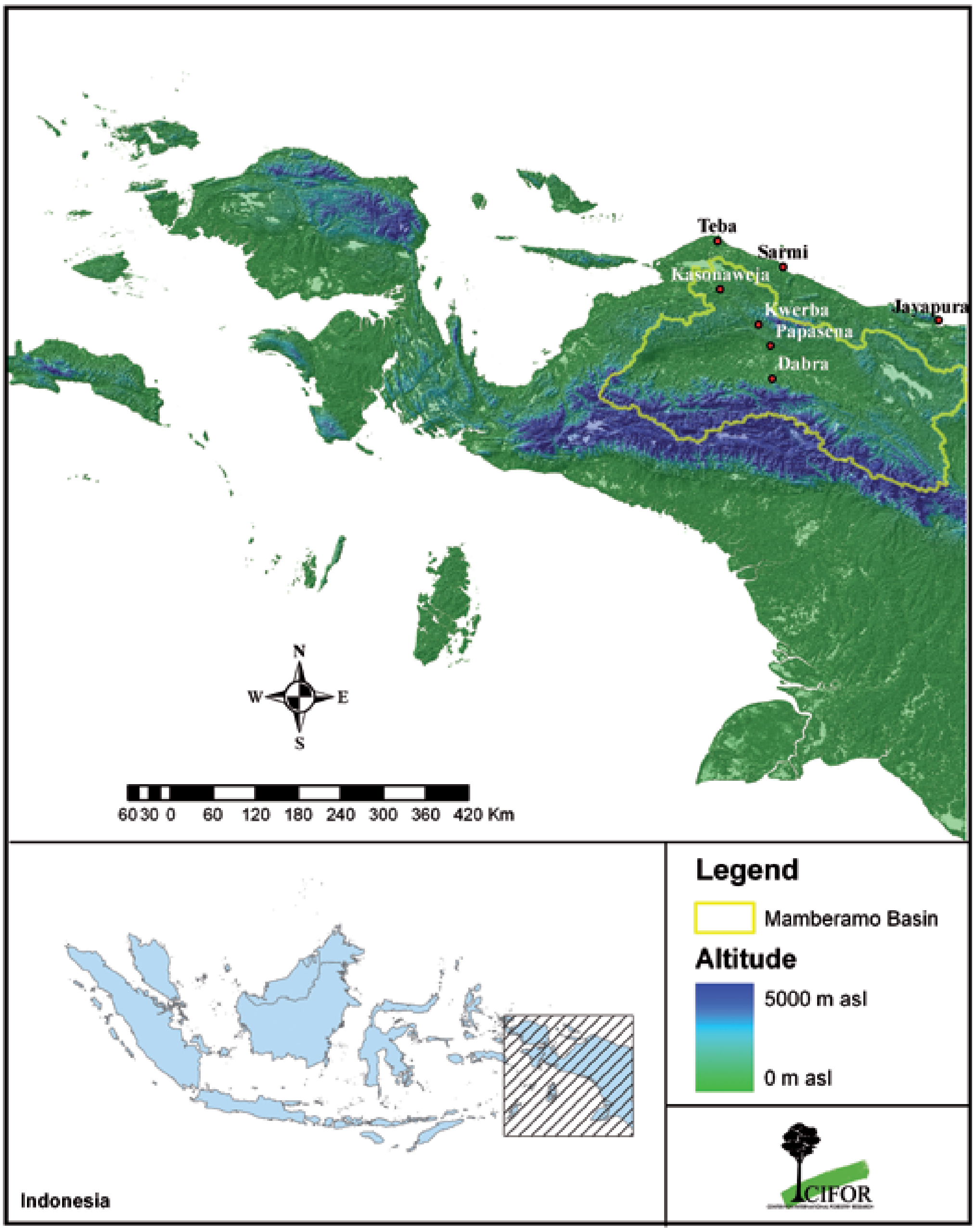

Figure 1. Location of Mamberamo Basin in northern Papua

the primary factors that indicate the current status of physical variables influencing flow, quality and timing of the hydrological processes. These factors will be used to establish the rate factors that represent the behaviour and responses of the flows due to the existing physiographic conditions without any intervention from human activity. Biological variables were introduced in the form of vegetation cover when the water balance components were calculated.

The results of this assessment will be used to interpret the potential changes under different development scenarios that involve land-cover and climate changes. The impact of changes and general interpretation of the results of the watershed analysis will provide a starting point for discussion of hydrologic and related resource issues.

Furthermore, one could raise questions in the context of biodiversity corridor and sustainable development planning. The likely impacts from various development scenarios (identified by CI through the Rapid Assessment of Conservation and Economy) and development plans being made at present by the local government can be analyzed and interpreted highlighting the impacts on important species and habitats.

2. General Overview

Most of the information described below was adopted from Conservation International (2006), a Project Document of the Mamberamo Biodiversity Conservation Corridor.

2.1. Geography, Geology and Lithology

The Mamberamo Basin is a unique region. With a total catchment area of about 7.7 million hectares (the largest in Papua province) and over 90 percent still undisturbed, the area comprises a large inland basin with many natural lakes, surrounded on all sides by high and steep hills and mountains. The elevation of the basin ranges from about 0 m asl in the northern parts of the basin to about 5,000 m asl in the southern part (Figure 2).

The geography of the Mamberamo region is unique and dominated by a vast flat 'Lakes-Plains' basin, or depression, where the river meanders greatly and shifts in direction produce many ox-bow lakes. The Mamberamo is unique in that this vast Lakes-Plains depression is found in the interior and not near the coast, as is normal for other rivers. The unique geography of the interior Lakes-Plains depression surrounded by mountains and hills of the Mamberamo has been formed by a complex geologic history with plate tectonic movement of New Guinea, Australia and the Pacific regions. Hall (2002) postulated that New Guinea and Australia have been slowly moving on a northern trajectory, whilst the northern coast (including the Van Rees, Foja, Cyclops, Bewani, Torricelli and Adelberts Mountains, as well as the northern section of Bird's Head termed the North New Guinea Terranes of the Caroline-Pacific Plate) have moved from the Pacific in a westerly movement, resulting in 'docking' of the aforementioned mountains and producing strike-slip faulting between these two tectonic plates. The distances travelled in the last 10 million years may have been as much as 1000 km. This movement did, not surprisingly, cause massive uplifting of the central ranges and terranes as well as the Lakes-Plains depression that stretches for several hundred kilometres and presumably was once located on the coast and could have formed a large inland lake with the arrival of the North Coast ranges.

The surface geology of the Foja Mountains is composed of resistant, intrusive plutonic and metamorphic rocks surrounded by arenaceous or argillaceous sediments. The Lakes-Plains depression consists of alluvium and terrace deposits from sedimentary deposits of the Tariku and Taritatu rivers.

The lithology in the basin is dominated by old volcanic and consolidated sedimentary rocks located in the southern and northern part of the basin (Figure 2). This formation, where the Kwerba sampling site is located, has low to moderate permeability, but is high in coarse materials. In the middle part of the basin Papasena is sitting on semiconsolidated sediment composed from clay to pebble size with low to moderate permeability. Dabra is located in the igneous or metamorphic rocks, mainly consist of granite, dionite, gabro, schist, and quartzite with very low permeability.

Figure 2 also shows aquifer productivity. In most areas of the region the aquifer productivity of the basin is without exploitable groundwater. The situation is supported by the map of groundwater basin discharge (Figure 3), which indicates that all basins have low discharge to the confined aquifer located between two impermeable layers. High discharge is shown only in the unconfined aquifer for the Taritatu (in the middle) and Warem-Demta basins (in the north).

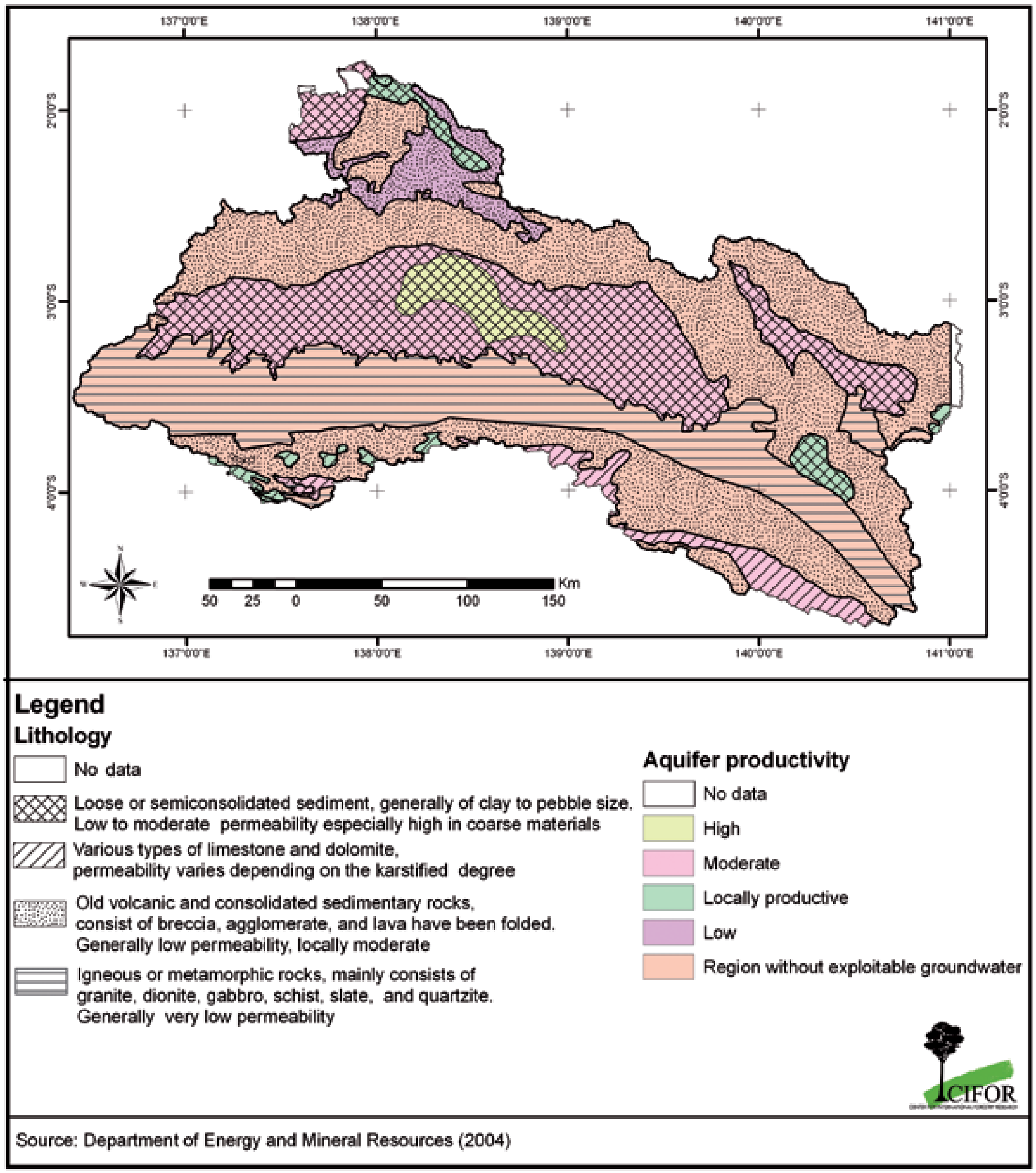

Figure 2. Hydrogeological map of Mamberamo Basin indicating lithology and aquifer productivity

2.2. Climate

Monthly rainfall data recorded with 77 rain gauges within and around the basin (Figure 4) were obtained from the Water Resources Management and Flood Control Project of Papua (DPU 1997). The period of recorded rainfall data is from 1950 to 1995, and the length of series data varies from 4 to 40 years depending on the station. The lowest annual rainfall of about 600 mm was recorded in the northern part of the basin with its gentle topographical condition. The highest annual rainfall of approximately 5,300 mm was recorded in the mountainous areas in the southern part of the basin. These values are an indication that topography clearly affects rainfall formation. The minimum monthly rainfall of about 220 mm was recorded in October, while the maximum monthly rainfall of more than 300 mm occurred in March (Figure 5). It means monthly rainfall varies very little.

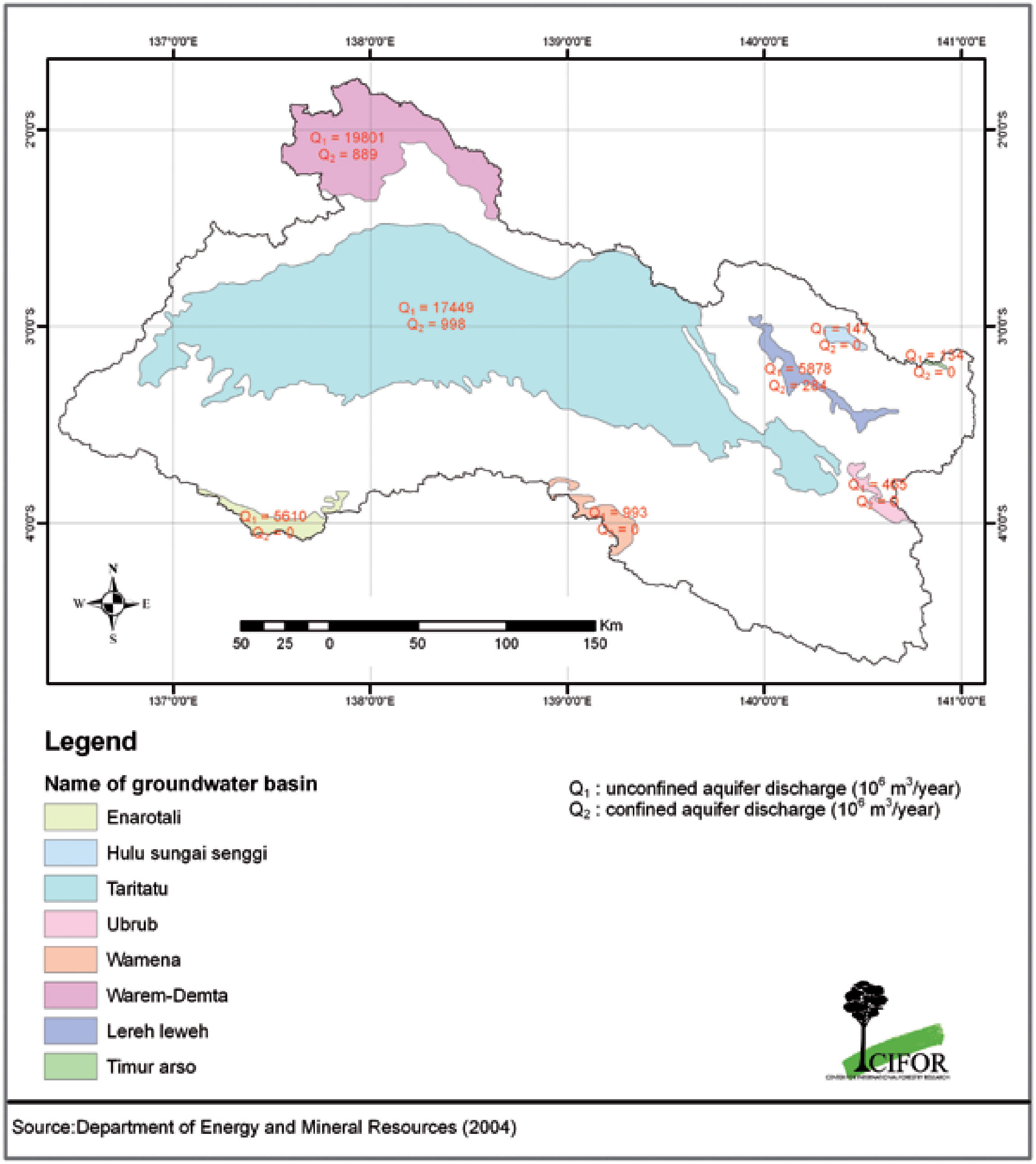

Figure 3. Groundwater basins and their confined and unconfined aquifer discharge of the Mamberamo Basin

Seven climatological stations around the region were maintained by the same project. Temperature data were available for the period of 1971 to 1991. Based on the elevation map, a spatially explicit temperature distribution was generated for the entire basin (Figure 6).

2.3. River Systems

The main rivers in the Mamberamo Basin form the shape of a giant inverted 'T' with two major branches, the Tariku River (previously known as the Rouffaer River) in the west flowing eastward and the Taritatu River (previously known as the Idenburg River) in the east flowing roughly westward. They meet in the Lakes-Plains to form the main Mamberamo River (Figure 7). Beyond the confluence of Tariku and Taritatu, the Mamberamo turns abruptly northward, flowing for 175 km to the coast at Cape D'Urville on the northeast margin of Cenderawasih Bay. The lower reaches of the river pass through a deep gorge in the Foja/Van Rees mountain chain, which contains several sets of navigable rapids, the most famous

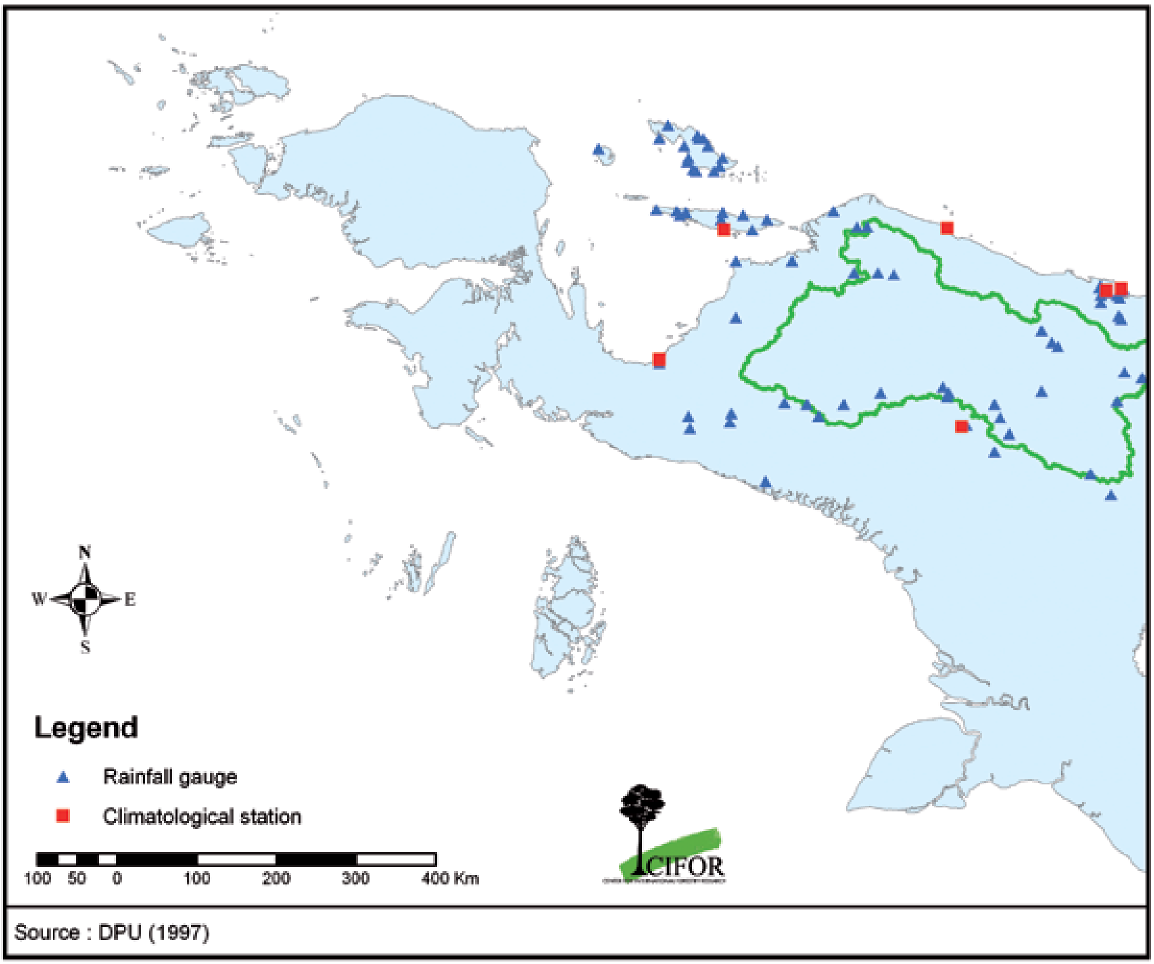

Figure 4. Location of rainfall and climatological stations within and around the Mamberamo Basin

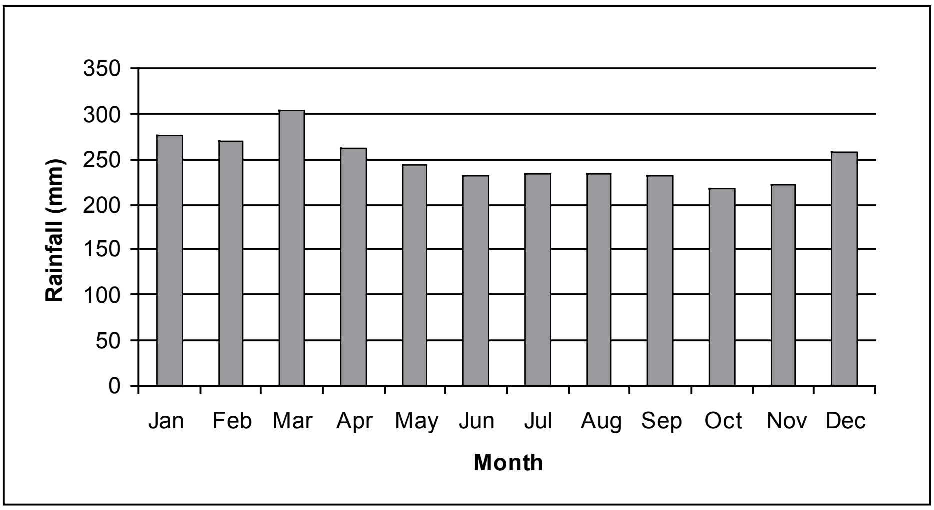

Figure 5. Mean monthly rainfall (1950–1990) in the Mamberamo Basin averaged over 77 stations

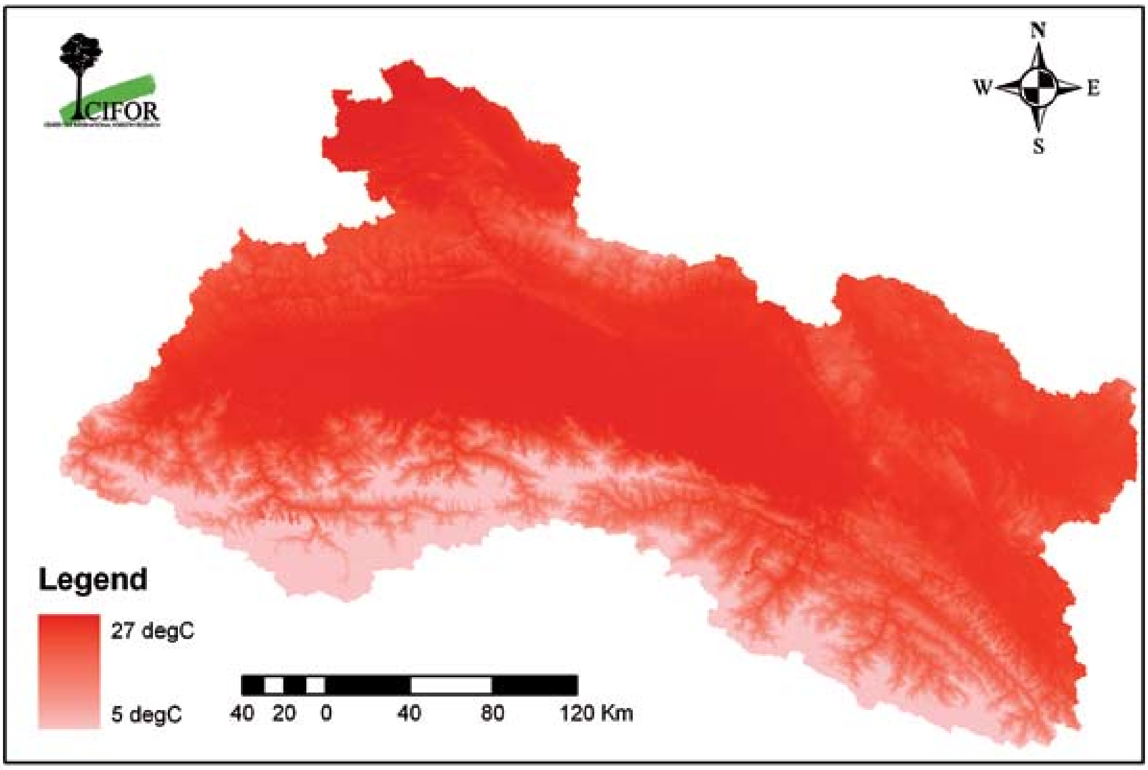

Figure 6. Mean annual temperature distribution in the Mamberamo Basin

of these being the Batavia Rapids. With a stream flow of 450 km/hour, this river can be navigated throughout the year by ships of up to 30 ton weight for 200 km upstream from the river mouth. There are also some lakes such as Rombebai Lake (13,749 ha) in the Lower Mamberamo and Bira Lake in the Middle Mamberamo (8,350 ha).

The upper Tariku branch rises at elevations above 4,000 m asl in the Pegunungan Tengah (Nassau Range), with most of this headwater drainage feeding into rivers that follow the east-west strike of the Derewo Fault Zone. The two most significant of these drainages are the Delo, or Hitalipa, in the west and the upper Tariku itself in the east; these two branches meet at a confluence below the rugged peak of Mt. Gulumbulu (4,041 m), which marks the ancient boundary between the countries of the Moni people to the west and the Dani people to the east. Below this confluence the Tariku flows north through a gorge for approximately 50 km, then turns east as it enters the Lakes-Plains depression, where it receives several large tributaries from its southern bank, including the Van Daalen and Swart rivers in its final 125 km before joining the Taritatu (CI 2000).

The Taritatu River rises in poorly mapped country north of Puncak Mandala (4,700 m), one of the highest peaks in Papua. It is an area of fractured karst topography with many structurally controlled drainages such as the Kloof, Borme and Sobger rivers, which form incised, reticulate networks with the main trend of flow towards the northwest. Near the village of Hulu Atas this complex of rivers coalesces with southward flowing drainages from the flanks of the 30 and 60 Mile Hills between Lake Sentani and the Lakes-Plains depression, forming the westward flowing Taritatu River. Beyond Hulu Atas the Taritatu flows across the Lakes-Plains depression in sinuous bends for nearly 200 km, receiving several major south bank tributaries. Most notable is the Van de Wal, which drains the eastern limb of the Derewo Fault Zone and contains Archbold Lake in its upper reaches (CI 2000).

2.4. Vegetation

Outlying mountains of the Foja and Van Rees not connected to the central mountains that form the spine of New Guinea contain many rare and endemic forms of wildlife and plants. The vast freshwater swamp forests, lowland and

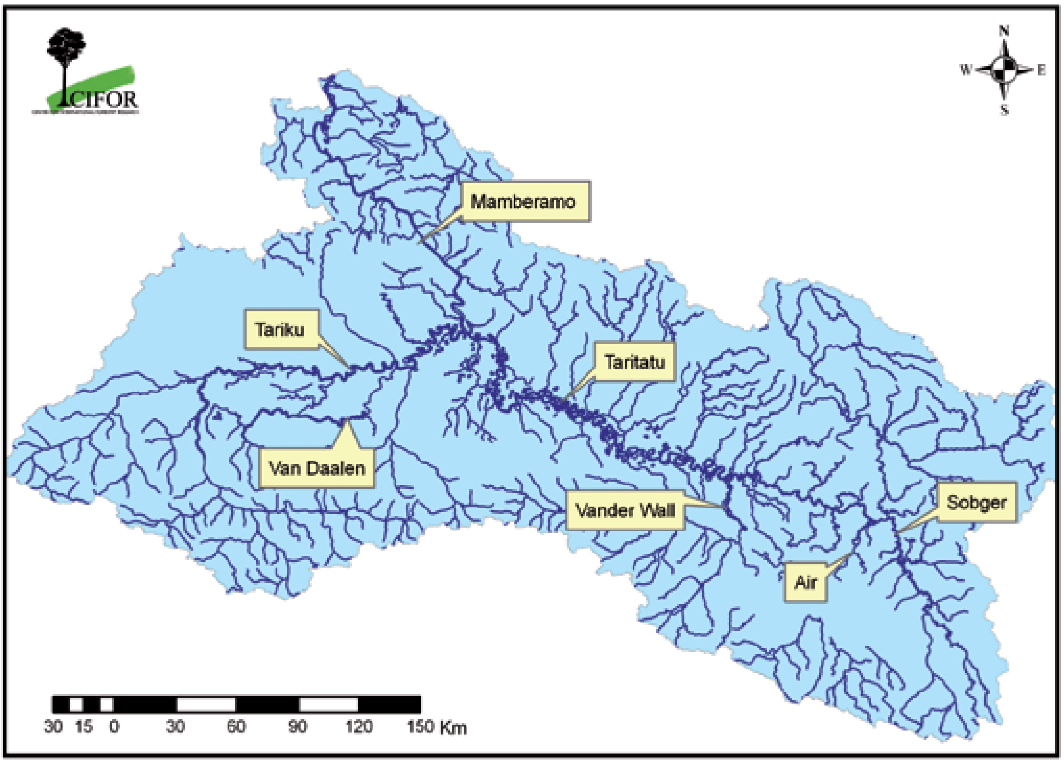

Figure 7. River systems in the Mamberamo Basin with inverted-T shape of the main rivers, Tariku, Taritatu and Mamberamo

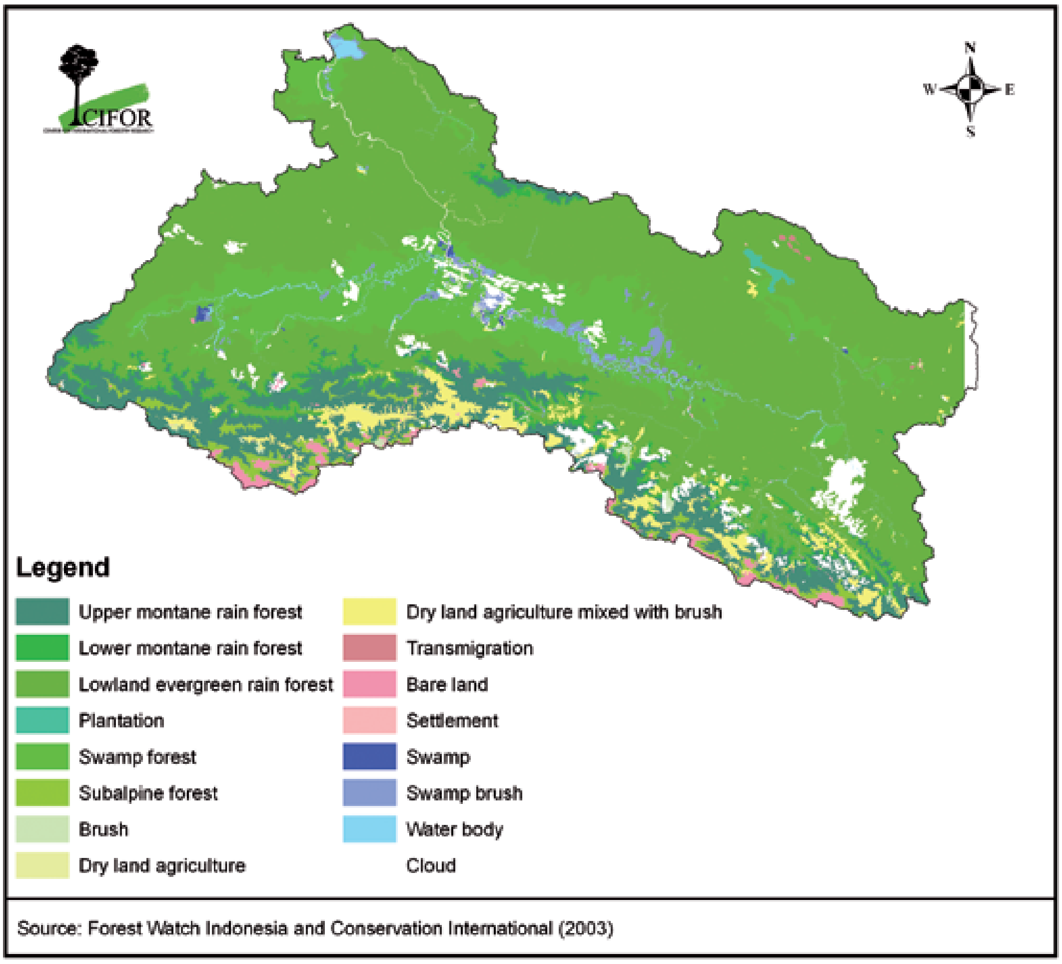

Figure 8. Land cover of the Mamberamo Basin

hill forests, and marshes, lakes and rivers contain many globally threatened species with healthy populations. The land cover in Mamberamo Basin is dominated by lowland evergreen rain forest area that covers about 58 percent of the entire basin (Figure 8). The swamp forest is in second position with 14 percent, followed by upper mountain rain forest with 12 percent of the entire basin. Settlements, transmigration area and dry land agriculture occupy the least portion and cover less than 0.1 percent of the basin. The remaining areas of the basin are bare land (1.2 percent), brush (0.5 percent), dry land agriculture mixed with brush (3.3 percent), lower mountain rain forest (3.3 percent), plantation (0.2 percent), subalpine forest (2 percent), swamp (0.1 percent), swamp brush (1.1 percent), and bodies of water (1 percent).

The most recent land use and land cover analysis carried out by Forest Watch Indonesia in partnership with CI and Department of Forestry found that forest and natural land cover extend over more than 90 percent of the basin (FWI 2004). The breakdown of forest land planning units is shown in Table 1. Currently a large proportion of forests in Mamberamo Basin have been designated as protected forest (3,544,571 ha, or 44 percent) followed by forests for conservation and recreation (2,304,475 ha, or 29 percent) and various types of production forest (2,100,438 ha, or 26 percent).

Based on the range of elevation, several different formations can be categorized. Their distribution is as follows:

- *High montane forests* (above 4,000 m) is represented in the upland headwaters of the Mamberamo in the central cordillera.
- *Upper and lower montane forest* (1,000-3,000 m) is well represented in the central ranges (including the Wapoga area) as well as in the Foja Mountains and to a lesser extent in the Van Rees Mountains.
- *Hill forest* (100-1,000 m) covers a narrow belt on the lower northern slopes of the central cordillera, but there are large expanses to the north of the Taritatu and Tariku rivers in the Foja and Van Rees foothills.
- *Lowland rain forest* (0-100 m) is confined to areas not inundated by flooding in the Lakes-Plains depression, along low-lying river valleys in the central portions of the Mamberamo River, and where the river emerges from the Foja-Van Rees gorge.
- *Swamp forest* and other swamp formations are extensive in the Lakes-Plains depression. This vegetation type experiences seasonal flooding from the Mamberamo.
- *Mangroves* can be found in the Mamberamo delta. Papua contains the largest expanses of mangroves in the world, with 29 of the

Table 1. Forest allocation based on forest functions for Mamberamo Basin (FWI 2004)

Forest functions	**Size (ha)**	**Percentage of total land (%)**
Forest conservation and recreation (*Hutan Suaka Alam dan Hutan Wisata*)	2,304,475	29
Protected forest (*Hutan Lindung*)	3,544,571	44
Limited production forest (*Hutan Produksi Terbatas*)	578,669	7
Permanent production forest (Hutan Produksi Tetap)	372,813	5
Convertible production forest (*Hutan yang dapat dikonversi*)	1,149,446	14
Non forest area	27,379	1
Total	**7,977,355**	**100**

34 mangrove tree species being recorded. Although the Mamberamo mangroves are not nearly as extensive as those on the southern coast and at Bintuni Bay, they represent an important habitat in the Mamberamo delta.

In addition to those categories, Figure 8 shows the distribution of vegetation cover in the Mamberamo Basin.

2.5. Wildlife and Its Habitat

The island of New Guinea (which includes Indonesian Papua and the eastern half of the Independent State of Papua New Guinea) is the third largest tropical 'high-biodiversity wilderness area' in the world, after the Amazon and the Congo Basin (Mittermeier *et al.* 2002). The term 'wilderness' connotes two key types of information for prioritization for conservation: species endemism (uniqueness to a particular area) and the level of threat.

Wildernesses of concern to CI are areas over 750,000 km^2, with over 70 percent of the original vegetation cover intact and low human populations of fewer than 5 individuals per square kilometre. The five largest high-biodiversity wilderness areas in the world cover a total of 11.8 million km^2 (6 percent of the Earth's terrestrial surface) and have as endemics at least 17 percent of all their plant species and 8 percent of all terrestrial vertebrates. These areas 'are vital to climate regulation and watershed protection' as well as being some of the last places on Earth where indigenous people can carry out a traditional lifestyle.

Papua's biodiversity is renowned. Of all the biodiversity found within Indonesia (a megadiverse country in itself, second only to Brazil for total number of terrestrial species), Papua supports over 50 percent of these. Many of the species represented in Papua are also endemic. Thus, Papua significantly contributes to Indonesia's status as the second most species rich country in the world for the terrestrial realm.

If the marine realms are included in the biodiversity discussion, then Indonesia is possibly the most diverse country on the planet, in large part due to biodiversity that Papua supports in her coastal waters and reefs.

The list of Papua's biodiversity is impressive. Within its fauna alone, Papua supports

- 191 species of indigenous mammals,
- 552 species of terrestrial breeding birds or water birds (shorebirds, pelagic and migratory species excluded),
- 142 species of lizard,
- 83 species of snake,
- over 130 species of frogs,
- 2,650 species of fish (about 60 percent of which are marine species), and
- more than 100,000 arthropod species.

Mamberamo was one of the objects of Archbold's famous 1929-30 expedition, on which he discovered the Dani people in the Baliem valley. As the expedition used a flying boat for logistic supplies and aerial exploration, the Mamberamo with its many hundreds of ox-bow lakes and long meandering rivers provided the perfect base camp from which to proceed further into the interior. During this expedition, biological forays were made into the northern slope of the central ranges and into the lower parts of the Mamberamo river.

The Archbold expedition, which focused mostly on terrestrial mammals and birds, provided the best information on species found in the Mamberamo until the 2000 Rapid Assessment Program (RAP) carried out by CI. Meant for training purposes, the program was carried out in the Dabra and Foja mountains. It was found that in 2005 the Foja Mountains and the Mamberamo contained over 100 species of mammals. In the Fojas alone, 42 species were recorded, including the confirmation of the golden-mantled tree-kangaroo (*Dendrolagus pulcherrimus*), which constitutes a new mammal record for Indonesia as this species was only previously known from the Torricelli Mountains, where it is extremely rare. In total, 6 of the 19 macropods (kangaroos) that occur in New Guinea were recorded in high densities. In the Mamberamo, unlike anywhere else in Papua, this group of animals is commonly and easily observed. The higher elevations of the Fojas also support a monotreme species (*Echidna bruijnii*). Echidnas are usually exceedingly rare in New Guinea due to hunting pressure but were apparently common in the survey.

The Mamberamo region supports an incredible 35 percent of all Papuan avifauna. Among the

250 species recorded in the entire region, at least 11 are endemic and 6 are globally endangered. A total of 13 birds of paradise have been recorded (including the discovery of the pied parotia, *Parotia berlepschi*, previously thought to be a subspecies but now elevated to species level), four species of bowerbird (including one endemic to the Fojas and photographed during the RAP, and a possible new taxon yet to be described), a new species of honeyeater (*Melipotes carolae*) apparently confined to the Foja mountains, 11 species of fruit pigeon, numerous parrots including Salvadori's fig-parrot (*Psittaculirostris salvadori*) and Pesquet's parrot (*Psittrichas fulgidis*) (both globally threatened), and two species of cassowaries (which are abundant in the area).

The Mamberamo Basin has an exceptionally rich herpetofauna. A number of reptile species including the saltwater crocodile and the New Guinea freshwater crocodile, a giant softshell turtle (*Pelochelys cantori*) and a number of smaller turtles, goannas (*Varanus*) and large snakes have economic or subsistence value for local communities. The basin is home to an extremely rare aquatic snake, the Mamberamo River watersnake (*Heurnia ventromaculata*), known only from the Mamberamo River system, and is the eastern-most extreme of the range of the spectacular sail-finned lizard (*Hydrosaurus amboinensis*).

There are likely to be more than 100 frog species in the Mamberamo basin. However the frog fauna remains poorly known and during recent surveys numerous new species were logged, so this total may increase substantially. For example, at least 20 new species were recently discovered in the foothills and at higher altitudes of the Foja Mountains. Many of these recently discovered frogs are likely to prove endemic to the Mamberamo Basin.

The last two groups are highly likely to be affected by the tidal systems (flooding and drying) of the Lake-Plains.

2.6. Socioeconomic Factors

The Mamberamo is very sparsely inhabited with approximately 11,000 people living in the lowlands along the river. Due to the remoteness of the region, communities continue their subsistence livelihoods and still maintain a very close attachment to the forest, swamps, lakes and rivers and their natural resources. Education, health and communications are poor with rudimentary services provided by the government and missionary groups. Small-scale economic activities are in existence and all rely on the exploitation of natural resources.

Economic activities of people in the Mamberamo normally use the barter system, although almost all people would prefer to exchange goods for cash. However, if there is a lack of money within a village, there is usually no alternative to bartering. Markets (featuring staples such as vegetables, meat, dried fishes and items such as sugar, instant noodles, cooking oil and soap) are held sporadically in the villages as there is not a steady supply of products to be sold.

Education and Health Services

According to one account based on 1993–94 data, 66.3 percent of the school aged (12–15) children do not continue to junior high school, as they must work to support their family (Sugiyono 1998). Education and health service levels are especially low in the Mamberamo. Almost 90 percent of Mamberamo people are illiterate, and the prevalence of proficient Indonesian speakers is lower than in other areas of Papua. The only senior high school in the whole Mamberamo region is located in Kasonaweja, and there is one junior high school in each of the three subdistricts (*Kecamatan*). There are only 4, 1 and 5 elementary schools in Mamberamo Hilir, Mamberamo Tengah and Mamberamo Hulu, respectively.

Health conditions for the local population are still very poor, and communities often suffer malaria and respiratory and skin problems. There are only six health care centres (*Puskesmas*) servicing the entire region with just 8 medical staff. The *Puskesmas* are poorly financed and medical supplies and equipment are often insufficient compared with the need. They frequently run out of medicines and/or basic medical equipment such as clean syringes.

Transportation and Communication

The entire Mamberamo region is serviced by scheduled once weekly flights from Sentani to Dabra through the national carrier Merpati, weather permitting. The airstrip at Dabra is asphalted, but the largest aircraft that can use the strip is a de Havilland DHC-6 Twin Otter with a passenger capacity of 16. The ticket price is low at about US$25 per single journey, but demand

Figure 9. Longboats and single-engine aircrafts from missionary aviation services are the main means of transportation (photos: D. Murdiyarso)

is high with government employees and security personnel receiving priority treatment.

Several missionary aviation services also provide transportation for preachers and community members to a number of grass landing strips in the region with their small 6-10 seat aircraft (Figure 9). At least 18 villages now have a grass landing strip for this purpose, but the flights are irregular and expensive (typically around US$100 for a single trip from the Mamberamo to Sentani). Missionary aviation service will always attempt to transport critically ill members of the community, especially if there is capacity and the trip fits existing flight plans.

A more frequently used transportation method for Mamberamo communities is river transport. Longboats are extremely important means of communication between villages. Most villages own a government-donated longboat. These boats can take up to 20 people plus goods. However, fuel for the outboard motors is extremely expensive, typically four times the Jayapura price. The journey can also be dangerous especially through the Mamberamo gorges. Lower sections of the river (Trimus and below) are serviced by biweekly ships from Sarmi and Jayapura. A journey from Dabra to Jayapura using longboats downstream to Trimus and then a ship to Sarmi and Jayapura would typically take a week (see Figure 1).

Income and Livelihoods

In 1999, average per capita income for people living in the Mamberamo region was around US$235 per year as compared with the provincial average of US$743 (Anggraeni 2001). The general lack of money in circulation has many knock-on impacts and exacerbates the conditions of education, health and transportation described above. Traditional Mamberamo communities live a seminomadic life and support their livelihoods through harvesting sago palms, agriculture, fishing and hunting.

Sago harvesting. The most common livelihood strategy in Mamberamo is sago harvesting in the swamp areas. Sago is a staple food for people in Mamberamo and the area has the largest stocks of this valuable starch-producing palm in the world. In a conservative estimate, almost pure stands of sago (sago forest) cover 60,000 ha in the three districts. Traditionally, males cut down the sago trunks when they are mature; it is the females' role to remove the fibrous pith (a process called *potok*), wash out the starch (*ramas*) and dry the resulting product. Sago is processed into porridge (*papeda*) and also can be baked (like bread). Sago is the local communities' main staple food, providing an estimated 90 percent of their energy needs.

Small scale agriculture. Cultivation is the main livelihood strategy in Mamberamo aside from sago harvesting. Cultivation in Mamberamo is still carried out traditionally using the simplest of tools (machete, axes and dibble sticks, or *uto*). Communities in the Mamberamo region use a shifting cultivation system based on slash and burn to plant banana, sweet potato and taro to supplement sago. Fields are planted only once and then abandoned as people move to another area. Fields are left fallow after 3–5 years of cultivation (Taime 2003).

Fishing and hunting. Fishing in rivers and lakes is an important livelihood strategy in Mamberamo. Fishing provides the largest proportion of protein consumed by communities. Fishing techniques

Figure 10. Sago processing from palm to main staple food for people in the Mamberamo Basin (photos: D. Murdiyarso)

include the use of spears, hook and line, nets, and occasionally poison. The main varieties of fish caught include fork-tailed catfish (*Arius uturus*), carp (*Cyprinus carpio*) and tilapia (*Oreochromis mossambicus*).

Many villagers are starting to extract the swim-bladders of the fork-tailed catfish (*Arius* spp), which are sun-dried and sold to traders by the kilogram for a relatively high price. This is a new industry, and an exploitative one. It is uncertain whether the stocks of these large New Guinea endemic freshwater fish have started to decline, and populations need to be surveyed in the future. Thus fishing as an activity to secure protein for consumption is being replaced by fishing for economic reasons. Often the flesh of the catfish is let to rot or attempts are made to preserve it over smoky fires with varying results. The bladders are reportedly exported to Singapore and Hong Kong for medicinal purposes.

Hunting rivals fishing as the principal livelihood strategy to provide protein in the diet. However, this activity is exclusively practiced by males. Hunting grounds are usually quite distant from the villages, due to tenure rights, management decisions about wildlife stocks, location of 'good places' for hunting and stocking density of wildlife. For this reason, whole communities may move temporarily to hunting grounds for several months while animals are hunted. As hunting is not a full-time pursuit, sago groves and crops are also tended in these more distant areas. Thus hunting has a central role in the patterns of livelihoods in the Mamberamo (CI 2006).

Species hunted include wild pigs, cassowary, cuscus, tree kangaroo, bandicoots and large rats, monitor lizards and freshwater turtles, but practically all animal proteins are eaten. Tools for hunting are traditional bow and arrow (*gehi*), spears, and snare (*loo*). The use of dogs to scent out and run down prey is key to successful hunting. No firearms are used at present, though compressed air pellet guns are used to shoot birds (Figure 11).

Crocodile (*Crocodylus novaeguineae*) hunting for trade started in 1960. Most communities with access to the main Mamberamo river now carry out this economic activity, which has become the mainstay of cash income. Hunters most commonly search for adult crocodiles with a belly width of greater than 12 inches. Skins are taken and salted for preservation and the meat is either eaten or sold (if there are buyers). Prices of skins vary with width. Today traders within the Mamberamo are located only in Dabra and Pulau Iri and belong to the same company group, the Bintang Mas company. The trading post typically tries to exchange goods (rice, sugar, coffee, batteries and flashlights, tobacco and cigarettes, clothing etc.) for crocodile skins, but also does cash transactions. Several communities have, in the past, caught juveniles, which Bintang Mas then transported to Jayapura. Some members of the community have started to take skins to Jayapura themselves in order to obtain a better price, but the problem of transportation in and out of the Mamberamo still persists. Crocodile hunting is an exclusively male activity and uses traditional hunting gear such as ropes made from rattan, spears (*dao*) and hooks baited with meat (CI 2006).

2.7. Regional Development and Extractive Industries

Mamberamo Mega Development Project

In 1996, State Minister of Research and Technology Habibie called a ministerial meeting attended by the ministers of mines and energy, public works, communications, and agriculture and a representative from the Department of Industry and Trade. At this meeting, the theme of 'Environment, Innovation, and Development (EID) of Intensive Energy Industries' was used to label the Mamberamo project. The thrust of the envisioned project was to exploit the hydropower potential of the Mamberamo River, estimated at between 7 GW and 20 GW out of the total hydropower potential of 100 GW. The power could be used to meet the needs of industry, commerce, residents and all other electricity users. Sectors to be developed would include metal and mining and petrochemical industries, agriculture, forestry, services, and trade. A month later, a Terms of Reference for the EID was issued (MIC 1997 in Sheng 2003).

Although the large-scale industrial development plans for the Mamberamo region have become stagnant, they may gain favour and be reconsidered in the next few years. The Department of Public Works carried out the study on hydropower plant development with an installed capacity of 14,000

Figure 11. Fishing and hunting in the Mamberamo Basin is part of the life supporting system (photos: D. Murdiyarso and M. Boissierie)

MW, by developing several hydropower reservoir types (Table 2). The power would potentially be absorbed by the mining sector (DPU 1997).

Figure 12 shows the locations of three planned major dams in Mamberamo (Kasonaweja, Karubaga and Bokondini dams). The Kasonaweja dam would be located in the lower Mamberamo around the gorges. It would likely be sitting on old volcanic and consolidated sedimentary rock. The Karubaga and Bokondini dams will be damming smaller tributaries in the upper Mamberamo, an area dominated by igneous or metamorphic rocks (Figure 13).

Table 2. Potential for electric power generation in the Mamberamo River basin

River	Potential power generated (MW)
Air	3,700
Sobger	1,500
Tariku	4,400
Taritatu	1,500
Van der Wal	2,900
Total	**14,000**

Source: DPU 1997.

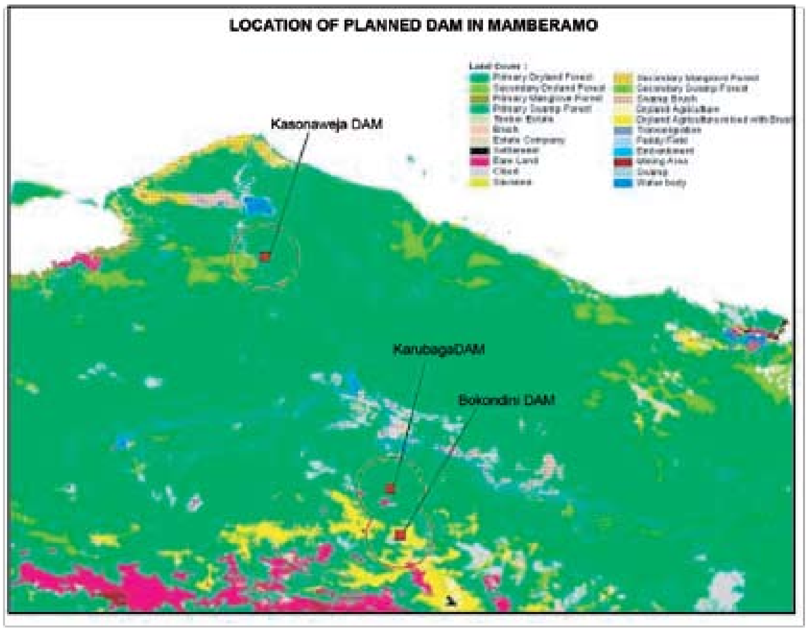

Figure 12. Location of the proposed Mamberamo dam network (Adapted from DPU 1997)

Figure 13. Proposed locations of the Kasonaweja dam (top) and Karobaga and Bokondini dams (bottom) (photos: D. Murdiyarso)

Total investment cost for the megaproject is estimated around US$13–21 billion. Details of the proposed investment cost extracted from the scoping report are illustrated in Table 3. The government of Papua expected investors from USA, Australia, UK, Japan, Germany, South Korea and the Netherlands as well as World Bank and Asian Development Bank loans to fund the Mamberamo project (BP PIM 2002).

Besides having the positive potential for improving people's welfare, the Mamberamo basin has the potential for earthquakes, high scale erosion and floods. The frequency of high magnitude earthquakes measuring 5 to 6 on the Richter scale is 7–8 times a year.

There area many active faults with shallow epicentres in the study area. Seasonal floods in the Lakes-Plains depression occur due to high seasonal rainfall and the narrow outlet for the confluence flood. High scale erosion such as mass movement occurs mainly at elevations of 1,500-2,000 m asl (DPU 1997).

Road construction

Existing and provincial government planned regional-scale roads are illustrated in Figure 14. The provincial and district governments plan to improve the existing road network in the next few years. If not well-planned the development could be a significant threat to biodiversity and wildlife habitats in the Mamberamo. The threats could include loss of habitat due to land clearing and sedimentation caused by erosion and landslides along the roads.

The government of Sarmi District wishes to pursue a plan to open up the Mamberamo by constructing a road from Kasonaweja over the Van-Rees mountains to Sikari. As the government does not have the funds to invest in this development project, it is soliciting tender from logging companies, who will be permitted to take timber from approximately 5 km either side of the constructed road (known as logs-to-roads deal). This amounts to 1,000 hectares of forest logged for every kilometre of road constructed. This in itself has major implications for conservation in the Mamberamo region. While easier access to the Mamberamo will vastly increase communities' access to services and markets for some sustainably managed natural resources, this benefit may be outweighed by the negative impact on biodiversity of uncontrolled exploitation of natural resources (CI 2006).

Mining

The entire Mamberamo region with the exception of the estuary area in the northern tip appears to be tightly packed with allocated or pending mining concessions (Figure 15). These concessions though at the stage of general investigation and exploration overlap significantly with conservation areas. There is a large pending mining concession in the upper stream of the Mamberamo River, around Dabra, north of the planned Enarotali–Wamena road. If this pending concession becomes active, another large portion of high priority conservation area equal to 7 percent of the conservation areas, or about 1.3 million ha, will be lost to mining (Mertens 2002).

Due to the lack of data on mineral reserves in this region, it is difficult to gauge the potential threat and economic significance of mineral extraction to the Mamberamo region (Hari, in Sheng 2003). However, at present there is an interest in coal mining in areas that have already been surveyed. These reserves are outside protected areas but due to similar geology similar coal deposits are expected to be found within the Mamberamo-Foja wildlife reserve as well, if exploration permits are issued. Development of coal mining in Mamberamo could provide much needed employment and revenue, but destruction of high conservation value ecosystems and pollution of Papua's largest river may result (CI 2006).

Logging Industries

An examination of the logging concessions located within the regencies covered by the Mamberamo region shows that in 2000, there were 15 concession owners with a combined area of 3,768,953 ha. A significant portion of the region's active concessions appears to be located within proposed conservation areas (see Figure 15). However, the only logging concession directly operating within the Mamberamo River catchment is PT. Mamberamo Alas Mandiri located in Sarmi District. This is the biggest concession in Papua with a total area of 691,700 ha. PT. Mamberamo Alas Mandiri started operating in 1994 under authorization from the central Forestry Department (SK Menhut No. 1071/Kpts-II/1992).

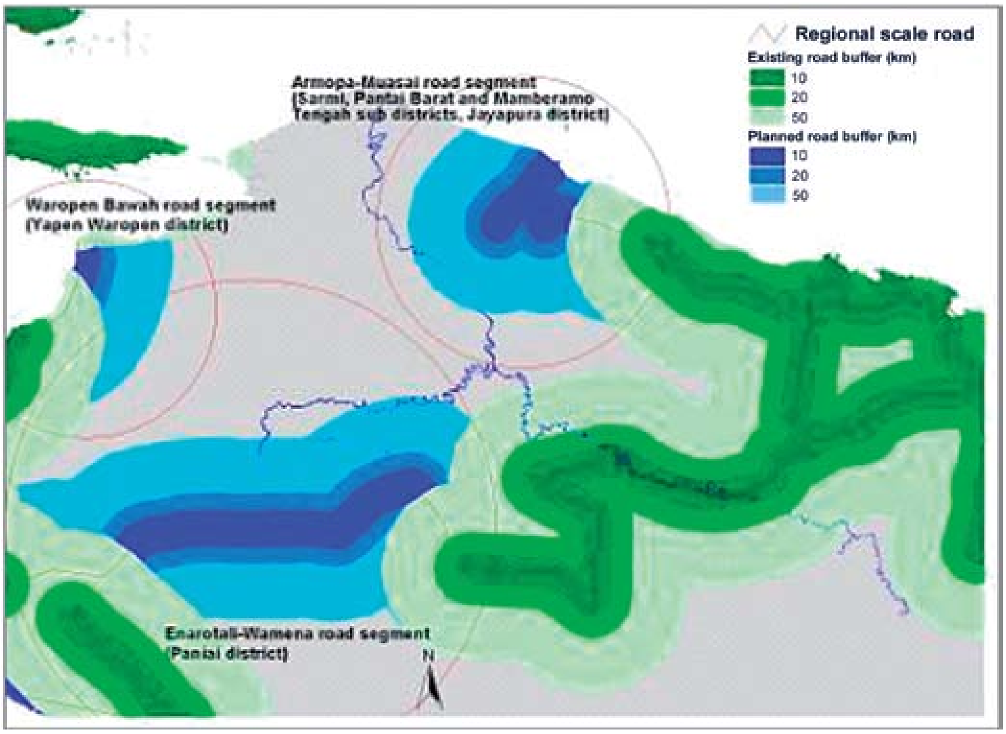

Figure 14. Areas affected by road development in the Mamberamo Basin (CI 2006)

Table 3. Investment cost of Mamberamo development project

Project	**Source of fund**	**Estimated cost range (US$million)**	
Dam and hydroelectric production: 5 GW	Multinational consortium	5,000	6,000
Industries			
Aluminium	Investor	1,000	1,500
Steel	Investor	2,500	5,000
Copper/gold/nickel smelting	Investor	500	1,000
Petrochemical	Investor	1,000	2,000
Pulp and paper	Investor	1,000	2,000
Dockyard	Investor	1,000	1,500
Automotive	Investor	500	1,500
Infrastructure/electric train	Government	400	600
Urban industries area	Developer	400	600
Total		**13,300**	**21,700**

(Source: BP PIM, 2002)

Production volume from PT. Mamberamo Alas Mandiri showed a steady increase during the period of 1995 to 2000, with 1999/2000 log production reaching 130,693 m^3. Logs from this concession were transported to a sawmill located in Serui (PT. Kodeko Mamberamo, established in 1995). The capacity of this sawmill is 250,000m^3/year and it produces 126,000 m^3 of processed wood (PT. Mamberamo Alas Mandiri 2001).

This logging operation transports lumber by both road and river. Road construction until March 2000 totalled about 61.8 km for main roads and 100.8 km for branch roads. As construction of roads is expensive, rivers play a significant role in the transportation of lumber to the sawmill. As the Mamberamo River itself is impassable to large timber barges, the areas logged within the Mamberamo catchment are limited to the lower extremities near the coast outside the Lakes-Plains depression.

PT Mamberamo Alas Mandiri stopped its logging operation in 2002. The company has contributed significantly to government revenues and local community economy, although the realization of taxes reached only around 30 percent of what was payable. Even though this is the case, there may be government incentives to encourage companies to resume logging activities in the Mamberamo. An even greater threat to biodiversity will be the leasing of forest natural resources to logging companies in return for road construction described above.

Plantation Development

The area with agricultural potential in the region is about 1.2 million ha (1,135,137 ha of rice plantations and 110,126 ha of oil palm plantations surrounding the Rombabei Lake (Sheng 2003). Low productivity and efficiency, security risks, traditional land tenure, and lack of an educated labour force were cited as major constraints to the development of the agricultural sector in the region. Currently, there are two active oil palm plantations around the Mamberamo region, which belong to PT. Sinar Mas II and cover an area of about 23,000 ha. One of these plantations near Lereh is within the Mamberamo corridor.

Transport is the main factor determining whether a plantation is viable or not. Spatial analysis shows that plantations and timber estates in Papua seem closely related to the main road network and are in close proximity to the main population centres such as Jayapura, Merauke and Sorong (Mertens 2002).

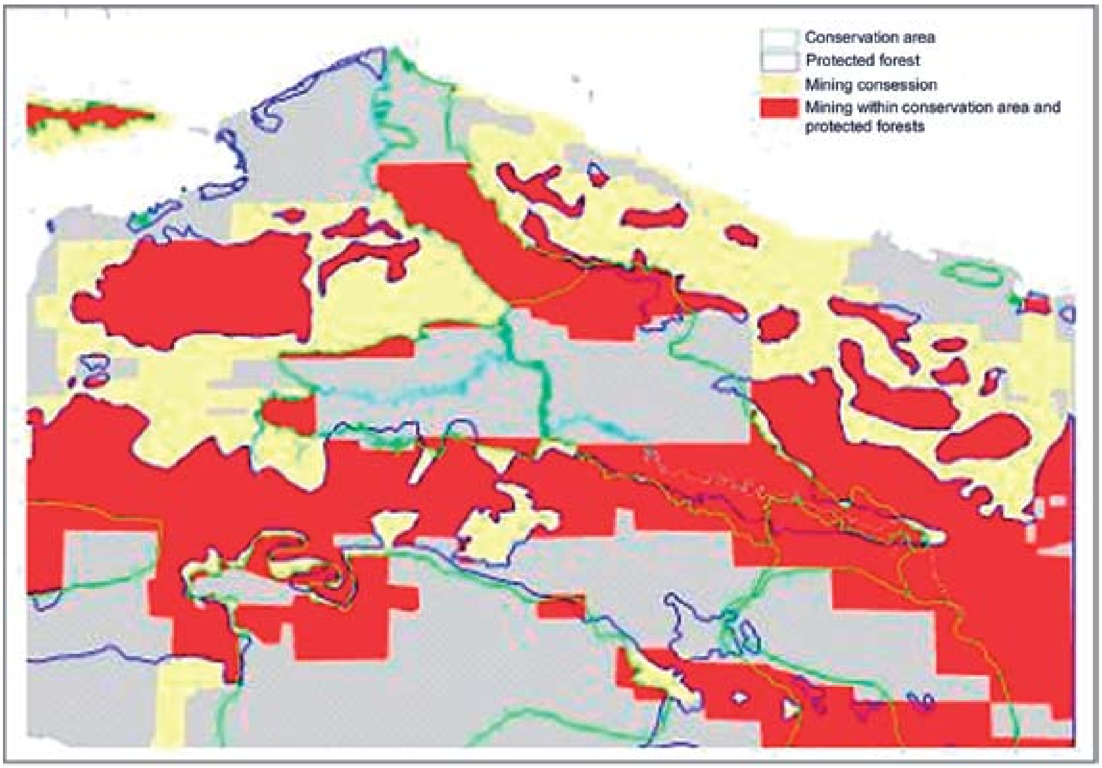

Figure 15. Mining concessions within conservation area and protected forest in the Mamberamo Basin (CI 2006)

3. Methods

3.1. Basin and Catchments Delineation

The boundaries of the Mamberamo Basin are determined by using the digital elevation model (DEM) extracted from the NASA shuttle radar topographic mission (SRTM v.3). The same technique was used to delineate the catchment areas representing the basin for more detailed studies. This way one could generate river network and subsequent river and catchment factors.

The model was then used to generate spatially explicit information based on tabular data such as rainfall and air temperature. The spatial information of these physical properties is required to calculate the basin and catchment evapotranspiration and water balance.

Other biophysical processes that demonstrate the interaction of physical properties (soil and climate) and biological characteristics such as vegetation cover with their rooting systems will also be generated. To a certain extent spatially explicit information on soil water content may be used to categorize habitat quality at landscape or catchment scale and its impact on species distribution.

There are three catchments selected as representative catchments for more detailed studies. These are:

- *Uge*, which represents the upper Mamberamo region with rugged terrain and is located on igneous or metamorphic rocks of the Nassau Range. Dabra was selected as base camp.
- *Beri*, which represents the middle Mamberamo or the Lakes-Plains and is located on loose sediment and dominated by clay. Papasena was used as base camp.
- *Wiri*, which represents the lower Mamberamo and is located on old volcanic consolidated sedimentary rocks of the Foja-Van Rees Mountains. Kwerba was chosen as base camp.

3.2. Determination of Primary Factors

In order to determine river and catchment characteristics, a river network may be generated from the DEM. The algorithm may be constructed by connecting every cell to its neighbours with the steepest downslope gradient. It consists of the following steps:

1. Import the DEM, generate the standardized DEM, apply 'stream burning' method.
2. Remove the sink.
3. Generate the flow direction.
4. Generate the flow accumulation.
5. Derive the river network by applying the threshold value to the flow accumulation.

ArcGIS 9.2 software was employed to run the above procedures and generate the primary factors, namely flow direction, flow accumulation, and river network. These factors will greatly influence flow, quality, and timing of ecohydrological processes.

The 'stream burning' method introduced by Wesseling *et al.* (1997) was used to ensure the correct location of the river in the Mamberamo Basin and its catchments. This method uses the additional information of location of the main river derived from the map. Renssen and Knoop (2000) used this method to derive the global river network that demonstrates good agreement with the real data.

The additional information of river location in the Mamberamo Basin was derived from the topographical maps issued by Bakosurtanal, the Indonesian national coordinating agency for surveys and mapping. We had to convert the river map to the Raster-ESRI format and apply it to the stream burning method. The idea for applying the river map is to lower the cells on which the river is located proportionally to the DEM values. Before applying this step, the standardized DEM is required, which results from DEMs with a range from 0 to 1 as follows:

$$stdDEM = \frac{DEM - DEM_{\min}}{DEM_{\max} - DEM_{\min}} \quad ....(1)$$

where DEM_{min} and DEM_{max} are the minimum and maximum values of the DEM respectively.

Next, the streams were burned into the standardized DEM by subtracting the value 1 from those cells where the main streams are located based on the river map.

For flow direction generating purposes, the burned DEM has to be free from sinks (a sink cell is a cell surrounded by cells with higher values than the sink cell itself). In reality, sinks represent natural depressions in the landscape. However, sink cells are often errors of the DEM (Karssenberg 1995). To eliminate these errors, sink removal is applied by using the fill-sink function in ArcGIS.

The flow direction map is determined by finding the neighbour with the steepest downslope gradient based on the values of the eight cells in its surroundings. In ArcGIS, the result of the direction map is an integer with the following values, which indicate directions: 1 = east, 2 = south-east, 4 = south, 8 = south-west, 16 = west, 32 = north-west, 62 = north, and 128 = sink.

Flow accumulation estimates accumulated flow as the accumulated weight off all cells into each downslope cell in the output raster. By adding the threshold value into the flow accumulation map, the stream network can be estimated by using equation 2.

$strNet$ = if ($flowacc > TH$,1,0). ....(2)

where *flowacc* is the flow accumulation map and *TH* is the threshold value.

The other primary factors of the representative rivers and catchments to be quantified are listed and defined in Table 4. Stream order estimation is the first step for catchment analysis. The Strahler (1964) method was used to determine stream order.

3.3. Establishment of Rate Factors

Rate factors are rivers' physical characteristics that have the potential of influencing flow, quality, and timing of hydrological processes and that thus impact on important species and their habitats. These will be established and tabulated based on estimated parameters. Assessments of the catchment made during the participatory survey and interviews with local communities during a two-week fieldwork in the Mamberamo Basin will be used to relate biophysical data and socioeconomic challenges.

One of the important characteristics of a river is the hydrograph, which represents the distribution of discharge in the channel as a function of time. For every catchment, the hydrograph has a unique shape that comprises antecedent flow rate, rising limb, peak flow, falling limb and groundwater recession. Therefore, the term 'unit hydrograph' was proposed to represent the average capacity of a catchment to discharge storm water. The unit hydrograph is defined as the direct runoff hydrograph that results from unit depth of excess rainfall produced by a storm of uniform intensity and specified duration.

The unit hydrograph of the specified catchment is generally derived from the recorded streamflow data and the temporal distribution of rainfall excess. Due to lack of observed streamflow and rainfall data, we derived the unit hydrograph of the representative catchments in the Mamberamo Basin by using basin physiographic data.

The Soil Conservation Service method is used to derive the unit hydrograph in this study. This method estimates peak discharge from the triangular approximation to the hydrograph as follows:

$$q_p = \frac{0.208A}{T_p} \quad ....(3)$$

where q_p is the peak discharge (m^3/s), A is the catchments area (km^2) and T_p is the time to peak (min), which is calculated as follows:

$$T_p = 0.5D + T_L \quad ....(4)$$

Table 4. Definitions of river and catchment factors to be quantified

Variable	Definition/formula
River factors	
Number of order	The smallest fingertips tributaries are designated order 1. If two first order channels join, a channel segment of order 2 is formed. If two channels with different orders joins, a channel segment of the higher order is formed.
Number of stream segment, N_u	
Bifurcation ratio, R_b	The ratio of number of segments of a given order N_u to the number of segments of the higher order N_{u+1} (u is order)
Total segment length, L (km)	
Mean length, $\overline{L}$ (km)	$\overline{L} = L/N_u$
Length ratio, R_L	$R_L = \dfrac{\overline{L_u}}{\overline{L_{u-1}}}$
Catchment factors	
Catchment length, L_b (km)	Distance from outlet to most distant point from outlet
Catchment perimeter, P_b (km)	Length of water divide encircling the catchment area
Catchment area, A (km^2)	Area of landscape bordered by the highest water divide with a river outlet at the bottom or lowest part of the landscape
Form factor, R_f	$R_f = \dfrac{A}{L_b^2}$
Law of stream area, R_a	$R_a = \dfrac{\overline{A_u}}{\overline{A_{u-1}}}$,where A_u is the mean area in the order u
Circularity ratio, R_c	Ratio of catchment area to area of circle having the same perimeter as the catchment $R_c = \dfrac{4\pi A}{P_b^2}$
Elongation ratio, R_e	Ratio of diameter of a circle of the same area as the catchment to the maximum catchment length $R_e = \dfrac{2}{L_b}\sqrt{\dfrac{A}{\pi}}$
Drainage density, D(km/km^2)	$D = \dfrac{L}{A}$
Stream frequency, F(1/km^2)	
Relief, H (m)	Elevation difference between catchment outlet and highest point on catchment perimeter
Relief ratio, R_h	Ratio between relief and Horizontal distance from basin outlet to highest point on catchment perimeter

where T_l is the time lag between the centre of the effective rainfall (min) and the peak runoff rate, which is calculated as follows:

$$T_l = 0.6T_c \quad ......(5)$$

where T_c is the time it takes a drop of water that fell on the most remote point of a drainage basin to reach the outlet, which is calculated as follows:

$$T_c = 0.0078\, L_f^{0.77} S^{-0.385}, \quad ......(6)$$

where L_f is the length of the channel from the basin outlet to the most remote point of the basin (ft) and S is the average slope (m/m).

3.4. Soil Sampling

Disturbed soil samples were collected from five locations by means of an auger at a consistent depth of 30 cm. These locations represent upper, middle and lower catchments with different geological formations. In order to overcome spatial variability of locations, composite samples were collected from three points.

Samples were analyzed in the laboratory to evaluate soil texture, bulk density and permeability. These parameters are needed for water balance calculation and interpretation.

The data will be interpreted in the context of soil infiltrability and water holding capacity at the landscape level. They will be rasterized to provide spatially explicit information in connection with vegetation cover, slope and river network.

The soil samples were sent to the soil laboratory for acquiring the soil physical properties such as soil texture, bulk density, porosity and permeability. The methods used were hydrometeric for soil texture, gravimetric for bulk density and porosity, and Darcy law for the permeability.

3.5. Water Balance Analysis and Modelling

The general water budget of the entire basin will be calculated based on the input and output of water in the basin. The budget is often called climatological or atmospheric water budget since no analysis on the lithosphere process is made. The budget simply shows the difference between rainfall as the only input and evapotranspiration as the only output. Rainfall data from neighbouring stations will be interpreted and employed since there is no rainfall station in the basin.

Estimation of the catchment water balance components such as actual evapotranspiration (*AET*), soil water content (*SWC*), soil moisture surplus (*SMS*), and soil moisture deficit (*SMD*) will employ *JavaWB* software (Murdiyarso and Kurnianto 2007), a spatially explicit and user-friendly modelling tool developed by using Java™ 2 Platform Standard Edition 5.0 (J2SE™ 5.0). The model requires two kinds of data, spatial data (i.e., DEM, land cover (*LC*), soil texture (*ST*), rainfall (*P*) and latitude map) and tabular data (i.e., temperature (*T*) and water holding capacity (*WHC*) table). The algorithms of the *JavaWB* is shown in Figure 16.

Potential evapotranspiration (*PET*) is counted by using the Thornthwaite method adjusted by a daylight hour factor. The formula for counting *PET* is:

$$PET_i = \frac{N_i}{12} 16 \left(10 \frac{T_i}{I}\right)^a \quad ......(7)$$

$$a = 0.49 + 0.0179I - 77.1 \times 10^{-6} I^2 + 67.5 \times 10^{-8} I^3 \quad ......(8)$$

$$I = \sum_{i=jan}^{des} \left(\frac{T_i}{5}\right)^{1,516} \quad ......(9)$$

$$N_i = \frac{24}{\pi} \omega_i \quad ......(10)$$

$$\omega_i = \arccos(-\tan(\theta)\tan(\delta_i)) \quad ......(11)$$

$$\delta_i = 0.409 Sin\left(\frac{2\pi}{365} J_i - 1.39\right) \quad ......(12)$$

Where:

PET : potential evapotranspiration (mm),
T : temperature (°C),
I : heat index,
ω_i : sunset hour angle (radian),
θ : latitude (radian),
J : Julian date,
δ : solar declination (radian), and
i : monthly time step.

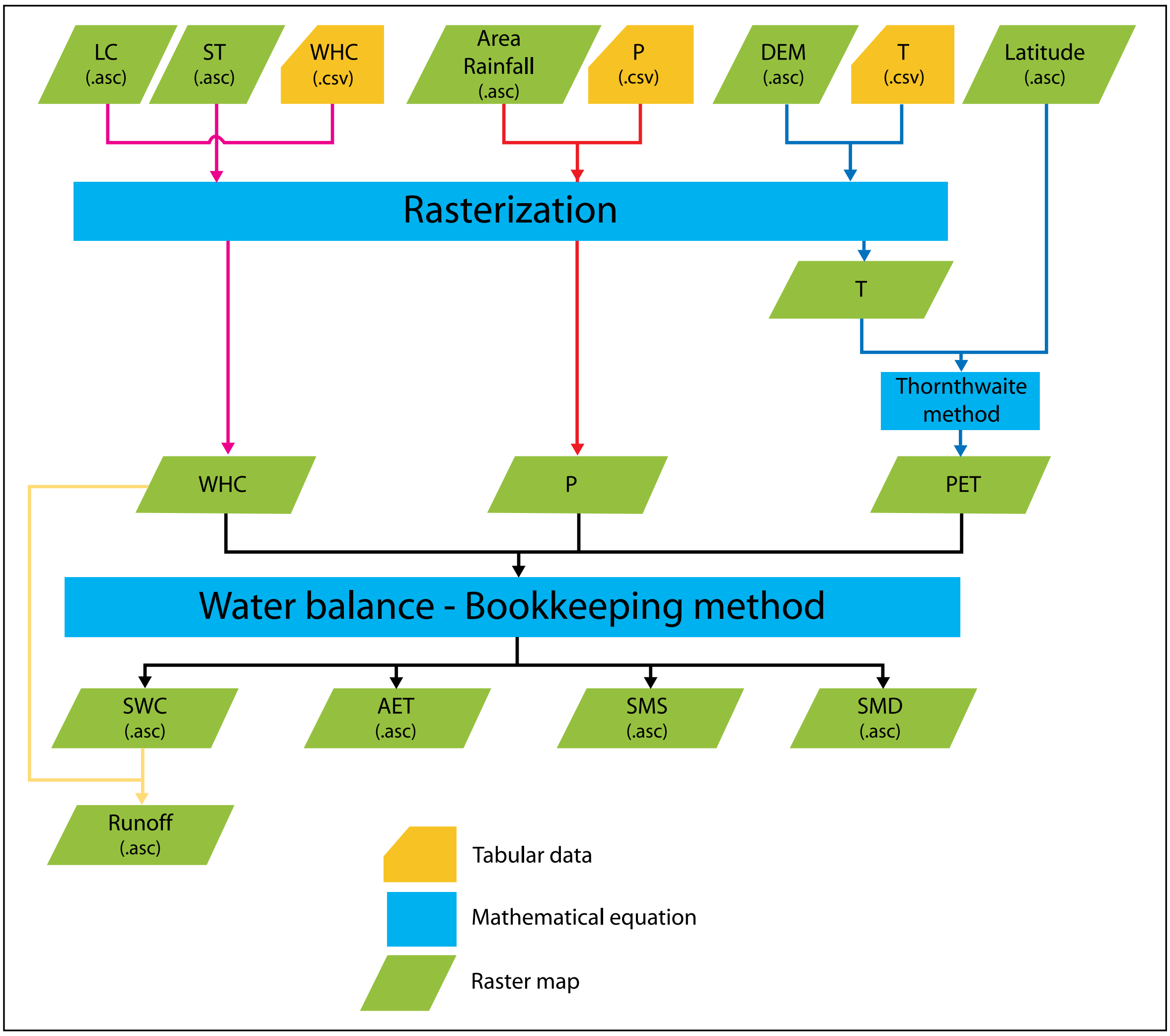

Figure 16. Flow diagram of *JavaWB* for calculation of water balance components by using both spatial and tabular data. Abbreviations are described in the text.

The bookkeeping method proposed by Thornthwaite and Mather (1957) was adopted by *JavaWB* for calculation of water balance components. This method requires *WHC*, *P* and *PET* as data inputs. When the difference between *P* and *PET* is positive, the amount will be added to the soil as *SWC*. On the other hand, *SWC* is an exponential function of *WHC* when the difference is negative. It is defined as follows:

$$SWC_i = SWC_{i-1} + P_i - PET_i, \text{ if } P_i > PET_i \quad \text{......(13)}$$

$$SWC_i = SWC_{i-1} exp\ (P_i - PET_i/WHC), \text{ if } P_i < PET_i \quad \text{.................................(14)}$$

When *P* is lower than *PET,* the soil will no longer be saturated and evapotranspiration will occur at actual rate *(AET)*. In the case of *P* > *PET*, *AET* will be equal to *PET*. When precipitation declines below the potential evapotranspiration, the soil begins to dry out and *AET* becomes less than *PET*. In those months, *AET* equals the precipitation plus the amount of water drawn from the soil moisture storage. It is calculated as follows:

$$AET_i = P_i - SWC_i + SWC_{i-1}, \text{ if } P_i < PET_i \quad \text{......(15)}$$

The difference between *PET* and *AET* is termed 'soil moisture deficit' (*SMD*):

$$SMD_i = PET_i - AET_i \quad \text{.................................(16)}$$

After soil moisture storage reaches the water holding capacity, any excess precipitation is counted as soil moisture surplus (*SMS*), which is calculated as follows:

SMS_i = max$(0, SWC_i – WHC)$ ....(17)

Finally, the water content in any particular month was calculated as follows:

$SWC_i = SWC_i - SMS_i$ .... (18)

The bookkeeping method and spatially explicit presentation of *SMD* and *SMS* allow us to carry out experimentation at catchment level. These are expected to mimic possible changes induced by humans when they alter vegetation cover and the subsequent effects on climate.

In order to assess the impacts of climate change and land cover change on water resources, a simulation model was run based on

- 11 climate change scenarios (i.e., combinations of temperature changes, ΔT = 0, +1 °C, +2 °C, +4 °C and rainfall changes, ΔP = 0 percent, +10 percent, +20 percent) and
- three land cover change scenarios (i.e., forest cover of 30 percent, 60 percent, and 90 percent of the entire catchment).

The water balance and its components are recalculated and re-evaluated. These scenarios are expected to provide information on the expected changes. Therefore, necessary policy interventions may be introduced.

Due to lack of sediment data for validation, the impacts of changes on sediment load on the water bodies were not evaluated.

4. Results

4.1. General Water Balance of the Mamberamo Basin

The general water budget estimated by the difference of annual rainfall minus annual potential evapotranspiration is calculated for the whole basin. The difference between atmospheric input and output is usually termed climatological water balance. The spatial expression of the balance is shown in Figure 17. In general, the entire basin experiences excess water as total annual rainfall is higher than total annual potential evapotranspiration. The range of the excess, however, is quite large. In the lower and middle parts of the basin, where altitude is lower and the land is flat to gently sloped, the excess was about 500 mm, while it is about 5,000 mm in the mountainous area. Such a large difference will likely have huge consequences in the overall flow when land use change occurs in the higher altitudes.

4.2. Primary Factors of Wiri, Beri and Uge Rivers and Their Catchments

The relative locations and shapes of the chosen catchments of Wiri, Beri and Uge are shown in Figure 18. Meanwhile, the calculated primary factors of the rivers and their catchments are listed in Table 5.

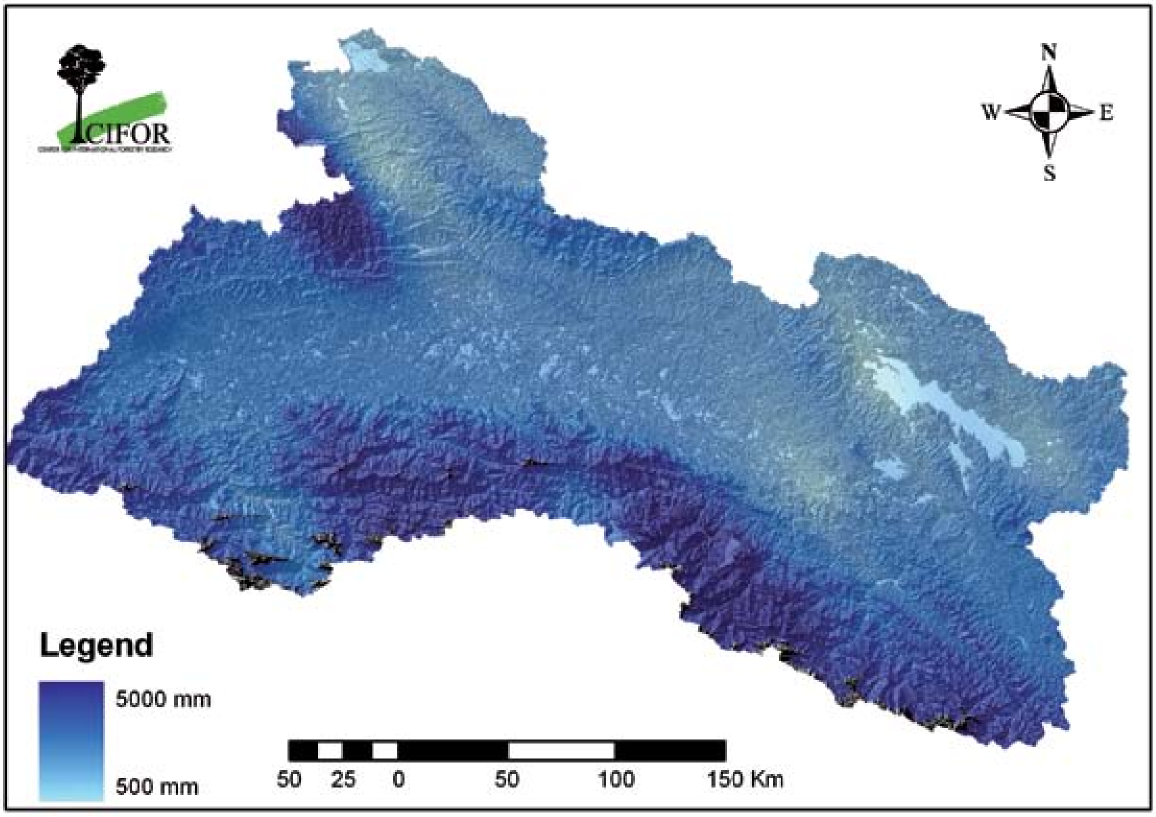

Figure 17. Climatological water balance of the Mamberamo Basin

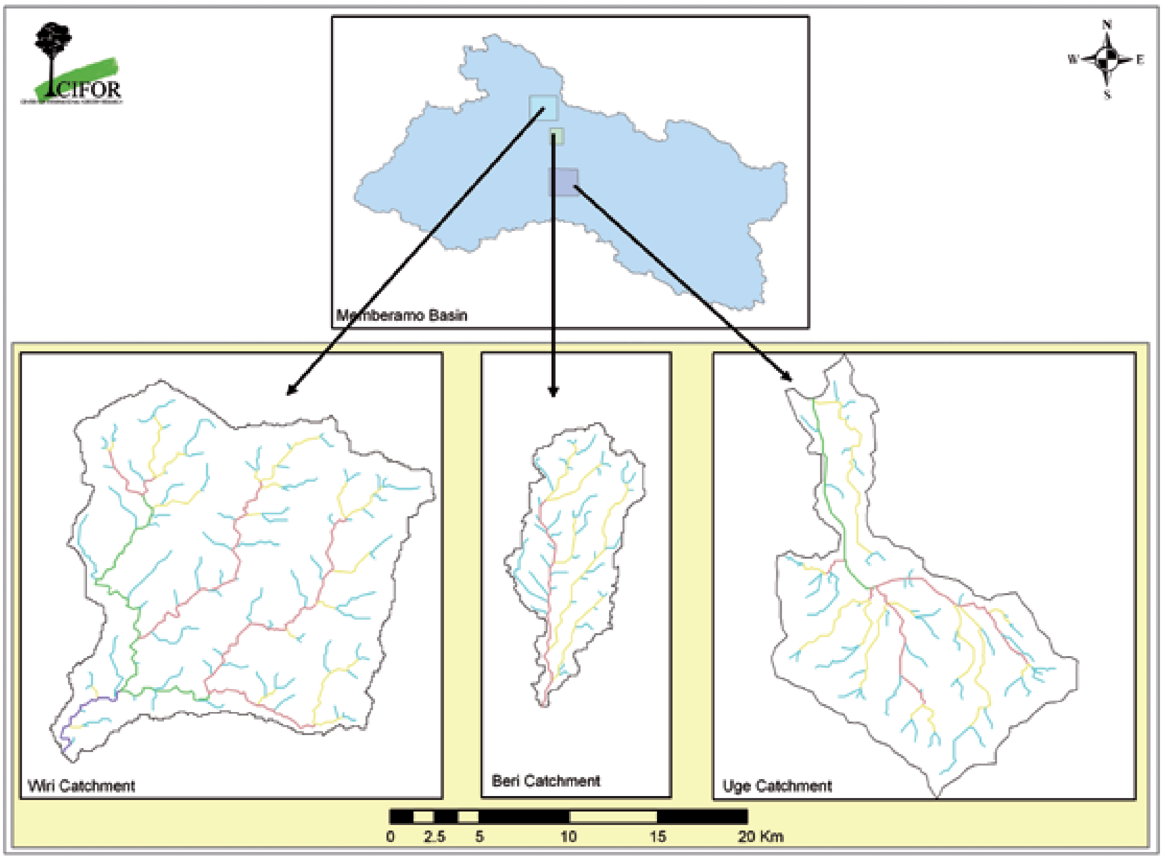

Figure 18. Relative locations of the Wiri, Beri, and Uge catchments in the Mamberamo Basin

Based on the arrangement of the river networks and water divide, Wiri catchment is being the most complicated one with 111 stream segments compared with only 45 and 76 for Beri and Uge catchments respectively. After considering the number of stream segments, however, the mean length of the stream is quite similar across these catchments.

Although the Beri represents the smallest catchment area, its bifurcation ratio, R_b, is the largest. This is expressed in the elongated shape, while the other two catchments with lower R_b values are more circular in shape, especially the Wiri catchment with its largest circularity ratio, R_c, of 0.57.

Another uniqueness of the Beri catchment is its high drainage density, *D*. With its small catchment area and relatively gentle terrain Beri has the highest risk of being inundated in the event of increasing excess water.

Another interesting comparison between the three catchments is the relief ratio, R_h. Uge catchment shows the highest R_h because it is located in rugged terrain with relatively steep slopes. The implications will be further discussed in the next section.

4.3. Primary Rates of Wiri, Beri and Uge Rivers

The primary rates indicated by the synthetic unit hydrograph of each catchment were estimated by using the primary factors listed in Table 6 and are shown in Figure 19.

Time of concentration, time lag, and time to peak of Wiri catchment are the highest, followed by Uge and Beri catchments. As a result Wiri catchment has the highest peak runoff of 690 m^3s^{-1}, followed by Uge's 440 m^3s^{-1}, which is about two thirds of Wiri catchment's value but more than double that of Beri catchment (190 m^3s^{-1}).

These figures also related to topographical conditions especially relief and relief ratio. Based on the DEM the average slope in Beri catchment is gentler than in the others catchments.

Table 5. Wiri, Beri and Uge river and catchment factors

Variable	Order	Watershed		
		Wiri	Beri	Uge
River factors				
Number of order		5	3	4
Number of stream segments	1	85	39	56
	2	19	5	15
	3	4	1	4
	4	2		1
	5	1		
	entire	111	45	76
Bifurcation ratio, R_b	1	4.5	7.8	3.7
	2	4.8	5	3.8
	3	2.0		4.0
	4	2.0		
	5			
	entire	3.3	6.4	3.8
Total segment length, L (km)	1	105.50	36.18	63.37
	2	38.94	28.42	50.91
	3	43.31	12.72	21.88
	4	23.12		12.24
	5	6.67		
	entire	217.54	77.32	148.40
Mean length (km)	1	1.24	0.93	1.13
	2	2.05	5.68	3.39
	3	10.83	12.72	5.47
	4	11.56		12.24
	5	6.67		
	entire	1.96	1.72	1.95
Length ratio	1			
	2	1.7	6.1	3.0
	3	8.7	13.7	1.6
	4	9.3		2.2
	5	5.4		
	entire	6.3	9.9	2.3
Catchment factors				
Catchment length,– L_b (km)		25.78	15.69	23.47
Catchment perimeter, P_b (km)		82.17	58.12	80.00
Catchment area, A (km^2)		304.66	67.92	175.83
Form factor, R_f		0.46	0.28	0.32
Law of stream area, R_a		0.96	0.94	0.98
Circularity ratio, R_c		0.57	0.25	0.35
Elongation ratio, R_e		0.76	0.59	0.64
Drainage density, D (m/km^2)		714	1138	844
Stream frequency, F (1/km^2)		0.36	0.66	0.43
Relief, H (m)		1817	454	2487
Relief ratio, R_h		0.07	0.03	0.11

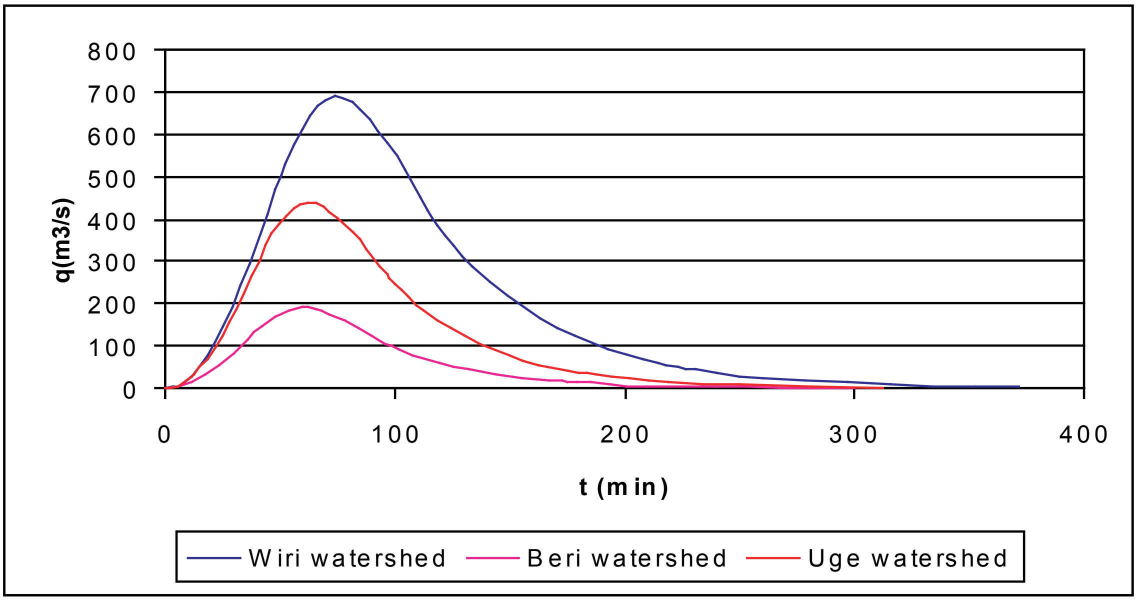

Figure 19. Synthetic unit hydrograph in Wiri, Beri and Uge catchments

Table 6. Elements for estimating the unit hydrograph in Wiri, Beri and Uge catchments

Variable	Watershed		
	Wiri	Beri	Uge
Flow length(m)	37,552.3	19,081.1	32,114.7
Average slope (m/m)	0.2	0.1	0.3
Time of concentration, T_c (min)	111.5	89.9	93.8
Time lag, T_l (min)	66.9	53.9	56.3
Duration (min)	14.8	12.0	12.5
Time to peak, T_p (min)	74.3	59.9	62.5
Peak runoff (m^3/s)	688.6	190.4	438.7

4.4. Soil Physical Properties of Wiri, Beri and Uge Catchments

The mean, maximum, minimum and standard deviation values of the measured soil physical properties bulk density, porosity and permeability, collected from five locations in the Mamberamo Basin, are given in Table 7, while Table 8 shows the textures for the same locations.

Kwerba, which represents Wiri catchment in the lower Mamberamo, has the highest bulk density of 1.41 g cm^{-3}, which is why this location also has the lowest values in porosity (47 percent) and permeability (2.36 cm h^{-1}). This signifies the properties of old volcanic and consolidated sedimentary rocks indicated in the hydrogeological map (see Figure 2).

In contrast Papasena I and II which represent the Lakes-Plain in the middle Mamberamo has the lowest bulk density, hence the highest porosity (on average around 57 percent) and moderate permeability. This property is typically found in semiconsolidated sedimentary rocks.

The highest mean permeability is found in Dabra with its sandy loam and loamy sand texture, although the geology is similar to that found in Kwerba.

The texture found at the sampling sites will be used to estimate the depth of rooting systems and water holding capacity of the soil profile. The finer the texture (e.g., clay and silt) the shallower the root depth compared with coarser textures like sand and loam.

Table 7. Bulk density, porosity and permeability in five locations

Location	Mean	Max	Min	Standard deviation
	Bulk density (g/cm³)			
Papasena I	1.12	1.25	0.89	0.15
Papasena II	1.19	1.27	1.07	0.09
Dabra	1.22	1.37	1.15	0.10
Wiri	1.28	1.39	1.19	0.07
Kwerba	1.41	1.49	1.34	0.06
	Porosity (% percent)			
Papasena I	57.63	66.48	52.98	5.76
Papasena II	55.09	59.72	52.26	3.22
Dabra	54.09	56.58	48.17	3.97
Wiri	51.51	55.06	47.38	2.82
Kwerba	46.88	49.38	43.84	2.28
	Permeability (cm/hour)			
Papasena I	7.26	9.99	3.69	2.41
Papasena II	4.02	5.44	1.86	1.75
Dabra	8.18	18.89	2.69	7.34
Wiri	6.06	11.40	2.11	3.41
Kwerba	2.36	4.03	1.22	1.31

Table 8. Soil texture estimated from four to five sampling points at each of five locations

Location	Soil texture
Papasena I	silt loam
	silt loam
	silt loam
	silt loam
	loam
Papasena II	silt loam
	silt loam
	loam
	loamy sand
Dabra	loamy sand
	sandy loam
	silt loam
	silt loam
	loam
Wiri	silt loam
	silt loam
	silt loam
	silty clay loam
Kwerba	silty clay loam
	sandy loam
	silt loam
	silt loam
	silt loam

4.5. Water Balance of Wiri, Beri and Uge Catchments

The annually averaged rainfall of three catchments was around 3,000 mm, the highest rainfall occurring in Uge catchment with its mountainous topographical conditions (Table 9). Beri catchment, located on the Lakes-Plains with the higher temperatures, showed the highest *AET.* As a result the soil moisture surplus *(SMS)* is smallest, even smaller than in Wiri catchment although its rainfall is higher. The smallest ratio between *SMS* and rainfall is found in Beri catchment (49 percent) and the highest in Uge catchment (60 percent).

For the monthly averaged water balance, all the catchments show the same pattern (Figure 20). Rainfall decreases from its maximum in March or April, which ranges from 300 mm to 350 mm, to its minimum in July or August, which ranges from 170 mm to 200 mm. The monthly pattern of *SMS* for each catchment closely follows the rainfall pattern: the maximum of about 150–250 mm in March or April will decrease and reach 50–100 mm in July or August. The monthly patterns of *AET* for all the catchments are also similar and vary only from 80 mm to 110 mm for Wiri catchment, from 120 mm to 140 mm for Beri catchment and from 90 mm to 110 mm for Uge catchment. Since the averaged rainfall is higher than *AET*, the catchments did not experience a deficit, with the

Table 9. Mean annual values of water balance components

Catchment	Rainfall (mm)	AET (mm)	SMS (mm)	SMD (mm)
Wiri	3,005	1,256	1,750	0
Beri	3,131	1,600	1,531	0
Uge	3,232	1,298	1,934	0

exception of Wiri catchment with its highest *SMD* of only 5 mm.

The monthly spatial distribution of *SMS* obtained from the *JavaWB* output and generated from about 40 years worth of rainfall data is shown in Figures 21, 22 and 23 for Wiri, Beri and Uge catchments respectively. Spatial variability of *SMS* in those catchments has similar patterns. They also show the obvious effects of topography. The minimum *SMS* occurs in the lower part of a catchment and it increases to reach its maximum in the upper part.

In the drier month such as July and August, *SMS* in the lower part of the catchment was very low at around 0 mm, 60 mm, and 10 mm for Wiri, Beri and Uge catchments respectively. These values increased with elevation and reached the maximum in the upper part of the catchments of around 100 mm for Wiri, 90 mm for Beri, and 130 mm for Uge catchment.

In March, when maximum rainfall occurs, most of the catchment areas have higher *SMS* than in August. In wet months, *SMS* for Wiri catchment ranged from 70 mm in the lower part to 250 mm in the upper part. The corresponding values for Beri catchment were 200 mm to 220 mm, and for Uge, 120 mm to 300 mm.

4.6. Impacts of Climate and Land Cover Changes on Water Balance

In this exercise the mean climatic conditions (rainfall and air temperature) for the period of 1950 to 1995 were considered baseline data. The expected changes generally follow the Goddard Institute for Space Studies' Global Circulation Model, which suggests that rainfall for the eastern part of Indonesia could increase between 5 to 50 percent. Meanwhile temperature change is expected to follow the Intergovernmental Panel on Climate Change scenario, which assumes an incremental increase of 1°C to 4°C.

The 12 climate scenarios (i.e., combinations of 0 percent, 10 percent, 20 percent change of rainfall and +0°C, +1°C, +2°C and +4°C change of temperature) are simulated to evaluate the changes in water balance components (*AET, SWC, SMS* and *SMD*). The baseline for the three catchments and the percent of change of mean annual water balance components under changing climate scenarios are shown in Figure 24.

The increase of temperature followed by rising *AET* is experienced in all catchments. In Wiri, the increase from 1°C to 4°C causes an increase of *AET* of about 10 percent to 62 percent. The increase of *AET* for the same range of temperature increase was 18 percent to 80 percent in Beri catchment, and about 15 percent to 70 percent in Uge catchment. This means that Beri catchment would be most severely affected, especially if rainfall does not increase while the temperature increases up to 4°C.

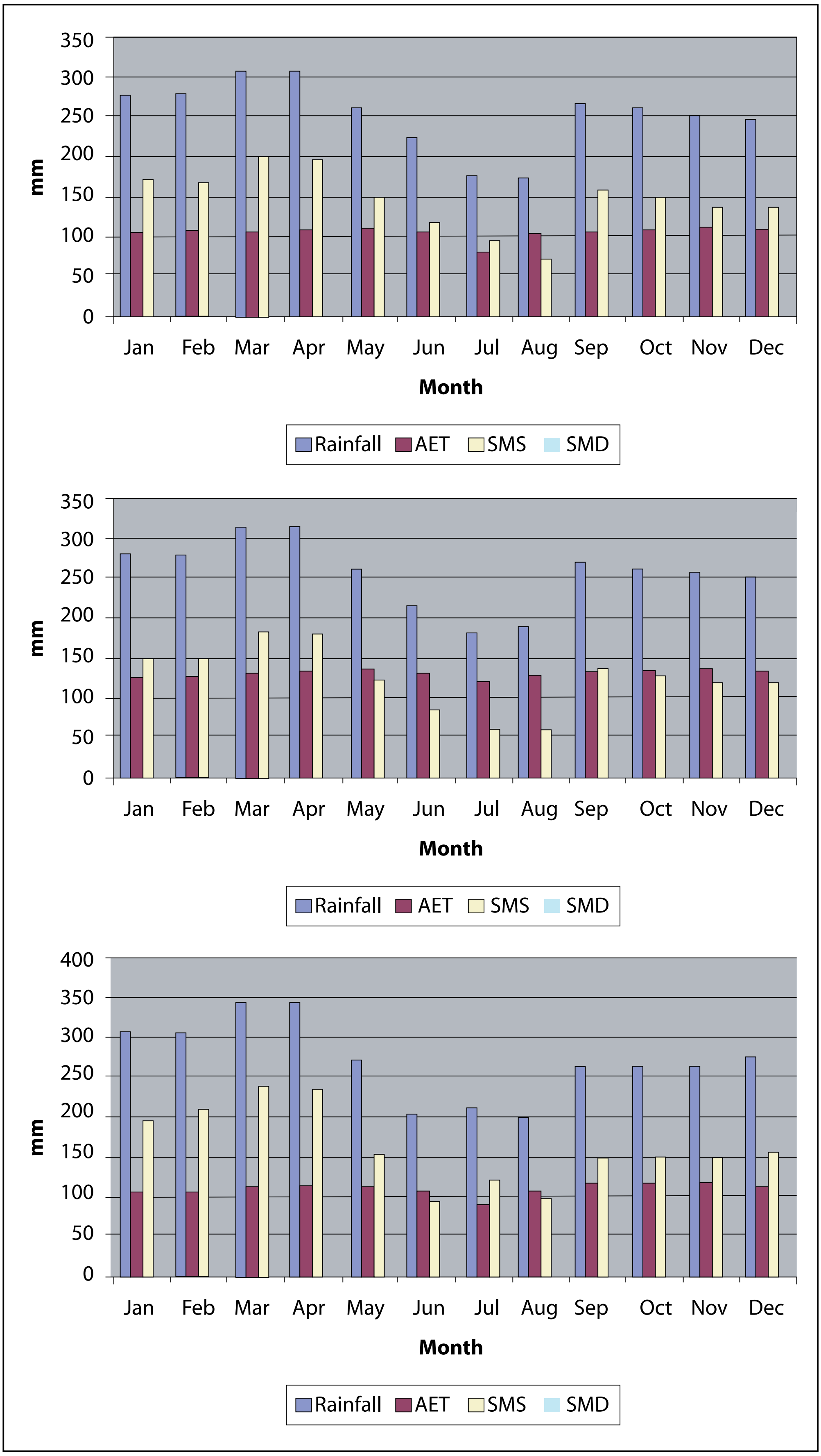

Figure 20. Monthly averaged water balance components of Wiri (top), Beri (middle) and Uge catchments (bottom)

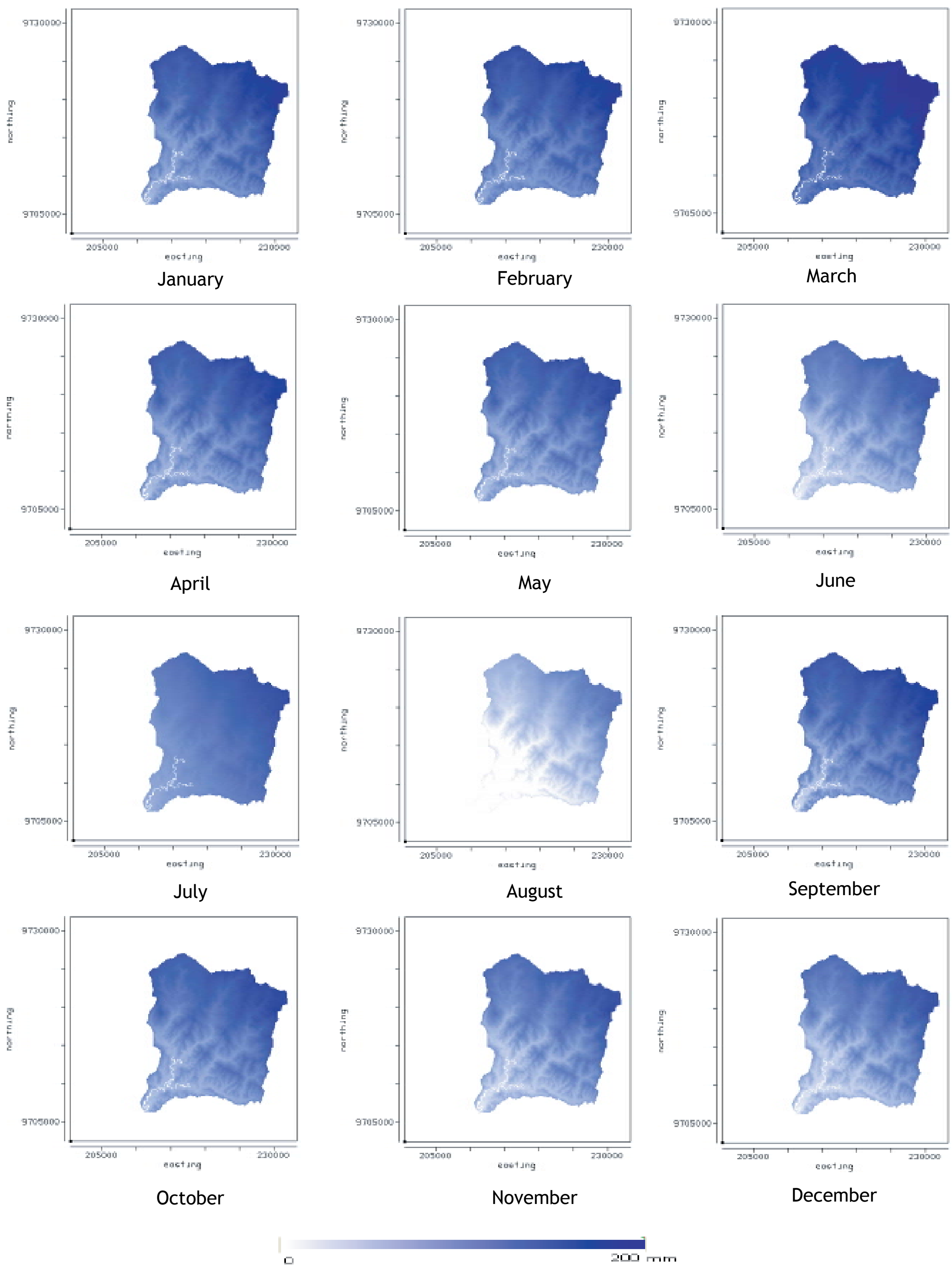

Figure 21. Monthly spatial distribution of soil moisture surplus (*SMS)* of Wiri catchment

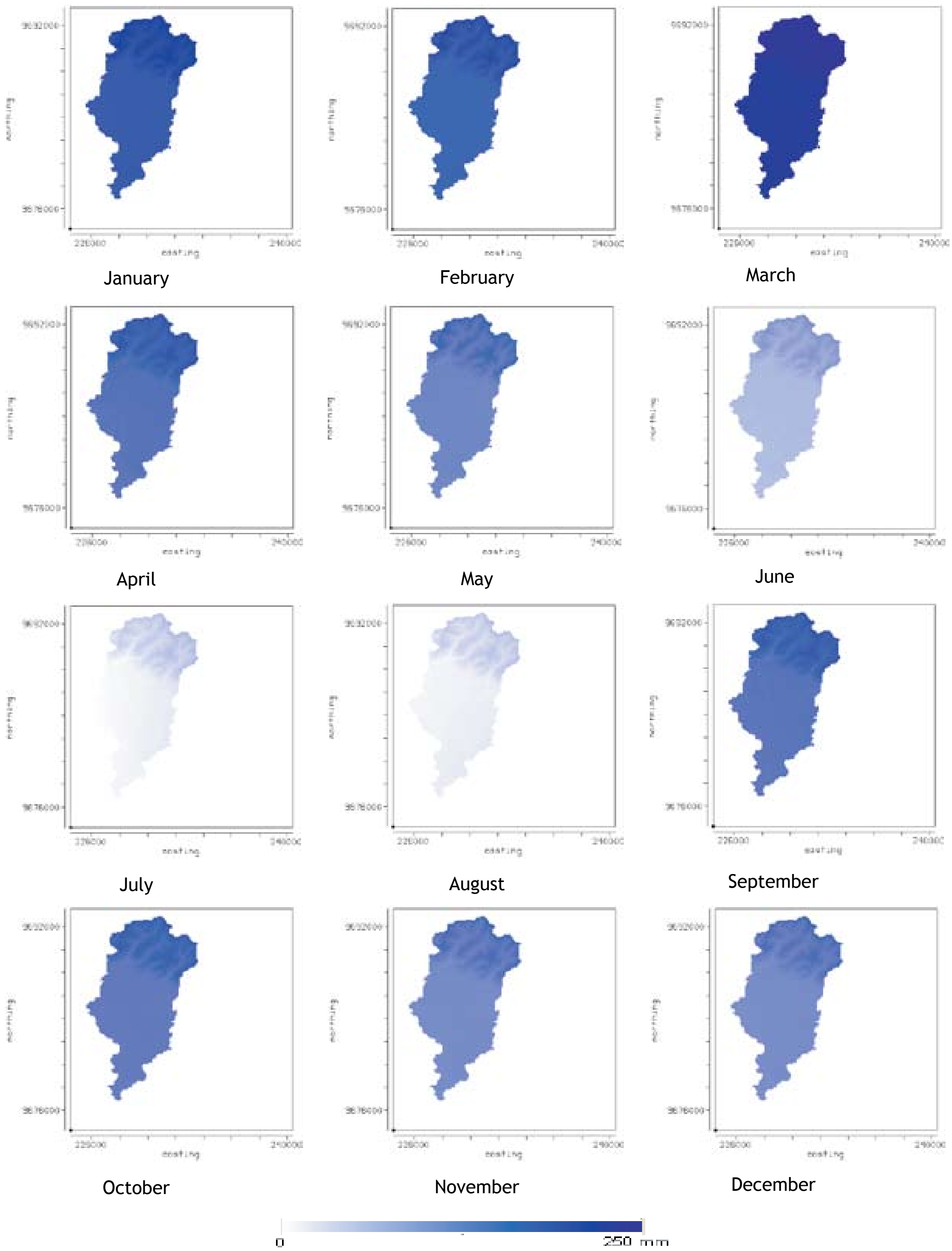

Figure 22. Monthly spatial distribution of soil moisture surplus (*SMS)* of Beri catchment

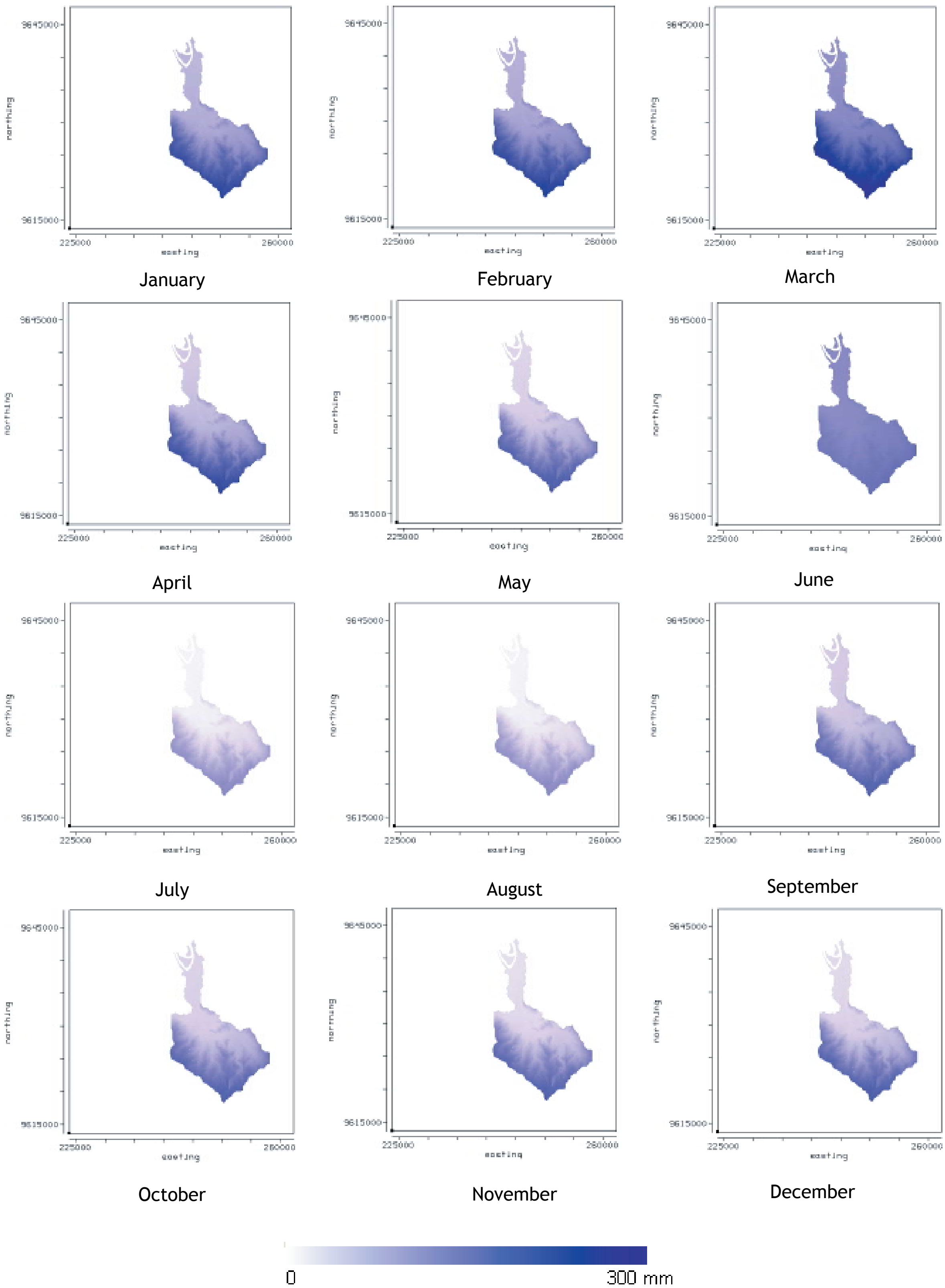

Figure 23. Monthly spatial distribution of soil moisture surplus (*SMS)* of Uge catchment

In Wiri and Uge catchments, a rise in rainfall and temperature would not influence the change in *SWC*. However, a different situation would take place again in the Beri catchment, where the mean annual *SWC* would decrease up to 8 percent if the temperature increased up to 4°C without an increase in rainfall. This is so because Beri catchment lies in the plains where evapotranspiration is substantially higher. Because the projected evapotranspiration is higher than rainfall in some parts of the catchment, the soil would begin to dry up.

SMS for all catchments is sensitive to both rainfall and temperature changes. However, pronounced changes occur in all catchments when the temperature increases up to 4°C and reach extreme values of *SMS* reduction of up to 82 percent, especially if rainfall does not increase. On the other hand, increasing rainfall could potentially increase *SMS* up to 40 percent if there is no temperature increase.

In general, the mean annual *SMD* is not sensitive to the range of climate change except in Beri catchment, where the annual deficit could be as much as 12 mm if temperature increased 4°C and rainfall remained at historical levels.

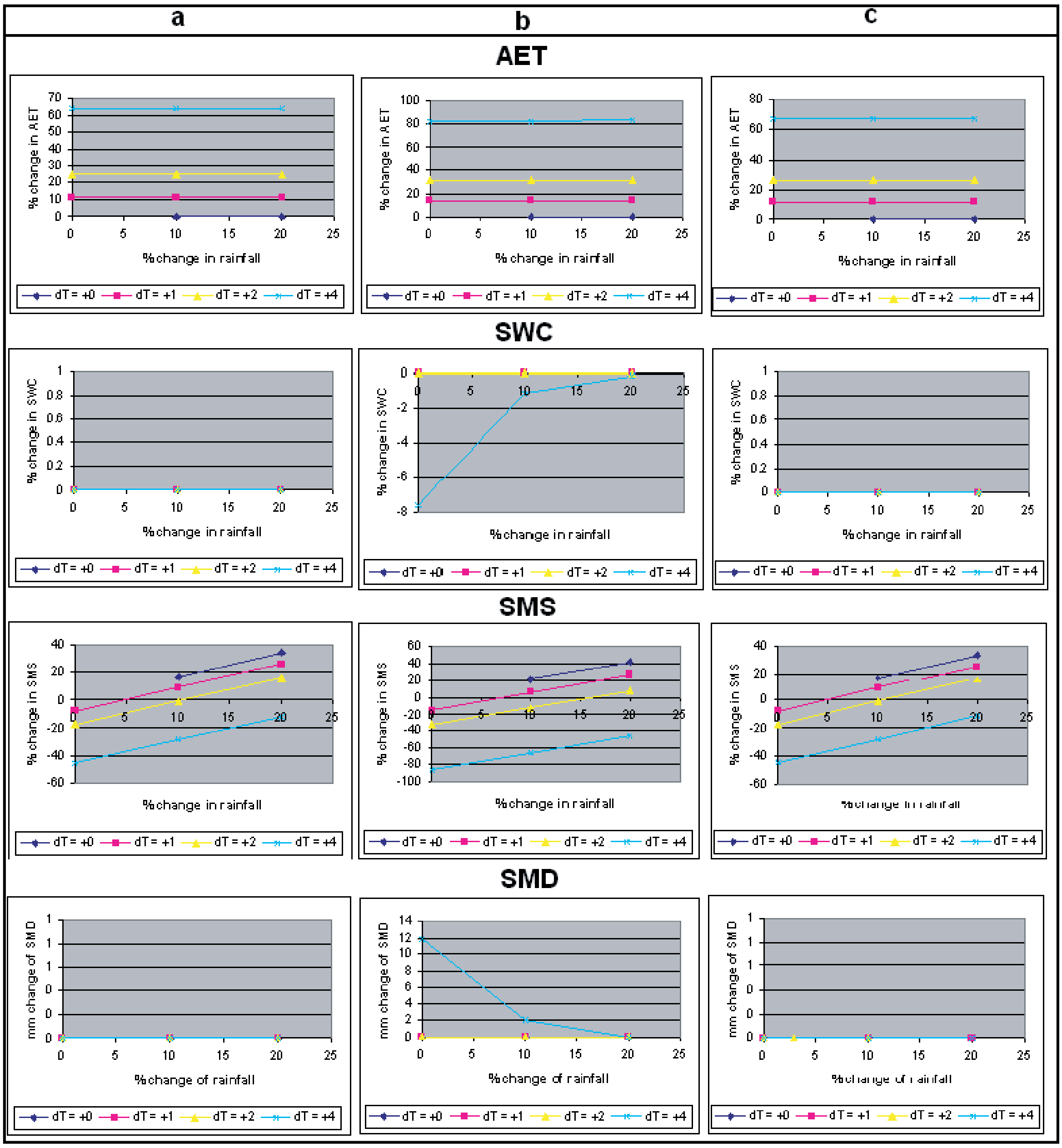

Figure 24. Percentage change of mean annual water balance components due to climate change in Wiri (a), Beri (b) and Uge (c) catchments

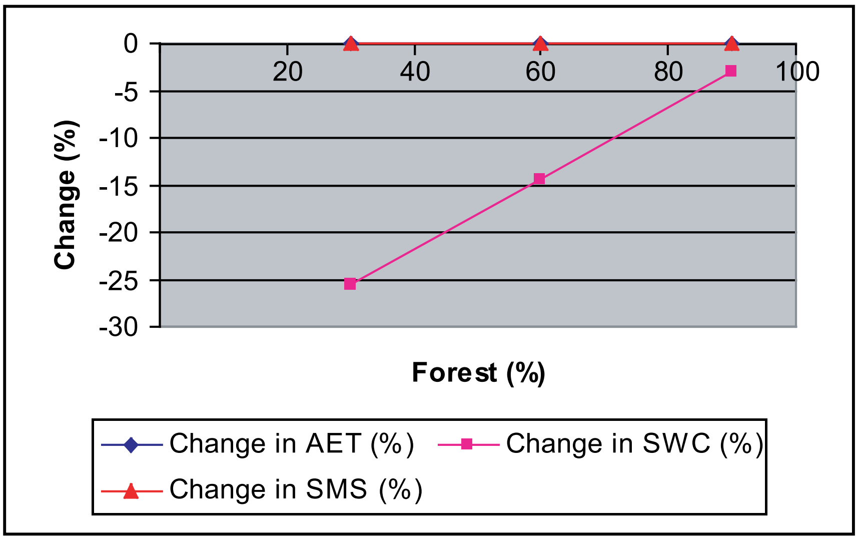

Figure 25. Effects of land cover change on water balance components

5. Conclusions

Based on long-term (1950–1995) records of climatological elements, the entire Mamberamo Basin receives more water from rainfall than it can release as evapotranspiration. As a result the basin experiences excess of water throughout the year. Since we do not have monthly data, the monthly discharge cannot be estimated.

When detailed studies were carried out in smaller scale by means of representative catchments, there was no indication whether the geologic formations on which the catchments are located affect river and catchment primary factors, including number of stream segments of a particular order and the ratio of lower-order stream segments to higher-order ones. Instead it was demonstrated that the rate factors indicated by the peak runoff which is affected by time to peak, time lag, and time of concentration. Of the catchments studied, Wiri has the highest peak runoff (690 m^3s^{-1}), followed by Uge (440 m^3s^{-1}) and Beri (190 m^3s^{-1}) catchments. In this situation Wiri would be more sensitive than the other two watersheds should deforestation occur.

Soil physical properties influence the water balance components at catchment scale. Although bulk density, porosity and permeability express geological properties of the catchment, soil texture directly affects the water balance components, especially soil water content, soil moisture surplus and deficit.

Due to the excessive water most areas experience surplus of water throughout the year. Even in the driest months, no deficit has been experienced. In wet months, soil moisture surplus ranged from 70 mm in the lower catchment to 300 mm in the upper catchment. When drainage is insufficient such water surplus could cause extensive inundation in the Lakes-Plains region. Consequently, habitats for mammals could be significantly reduced. The situation may worsen if flooding is accompanied by sedimentation that causes a reduction of channel capacity. Beri watershed with the highest river density will be collecting more sediment in the water body.

When the water balance model was simulated using climate and land cover change scenarios, it was demonstrated that water balance components were more sensitive to climate change than to land cover change. More specifically catchments in the Lakes-Plains are most sensitive to climate change. Increasing temperature not accompanied by a significant increase in rainfall would severely dry up soil moisture. Meanwhile, the catchments representing Nassau Mountains in the south and Foja-Van Rees Mountains in the north are less sensitive because these areas experience high rainfall throughout the year.

The effect of land cover change was simulated to anticipate human-induced activities involving road construction, logging and mining operations, and plantation development. By way of decreasing forest cover it was found that only soil moisture was affected. Both evapotranspiration and soil moisture surplus remained stable. These results indicate that the absence of trees reduces soil water holding capacity. In other words forest cover might decrease the vulnerability of the terrain to the effects of landslidse, erosion, and sedimentation. There is no evidence that deforestation would affect water yields. The above-mentioned activities should, therefore, consider an appropriate balance of forest cover, especially in the mountainous areas, where topography could trigger hazards and disasters.

Increases in rainfall depth could be associated with increased rainfall intensity, hence rainfall erosivity. Since no sediment data was collected, there is no opportunity to test the effect of climate and land cover change on erosion and sedimentation.

6. Recommendations

Knowing the huge variability of the weather across the region it is appropriate to suggest improvements in terms of quality and quantity of weather stations. A few complete sets of weather stations need to be added and distributed evenly within the Lakes-Plains region. This measure would eventually improve the estimation of water balance components.

River gauging stations, which are now lacking, need to be installed in a number of places. The main rivers, Tariku, Taritatu and Mamberamo, badly need to be instrumented as do several tributaries. In addition, observation of sediment load may be included to monitor the impacts of human activities.

A new scheme undergoing international debate called reducing emissions from deforestation (RED) in developing countries may be considered as both nonmarket- and market-based mechanisms to combat further deforestation. The scheme could potentially include production forests and limited production forests as well as conversion forests.

Collaboration with local communities is highly recommended to ensure fair distribution of benefits while addressing property rights and poverty eradication.

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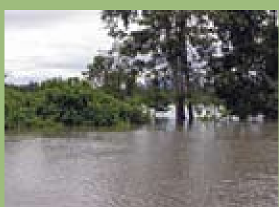

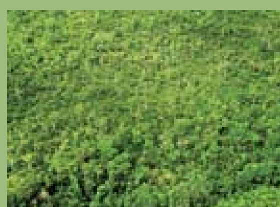

ISBN 978-979-14-1262-9