

## Article

# The Interplay between Tectonic Activity, Climate and Sea-Level Change in the Suriname River Valley, Tropical South America

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**Abstract:** Suriname is part of the Guiana Shield, a cratonic area in northern South America. It is drained by several major rivers that are characterized by river terraces. The formation of terraces along the Suriname river is closely related to climatic changes during the Quaternary, due to the effects of climate on vegetation and precipitation changes. The terraces along the Suriname River valley show levels of 5, 15, and 20 m above the current mean water level. The reason behind the scarce terrace differentiation is the limited amount of long-term vertical incision. Therefore, each level along the Suriname River valley encompasses multiple climate cycles, which cannot be separated on morphological grounds. The limited incision reflects tectonic stability, which is typical for cratonic areas. Fieldwork along the river combined with topographic maps were used to determine and correlate the various terrace levels. While in the upper part of the river, climatically induced changes in vegetation cover and sediment delivery is dominant. In the lowermost reach, sea level change is especially important.

**Keywords:** fluvial terraces; tropical South America; craton; Northern Suriname



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## 1. Introduction

Fluvial landscapes are an important part of the general geomorphological system. Among these, rivers in stable cratonic areas covered by rainforest are among the least studied ones. While they may show a large range of mean annual discharges and drainage basin areas, they are distinguished by unusually low sediment yields and sediment yield per square kilometer [1]. However, contrary to what these authors state, these rivers are not dominated by bedload but instead by a predominance of suspended load. This is due to the fact that the deeply weathered land surfaces hardly provide bedrock gravel but only their weathering products, e.g., sand, silt, and clay. This results in a lack of erosive power of the rivers, even at high discharges, so that when during incision hard bedrock is encountered, they are incapable of eroding them away due to the lack of bedload, and instead the channel splits itself up in several branches in order to avoid the obstacles. In this way, a very specific channel form develops, i.e., multibranch cataracts called *raudales* in Spanish South America such as in the Orinoco River, and well described by [2] for the Caroni River in Venezuela, *cachoeiras* in Brazil, and *sulas* in Suriname [3]. These channel forms resemble to some extent braided river channels but differ from them in the fact that they consist of rocky islands with fixed positions, instead of sand bars which change position during each flooding event. Even those outcrops in the river do not lead to the formation of bedload gravel as exfoliation sheets falling from them into the river, for instance, which usually disintegrate by weathering before being able to form solid clasts.

Yet, like rivers from other environments, these rivers flowing in cratonic areas may exhibit river terraces with rounded gravel, suggesting different hydrological regimes and climatic environments in the past [4,5]. We present here a case study on the terraces of the Suriname River in the Guiana Shield in tropical South America, with a drainage basin wholly covered by tropical rainforest. It is known from palynological studies that the Guiana Shield has suffered periods of greater drought and lesser vegetation cover [6,7]. The study of terraces in this environment, however, is hampered by several factors, including low uplift rates, deep sediment weathering, and a scarcity of datable material.

Terraces are being recognized as an important source of evidence for Quaternary paleoenvironments [8] and, therefore, represent paleo-fluvial floodplains. Terrace formation in the lower reaches of rivers is driven by fluctuating sea level [9], whereas in areas remote from the marine influence, climate change produces a contrasting effect, with aggradation during glacial and incision during interglacial. However, the upstream influence of sea level fluctuation is likely to be limited because many rivers today flow in valleys that formerly extended over wide areas of continental shelf, but have been truncated by the Holocene marine transgression, which inundated and submerged their lower reaches [10]. Where the shelf is narrow, sea level fluctuation has given rise to terraces that can be traced for considerable distances inland, which is the case for example for the Susquehanna in North America [11] and other neighboring rivers in northern California [12].

The formation of terrace staircases is in most cases a response to regional uplift, which forces long-term incision [8,13–15]. The rivers in tropical Suriname have a maximum of about 20 m high, which is much less compared to what is commonly observed in high latitudes. Suriname is underlain by cratonic crust. In general, such crust is tectonically very stable and lacks a weak lower crustal layer, which would otherwise enable vertical motions by isostatic responses to loading [16]. Therefore, if this 20-m long term incision is caused by uplift, then this is in agreement with Suriname's cratonic crust.

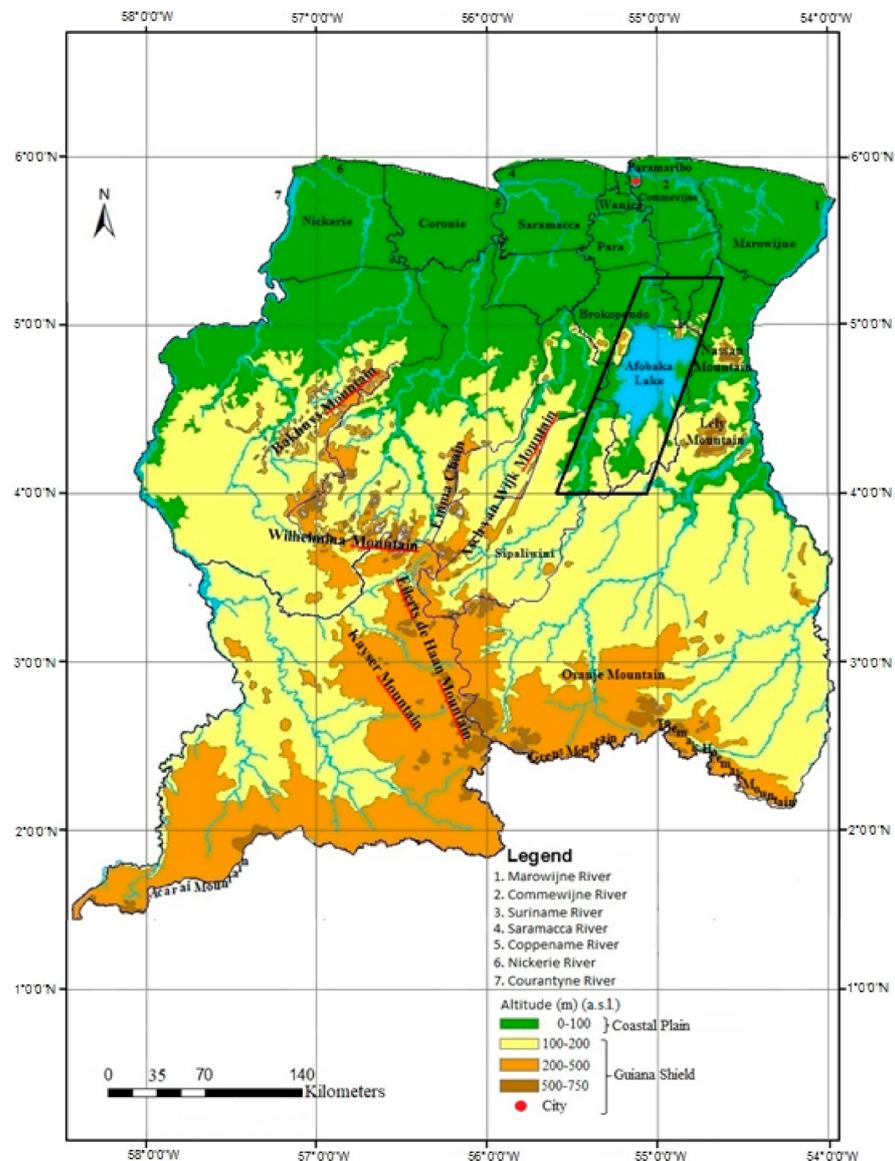
According to [5], the formation of terraces along rivers in Suriname is closely related to climatic changes during the Quaternary due to the effects of climate on vegetation and precipitation changes. In his model, glacial alluvial sediments are deposited in the river valleys and valleys are widened during glacials. During interglacials, the rivers incise, leaving the former floodplain behind as a terrace in the landscape. However, the number of terraces in Suriname (~3) is much smaller than the number of climate cycles during the Pliocene and Quaternary. In addition, close to the coast, climate driven eustatic sea level fluctuations also should have an important control on river terrace formation. For example, when low stand base levels were lowered by up to ~120 m and were submerged, 160 km Suriname shelf was exposed and incised by fluvial systems.

This study gives an overview of the Pleistocene terraces and the Holocene floodplain along the Suriname River valley, located in the central part of Suriname. Economically, this is Suriname's most important river, and it flows along the capital, Paramaribo. River terraces and floodplains are preferred sites for human settlement (villages) in the hinterland of Suriname. A detailed study would give more insight in the key controls (e.g., uplift, sea level fluctuation, climate changes) that are responsible for river terrace development along the Upper and Lower River valley parts. Literature studies, fieldwork, and laboratory analysis were used to determine the various characteristics of the terraces (e.g., height relative to mean water level, lithology). Our results are based on previous field work carried out in the 70s and 80s in the upstream parts and new mapping based on interpretations using historic land use maps in the midstream part, and a combination of Digital Elevation Model DEM and topographic maps analyses and field work in the downstream part. We provide, for the first time, full detailed maps of the distribution of terrace remnants of the whole river, and we show the terrace remnants in a longitudinal profile. Using these results, we discuss the formation mechanism and the relation to climate change.

## 2. Regional Settings

### 2.1. General

Suriname is drained by seven rivers that are subdivided in three main groups based on the extent and shape of the drainage area (Figure 1). The first group consists of the border rivers Marowijne (East) and Courantyne (West), which have their sources in the border mountains with Brazil and drain almost 58% of the country. The second group has their origin in the high uplands in the middle of the country, and is represented by the Suriname and Coppename Rivers, which drain almost 24% of the country and debouch directly into the sea. The third group consists of the Commewijne, the Saramacca, and the Nickerie Rivers, that together drain approximately 16% of the country. The rivers of the last group bend westwards close to the coast to drain into the sea through the mouths of the second group, due to the westward migration of important mud banks along the coast [17,18].



**Figure 1.** Simplified topographic map and hydrographic network of Suriname with its seven main rivers (Marowijne, Commewijne, Suriname, Saramacca, Coppename, Nickerie, and Courantyne Rivers) in the north. The frame indicates the location of the study area.

The rivers run through two geologically different parts of the country, first through the hills and mountains of the cratonic Guiana Shield, while the estuary part runs through the Coastal Plain [18,19].

## 2.2. Geological and Geomorphological Overview of the Study Area

Suriname can be divided into a southern rainforest-covered interior, which represents almost 80% of the country's surface, and a northern coastal plain that makes up the rest of the country's surface area. The rainforest-covered interior, which forms part of the Guiana Shield, is underlain essentially by Precambrian igneous and metamorphic rocks, also called the basement (Figure 1 shows that the Guiana Shield roughly corresponds to the areas > 100 m). Thick dolerite dykes with a 1782 Ma age (Avanavero Dolerite) and narrow ones of Jurassic age (Apatoe Dolerite) intersect the basement of Suriname [20].

The morphology of the major part of the rain-forest covered basement consists of an endless mosaic of low hills with flat tops and steeply cut creek valleys. A distinction can be made into mountain tops up to 1280 m high, inselbergs at more than 700 m elevation, duricrust planation levels at more than 500 m, and river terraces at levels of approximately 20 m, 15 m, and 5 m above the mean water level. The terraces along the rivers are the only morphological units that are aligned with the present drainage pattern [21]. Structures in the bedrock (e.g., faults and fractures) control the drainage directions, as shown by the rectangular patterns of the larger rivers (Figure 1).

The coastal plain consists of the Savannah Belt, the Old Coastal Plain, and the Young Coastal Plain. The Savannah Belt is a gently sloping north-facing hilly landscape between 10 to 50 m above sea level. The Savannah Belt is underlain by the Pliocene Zanderij Formation, which consists of horizontally layered deposits of coarse sands with small amounts of loams and fine sands. The Zanderij deposits can reach a thickness of up to 20 m. Gravel deposits, up to 2 m thick, are locally found at the base of this formation. The Zanderij Formation was deposited during dry climate conditions [22].

The Old Coastal Plain is situated 4 to 11 m above sea level and is a dissected Pleistocene marine terrace, consisting of numerous small plateaus, the so-called "schollenlandschap". This landscape has a variable width of 20 km in the east to 70 km in the west. Remarkable features are the Old Ridge Landscape, and the Old Clay Landscape that originated due to the westward transport of sediments along the coast under the influence of the Guiana Current. The Old Coastal Plain consists of sands and clays of the Coropina Formation, which can be subdivided into the lower clayey Para member and the upper sandy Lelydorp member. The Para member has been deposited around circa 700 ka, while the Lelydorp member is of Eemian age, which is approximately 120 ka [22].

The Holocene Young Coastal Plain deposits are subdivided into the Mara Formation, which formed between 10–6 ka, and the Coronie Formation formed between around 6 ka to the present. This younger part of the coastal plain is a flat clay-prone surface that is locally interrupted by east–west oriented sandy cheniers. These cheniers mark former coastlines and appear as single units or bundles [17].

The Suriname River valley has a total length of 480 km and has its sources in the highlands (Figure 1). Its catchment size is approximately 16,500 km<sup>2</sup>, and 84.8% of the total catchment area is located in the rainforest-covered interior of the Guiana Shield, 4.5% in the Savanna Belt, and a 10.7% is in the Old and Young Coastal Plain [18,23]. The Afobaka Dam (1964) and Prof. Dr. W.J. van Blommestein Lake (also known as the Brokopondo or Afobaka Storage Lake) lie in the midstream part of the Suriname River valley. Downstream of the Afobaka Dam (km 194) the average annual discharge of the river is 324 m<sup>3</sup>/s. At the river mouth, the average annual discharge is estimated to be about 440 m<sup>3</sup>/s, while the estimated sediment discharge is 0.25 million tons per year [19].

The river can only incise in saprolite or regolith because of the lack of abrading bedload [24]. A specific characteristic of all rivers in the basement area, including the Suriname River valley, is the presence of cataracts (sulas, in Surinamese). These are hard rock sills. At such locations the river's channel pattern resembles that of a braided river.

However, in contrast to the gravel or sand banks in real braided rivers, the islands between the branches consist of hard rock [3,25]. The most downstream sulas in the Suriname river valley are the Brokopondo and Balling Sulas, just downstream of the Afobaka dam. They are situated at the northern edge of the basement, the Guiana Shield. They form semi-permanent knickpoints in the river that they are supposed to be stable but are subject to slow erosion and have an important impact on river dynamics during climate-driven base-level change and upstream changes in vegetation and sediment output (see Discussion).

### 2.3. *Climate and Environmental Conditions from the Pliocene to Holocene in Northern South America*

#### 2.3.1. Pliocene and Pleistocene

The Miocene and Pliocene tectonics affect the Eastern Andes, fundamentally changing and the regional climate and the drainage patterns, which leads to the formation of the present-day Amazon and Orinoco river systems [26]. The Suriname River valley might have originated during the same time span. Climate conditions during the Pliocene seem to have been generally cooler than during the Miocene. Especially the final part of the Pliocene (between about 3 and 2.5 Ma BP) experienced a strong cooling [27–30].

Climatically, the Pliocene can be subdivided into a warm early Pliocene, a relatively warm Mid-Pliocene, and a relatively cool Late Pliocene [31]. Yet the average climate during the Pliocene appears to have been warmer than present day [32]. The pattern of temperature and precipitation change during the Pliocene was similar to weather and climate patterns observed during a modern El Niño event [33].

In general, very little is known about the Pleistocene climate in tropical South America before 0.5 Ma [34]. The best data available refer only to the Last Glacial and the Holocene. We therefore restrict the discussion to that period, taking it as an analogue for previous Pleistocene climate cycles. During the Middle Pleniglacial (ca. 60–26 ka), most or all of warm and cold tropical South America had a considerably cooler climate and relatively high precipitation values. It became markedly drier between ca. 21 and 14 ka during the Late Pleniglacial (last glacial maximum) [7]. During the relatively cold and dry part of the Late Pleniglacial, savannah vegetation extended in Suriname, replacing the rain forest in the interior. During (and part of) the LGM savannah vegetation replaced wet forest at the entire present coastal area of Suriname [6,35]. It was estimated by Van der Hammen and Absy [36,37] and Van der Hammen [37] that precipitation in Suriname during the LGM was about 500 to 1000 mm/yr., which was needed in order to sustain a natural grass savannah and 1000 to 1500 mm/yr. for a mixed grass/woodland savannah. The rainfall regime was also more seasonal with a prolonged dry season. This is in accordance with predictions of 750 to 1500 mm/yr. for the LGM by global climate models [38].

During the Late Glacial (13–11.3 ka), the climate of northern South America became wetter, the rivers carried an increasing quantity of water and a new cycle of sediment deposition began and continued into the Holocene. The increase in water level in the rivers seems to have been considerable, locally leading to temporal permanent inundation of the (upper to) middle river valleys [39–41].

#### 2.3.2. Holocene

Records from the savannas of eastern Colombia, indicate that there was a shift from dry early Holocene to wetter environments after ~6 ka [42]. This can be explained by changes in the position of the Inter Tropical Convergence Zone. During the early Holocene, the ITCZ apparently had a more northerly position than today [43,44], causing dry conditions in the savanna. The ITCZ shifted southwards during the mid- and late Holocene, leading to more precipitation in the savannas.

During the early Holocene (12 to 6 ka BP), sea level rose from a depth of more than 100 m to the present level [45,46]. Sea level rise slowed down between 6 and 7 ka BP (Figure 2) [47]. Precipitation increased during the early Holocene. Rainfall still was concentrated in the summer monsoon, which may explain the persistency of the savannas during

the early Holocene. The average yearly temperature was about 5 to 6 °C lower than today during the LGM [36,38]. The yearly actual evapotranspiration was 15% lower than today, which was approximately 1300 mm/yr. in Suriname [38].

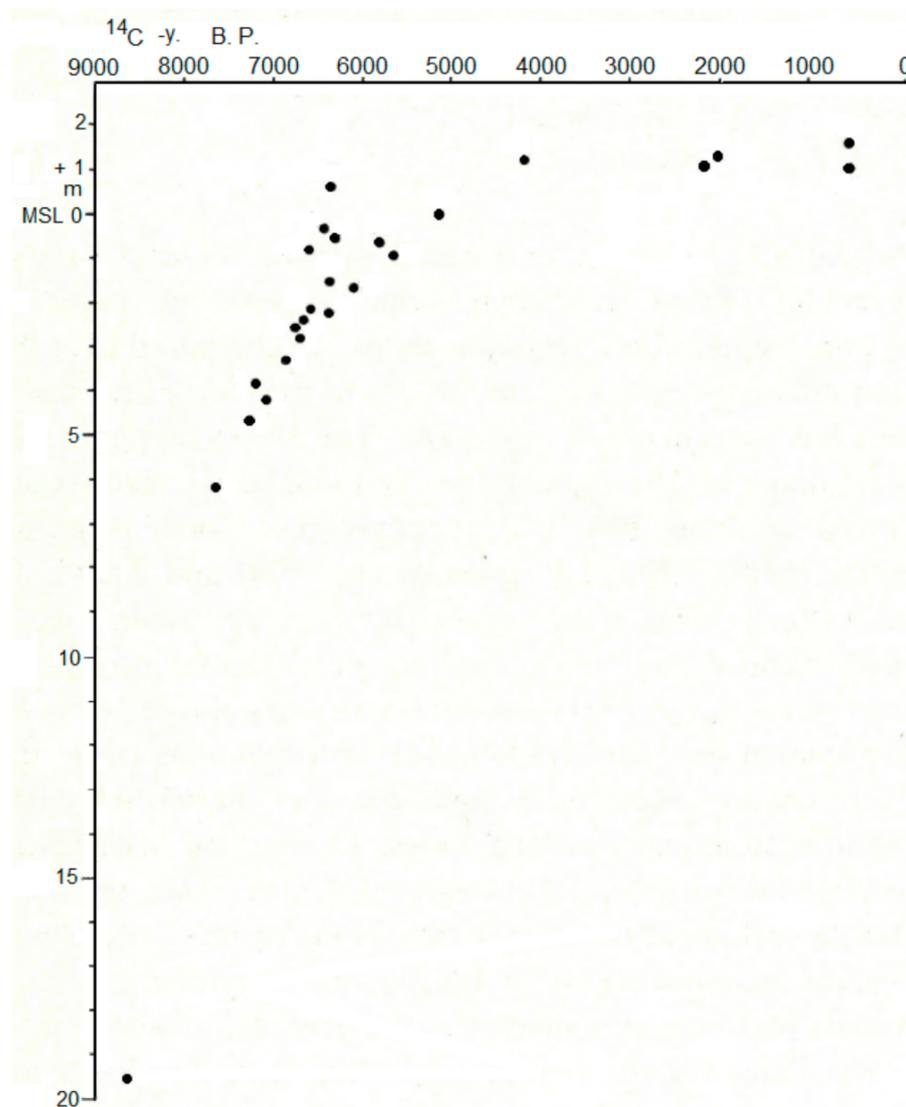


Figure 2. Sea level rise at the Suriname coast (modified after [46]).

### 3. Materials and Methods

In the practically inaccessible hinterland of Suriname, aerial map analysis is a very important research method. This is based on the existence of a relationship between soil and landscape. The geology of the study area is also involved in the analysis. However, height and slope differences are at least as important as soil data in the evaluation of the landscape. The research methods of this study consisted of desktop, fieldwork, and laboratory parts.

A preliminary map analysis was made of the study area. This map analysis was aimed at distinguishing geomorphological units (e.g., terraces) that differ markedly from each other in terms of height. Subsequently, a limited number of observations were made to check the preliminary map data to obtain detailed information about the morphometry of the different landscapes (height and slope differences, etc.) and the soil characteristics.

Fieldwork was done from the river inland. On selected locations boreholes were made using an auger and a gouge to determine terrace sedimentary successions and to collect

samples. The locations of the boreholes were chosen in parts of the various terraces that were representative of the landscape. This means that data obtained from the drilling survey was considered to be representative of the remaining area.

Samples from five boreholes were selected for analyzing the sediment texture in the laboratory. A Sympatec HELOS laser diffraction machine was used for the particle size analyses, ranging from 0.1  $\mu\text{m}$  to 3500  $\mu\text{m}$ .

Before collecting the field data, terraces were mapped in the upper, middle, and lower Suriname River valley stretches with the aid of a Space Shuttle Digital Elevation Model (SRTM DEM) and topographic maps. Historical topographic maps revealed that inland residents used the terraces for laying out their agricultural lands. This information was used to infer terraces in the midstream part of the Suriname River valley, because this part is nowadays submerged due to the construction of the Afobaka dam.

The resulting terrace maps were largely based on a map of the upper Suriname and Saramacca River areas produced by Balsem and Rhebergen [48] in the framework of a geomorphological-soil science cooperation project between the Soil Survey Institute of Suriname (DBK) and the Vrije Universiteit Amsterdam (VU), as well as on a detailed study of the upper Suriname River valley, which was also part of the Soil Mapping Service (Dutch: Dienst Bodem Kartering)/Vrije Universiteit DBK/VU project by Kips and Snel [49].

## 4. Results

### 4.1. General Characteristics of the Terraces

For practical purposes, we divided the Suriname River valley into an upper (Figure 3), middle (Figure 4), and lower valley part (Figure 5), corresponding, respectively, with the part upstream from the Afobaka storage lake, the Afobaka storage lake itself, and the part from the Afobaka dam to Cassipora. The terrace remnants were plotted at a longitudinal profile (Figure 6). Apart from potential correlations, the profile also showed that the current river profile has three important knickpoints.

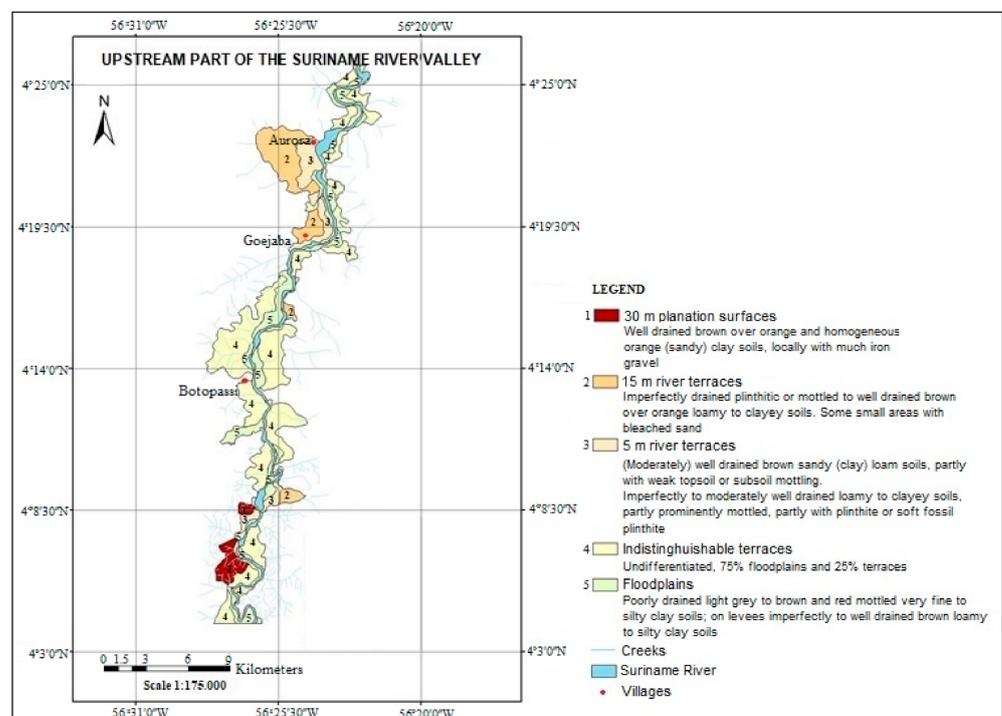


Figure 3. Map of terraces along the upstream river valley part of the Suriname River.

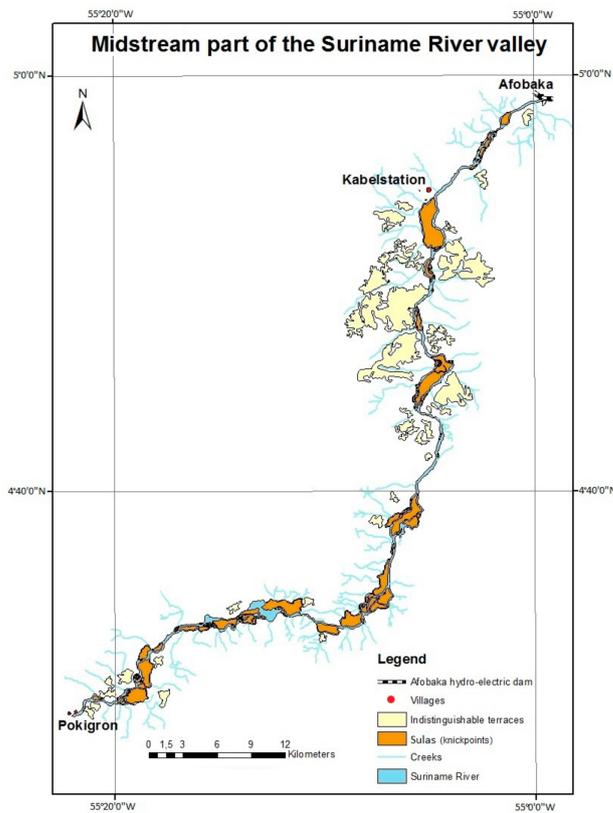


Figure 4. Inferred terraces along the mid-stream river valley part of the Suriname River, now submerged in Lake Afobaka.

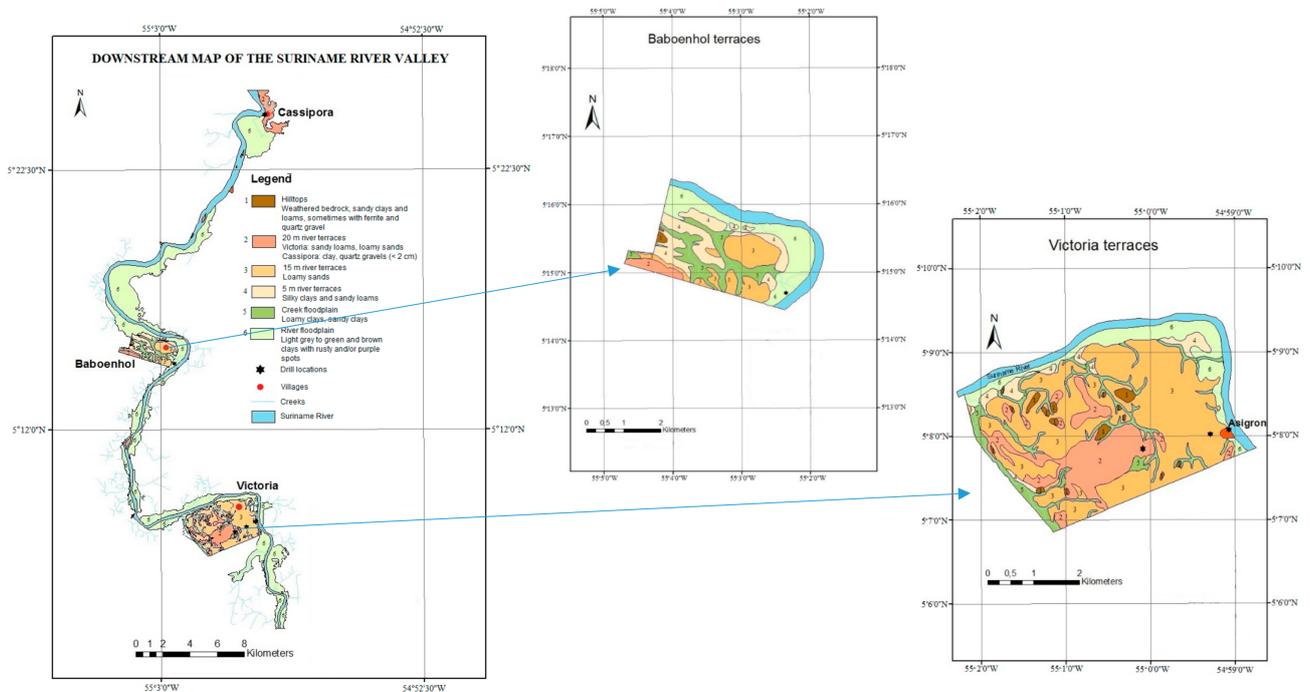
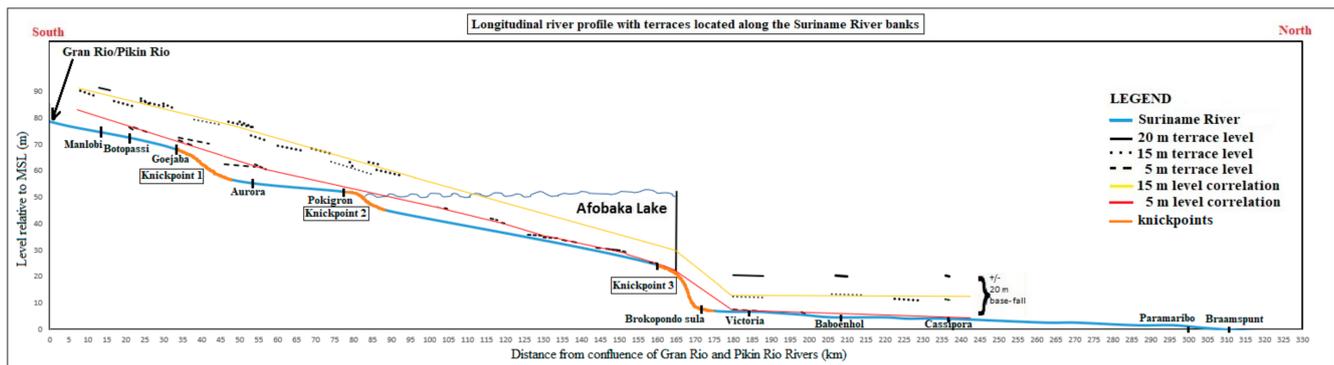


Figure 5. The downstream part of the Suriname River valley.



**Figure 6.** Longitudinal profile of terrace remnants and their correlation along the Suriname River valley. Knickpoints coincide with larger sulas (cataracts).

#### 4.2. Upper River Valley Part

The terrace map of the upper river valley (Figure 3) is based on maps of the upper Suriname and Saramacca River areas by Balsem and Rhebergen [48]. They distinguished a 20 m, 15 m, and a 5 m high terrace level. The 20-m terrace level has a relief up to 25 m and slopes up to 18%, and consists of regolith of mainly felsic rocks, and local river sediments. The 15 m terrace level has an undulating morphology with a relief up to 15 m and slopes up to 8%, consisting of Pleistocene river deposits (50%) (fluvial sediments) and regolith of mainly felsic rocks (50%). The terrace deposits have a thickness of 0.5 to 4 m. The 5 m terrace level remnants are almost flat plains with depressions, relief up to 5 m, and slopes up to 4%. They consist of relatively thin fluvial loam deposits.

Kips and Snel [49] also distinguished a 30-m high level (Figure 3) with a sediment sequence of 3.5 to 5 m in thickness. The deposits contain fine, rounded gravel and show a fining upwards sequence of loamy sand at the bottom, passing into (sandy heavy) loam at the top of the sequence.

The sediments in the present floodplain differ considerably from the three levels, and according to a few deep auger drillings, consists mainly of silty to heavy clay without any fining upwards sequence. At some locations the floodplain and the 5 m terrace level are absent, and the 15- m and 20- m terrace levels directly border the river channel. According to the Geological Mining Services of Suriname (GMD) the river terraces in the upper reaches have developed entirely on granitoid and gneissic rocks of the Precambrian basement.

The terrace remnants mapped by Balsem and Rhebergen [48] and Kips and Snel [49] are plotted in the longitudinal profile of Figure 6. Based on the correlation of the remnants, we conclude that three levels are present, at 5, 15, and 20 m above the present-day river level.

#### 4.3. Middle River Valley Part

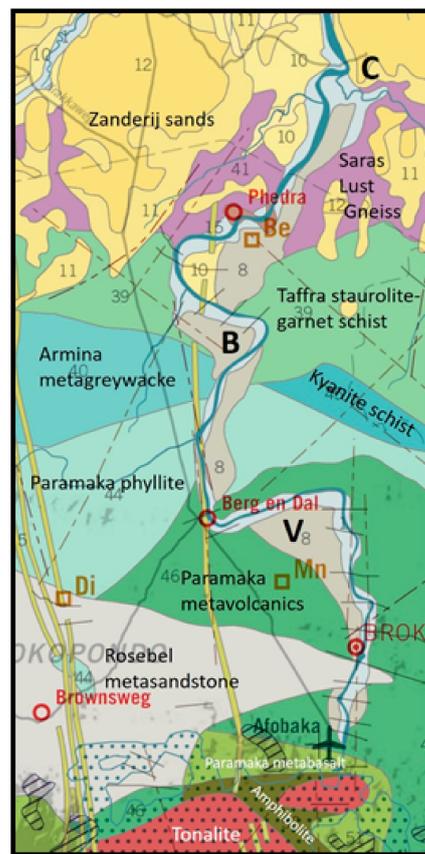
Up to now, little is known of terraces along this part of the river, especially regarding their height levels. The geological map of sheet Kabel (31) by D'Audretsch [50], made before the construction of the Afobaka dam, shows a continuous strip of terraces, all developed on tonalitic granitoid rocks. D'Audretsch [50] gives a terrace height of 10 m above low water level, on which the Maroon villages were built. Martin [51] measured the height of 7 Maroon villages on a terrace situated between 5 and 9 m relative to the river level. Whether higher terrace levels are also present is unknown, as most earlier researchers mainly surveyed from the river. In the present research, additional lower terrace fragments (Figure 6) were derived based on the locations of former farmlands depicted on historical maps.

According to D'Audretsch [50], the present floodplain is up to 6 km wide. Locally, low levees occur in the outer bends. Where the river incises in its own deposits a gravel

layer resting on weathered basement rock is exposed. The fill of midstream part of the river valley consists of cream-colored to yellowish clay.

#### 4.4. The Lower River Valley Part

According to our analyses, the main terrace levels along the downstream reach are situated at heights of 20 m, 15 m, and 5 m above the mean water level of the river. They are particularly well developed at three locations, which we studied in detail, i.e., from south to north the remnants of the Victoria terraces, the Baboenhol terraces, and the Cassipora terraces (for location see Figure 5). According to the geological map, the Victoria and Baboenhol terrace remnants are developed on basement rocks, whereas the Cassipora terrace remnant sits on Zanderij Formation sands (Figure 7).



**Figure 7.** Geological map with Zanderij Formation indicated in yellow. Other colors represent basement rocks (V = Victoria; B = Baboenhol; C = Cassipora).

##### 4.4.1. The 20-m Terrace Level ( $T_{20m}$ ) at Victoria

The 20-m terrace level situated at Victoria consists of fluvial deposits and is developed on hard rock, while at Cassipora it is developed on the Zanderij Formation of Pliocene age. The lithology at the base at Baboenhol is unknown, but is likely also hard rock. At Baboenhol and Victoria, the topography of the upper surface of this level is irregular as a result of numerous incised local creeks (Figure 5). The height of the terrace level increases with increasing distance from the river. At Victoria, transitions from the 15 m terrace level to the 20-m terrace level occur gradually. Compared to Cassipora, the sands of the 20-m terrace level at Victoria are loamier (Figure 7).

The 20-m terrace level located at Victoria, on the left bank, extends to approximately 1.5–2 km inland from the river. The topography is fragmented by small, incised creeks, and shows a gradual increase in height. Its subsurface consists, from top to bottom, of

sandy loams with gravel, loamy sands, and loamy sands with gravel (Figure 8). The sands resemble those of the Zanderij Formation, suggesting they could be related.

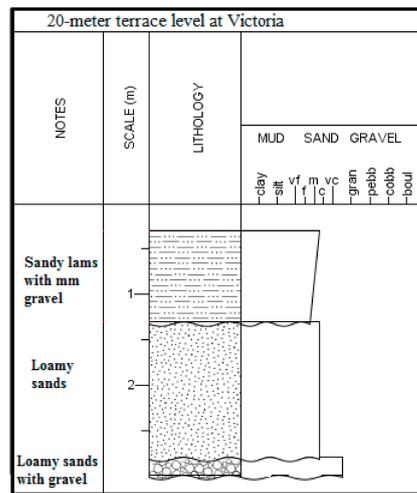


Figure 8. Sediment log of drilling core at the 20 m terrace level at Victoria.

The 20-m terrace level at Baboenhol, located at the left bank of the river (Figure 5), is also fragmented by incising tributary creeks. However, it also shows very different morphological characteristics compared to the 20-m level at Victoria. Starting from the river, the land surface rapidly increases in height from 5 to 15 m. There is a sharp transition from the 15-m to the 20-m terrace levels.

The width of the 20-m terrace levels is about 0.5 km. A sharp transition from the floodplain (at 1 m) and 20-m terrace levels over a distance of circa 50 m occurs at Cassipora (right bank). Both locations had sharp transitions. Baboenhol and Cassipora (right bank) are situated in the outer river bends, while Victoria, with gradual transitions, lies in an inner bend.

The shallow subsurface of the 20-m terrace level at Cassipora consists of fluvial fine and angular quartz gravels, overlain by a clay deposit. The gravels show a fining upward trend (Figure 9). The gravel clasts have a diameter of up to 2 cm. They are interpreted as part of the Pliocene Zanderij Formation. The overlying clay deposits has orange (oxidized) and green colored (reduced) spots, which are related to soil formation.

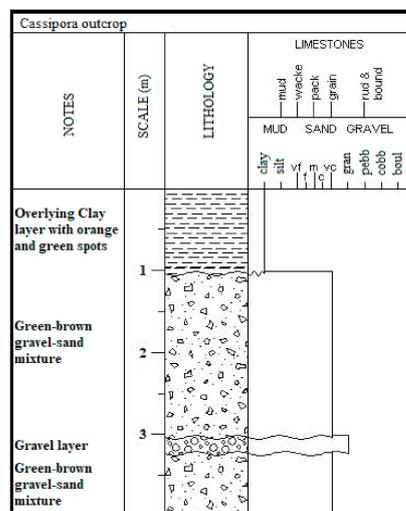


Figure 9. Sediment log of the outcrop at Cassipora.

4.4.2. The 15-m Terrace Level (T<sub>15m</sub>)

The width of the 15-m terrace level ranges from about 0.25 to 0.5 km. The upper surface of the 15-m terrace level ranges between 10 and 20 m above the river, but is mostly at about 15 m, which corresponds with the findings of Kips and Snel [49] in the Upper Suriname River valley. The terrace landscape is undulating and locally incised by some large creeks in shallow fairly flat valleys.

4.4.3. The 5-m Terrace Level (T<sub>5m</sub>)

Along the downstream part of the Suriname River valley, the 5 m terrace group is present at Victoria and Baboenhol. At Cassipora the floodplain is absent and the present outcrop of the Zanderij Formation directly borders the river. The average width of the 5-m terrace level goes up to 50 m, but where it is narrow the 5-m passes gradually into the 15-m terrace level. The upper part of the terrace deposits consists of clays locally with rusty or purple spots (soil formation) (Figure 10).

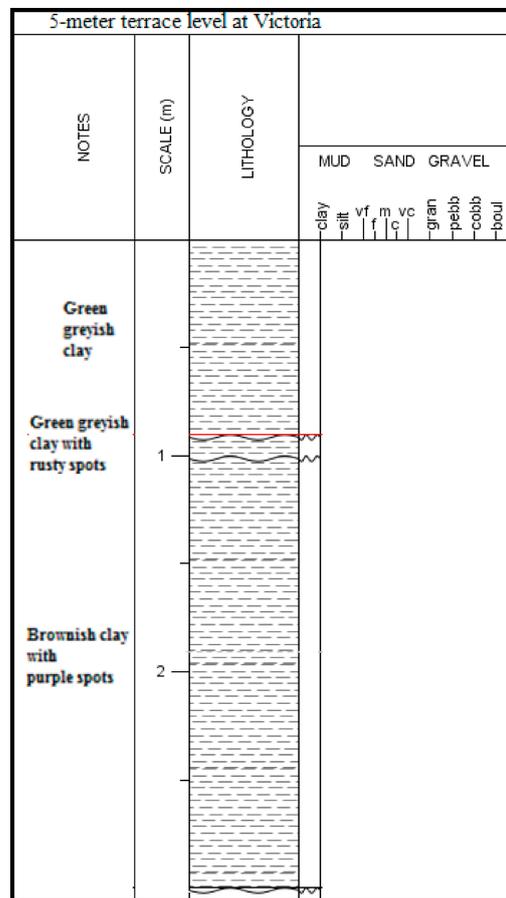


Figure 10. Sediment log of drilling core in the 5-m terrace level at Victoria.

At Brokopondo Sula, further upstream between Victoria and the Afobaka Dam, a 5- m terrace level is present on an island in the middle of the river. A profile across the island was obtained for the purpose of exploring a possible dam site [52]. The profile shows an irregular bedrock surface at 7 to 12 m depth, covered by a fluvial fining upward sequence, with coarse sand at the bottom and loamy sand at the top (Figure 11) [52].

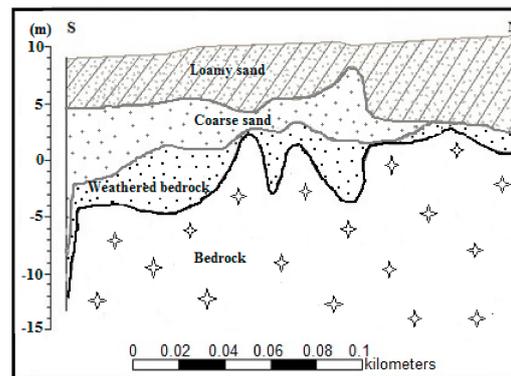


Figure 11. Cross-section through the island at the Brokopondo Sula (modified after Bleys [52]).

### 5. Discussion

The studied section of the Suriname River valley shows generally three terrace levels above the present mean water level. In the most upstream and downstream parts, the highest level is at 20 m above river level. Information about higher terrace levels in the now submerged intermediate part (Afobaka Lake) is lacking, so it is not clear whether these levels are the same. In view of the fact that water levels in the Suriname River valley may vary up to 7 m between high and low discharges [50], estimations of the height of the terraces above river level may have a large error margin.

We correlated the 20-m level in the upstream part to the level at the same height in the downstream part for two reasons: (1) this correlation follows the shape of the present-day longitudinal profile, including the sulas; and (2) the number of terrace levels is the same in the upstream and downstream parts. The first argument assumes that the sulas are a permanent feature of the fluvial longitudinal profile, for which we provide arguments below.

The consistently presence of terraces at the 20, 15, and 5 m levels at both the up- and downstream parts of the Suriname River valley (Figure 12), can be explained by lowering of long-term eustatic sea level and/or low amount of uplift. There is more evidence of recent tectonic movement than originally thought, primarily as a result of rift shoulder development due to the separation of South America and Africa, and the development of the Takutu failed arm along the border between Suriname and Guyana. Data from northeastern Brazil suggest a possible uplift of 20 m in the Quaternary [53]. Cenozoic uplift of the Bakhuis Horst in western Suriname along reactivated Precambrian faults parallel to the Takutu rift is even recorded in seismic sections in the coastal plain [54,55].

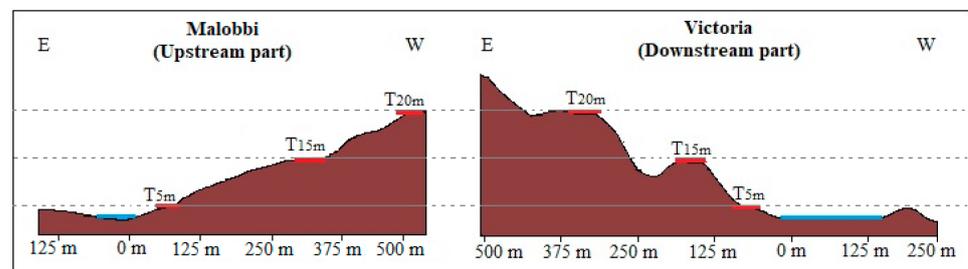


Figure 12. Cross-sectional topographic profiles of Malobbi (Upstream part) and Victoria (Downstream part) with correlated terrace levels.

#### 5.1. A Model for Terrace Evolution in the Upstream and Middle Parts

Terrace development in the humid tropics is largely attributed to the effects of climate change. During glacials, the climate is relatively dry, because less water-vapor is available in the atmosphere, causing reduced precipitation. In contrast, interglacial climates are relatively wet. Reduction of precipitation during a transition from an interglacial to a glacial

period leads to the conversion of the dense tropical forest into savannah vegetation. At the same time, because the surface is less covered with vegetation during glacials, more erosion occurs, leading to more sediments available for fluvial transport. Thus, fluvial sediment load increases, whereas transport capacity decreases. This results in sediment storage (aggradation) in the river valleys and raising of the river valley floor. During interglacials rivers incise, because the climate is relatively wet, resulting in increased precipitation and vegetation cover [56,57].

During the Quaternary many glacial/interglacial cycles have occurred, and some rivers, such as the Meuse in the Netherlands, show a terrace for each climate cycle, up to 30 for the whole Quaternary [58].

In general, the preservation of terraces in a terrace staircase requires a long-term incision. In case of the Suriname River valley, the 20-m of incision during the Pliocene and Quaternary is insufficient to produce a visible staircase of about 30 terraces, whereby each would represent a climate cycle.

The long-term 20-m incision since the Pliocene requires an explanation. It may have been caused by the long-term eustatic sea level fall since the Pliocene [59] and/or by uplift. A slow and relatively low amount of uplift may have resulted from the rifting processes that led to the formation of the Atlantic Ocean (passive margin uplift). According to studies in north-east Brazil [53] rift shoulder uplift and denudation along the Atlantic coast due to rifting since the Cretaceous amounted to 10 m/Ma, that is 20 m for the whole Quaternary. Alternatively, the differential uplift can be explained as a result of erosional isostasy of the hinterland [60]. The small amount of uplift and the consequent limited vertical separation of the terraces can be explained by absence of lower crustal flow in of this cratonic crust [16].

Knickpoints in the upstream part of the river valley are present in the present-day longitudinal profile, particularly at Goejaba and Pokigron (Figure 6). The knickpoint at Goejaba is likely caused by a northeast–southwest oriented dolerite dyke that cuts across the river and acts as a sula, whereas the knickpoint at Pokigron is controlled by the Kwai-Kwai sula as a result of differential weathering. Sulas are very stable and non-migrating on geological timescales. In non-tropical conditions, knickpoints can be abraded by fluvial gravel and sand. However, under tropical conditions such as in Suriname, chemical weathering in the basement is very intense and produces only sand and clay. Any local gravel will also be rapidly transformed into sand and clay before reaching the sulas. Sand and clay are largely transported in suspension, and they are too fine to be able to significantly abrade the sula knickpoints [24].

The situation at the knickpoints may have been different in glacial times with semi-arid climatic conditions. The fining upwards sequences in the terraces often show rounded gravel at their base, suggesting less intense weathering in the drainage basins and more bedload transport in the channels. Under such conditions rocky knickpoints can therefore be lowered by the erosive power of the bedload. This is suggested by the northernmost knickpoint, the Brokopondo sula, just downstream of the Afobaka Lake (Figure 6). The island in the middle of this sula consists of a buried irregular rock outcrop covered by sediments belonging to the 5-m terrace level. This suggests that the buried rock surface has been a sula in its own right in glacial times, which probably first suffered erosion by the increased bed load and then became covered by the fluvial fining upwards sequence. This possibly encompasses a smoother length profile of the river in glacial times than in the present interglacial times. Unfortunately, the absence of datable material in the terrace sediments so far precludes confirming this scenario.

### 5.2. A Model for Fluvial Development in the Downstream Part

The upstream influence of sea level fluctuation is likely to be limited [10]. Many rivers today, such as those around NW Europe, flow in valleys that formerly extended over a wide continental shelf, but their lower reaches were inundated and submerged by the Holocene marine transgression [8].

While the river valleys fill-up in the upstream part of the river during a glacial, in the downstream part they are incising due to sea level fall, and vice-versa, during an interglacial (e.g., [61]). The location of the transition between incision and aggradation during a certain climatic situation, the terrace-intersection likely is located at those points in the river valley where the most downstream bedrock-controlled cataracts (sulas or rapids) occur. These sulas limit the upstream migration of sea level induced knick-points. In the case of the Suriname River valley, they are situated at the transition from Guiana Shield bedrock to the coastal plain deposits, at the Brokopondo Sula (Figure 12).

For example, eustatic sea level dropped to about 120 m during the LGM. During this period the Suriname coastline was situated at 130 to 150 km north of the present coastline [48], leading to exposure of the Suriname Continental Shelf and, as a consequence, the extension of the downstream part of the Suriname River valley. From the river mouth, incision migrated landward, incising into the shelf and into the previous river floodplain of the present lower Suriname River valley.

From the LGM to the early Holocene, rivers and creeks close to the sea were very deeply incised (10–30 m). Erosion also took place in the Old Coastal Plain and on the shelf of Suriname [46,62–64]. Moreover, the large Suriname River must have eroded into the sediments of the coastal plain and continental shelf. Core drillings by Groen (2002) show that near Paramaribo the base of the paleochannel of the Suriname River valley was about –35 m (below msl). After the steep sea level rise at the beginning of the Holocene (12 ka BP), the coastline shifted circa 20 km landward of its present position. Sea level reached its current level at 6.5 ka BP [45,46]. Since then, the coastline shifted seawards 10s of kilometers due to coastal aggradation.

In contrast, for the middle and the upper part of the river valley it is very unlikely that eustatic sea level changes have led to the formation of terraces (i.e., deposition during highstands and incision during lowstands), as the Brokopondo Sula forms a rock sill that cannot be cleared away by headward river erosion.

The 5 m terrace level fragments at Victoria and Baboehol, i.e., downstream of the Brokopondo sill, theoretically could represent a terrace formed as a result of the 7-m Eemian highstand that also formed the Old Coastal Plain. These terrace deposits do not show the common fining upwards sequence of the upstream 5-m terrace levels but consists primarily of clay (although the depth of the augering was only 3 m). In a similar situation near the mouth of the Marowijne River valley, marine clay was found in a 5 m terrace level profile in the Coropina Formation (Eemian) [5,65].

However, the Victoria 5-m terrace level is located at about 130 km from the mouth of the Suriname River valley, measured along the river channel (100 km as the crow flies), and the nearest Coropina (Eemian) marine deposits of the Old Coastal Plain are 40 km north from Victoria. Moreover, the Old Coastal Plain marine deposits do not reach higher elevations than 7 m above present sea level, whereas the Victoria 5-m terrace level is at 12 m above present sea level. Therefore, we conclude that that the 5-m terrace level at Victoria is a fluvial deposit.

As discussed above, the third knickpoint in the Suriname River valley at the Brokopondo sula shows a fining upwards fluvial sequence on top of an irregular bedrock profile [52]. This sula was buried by fluvial sediments of the 5 m level during the last glacial semiarid period and dissected during the present humid interglacial. Fluvial deposition during the last glacial apparently went downstream beyond the last knickpoint and is probably also responsible for the 5-m terrace levels at Victoria and Baboehol. Therefore, it is unlikely that any of the studied terraces in the study area has formed as a result of Eemian highstand deposition and Last Glacial dissection.

## 6. Conclusions

Like other rivers in cratonic drainage basins covered with exclusively tropical rainforest, the Suriname River at present is characterized by the virtual absence of bedload transport, because the deeply weathered basement does not provide coarse-grained sed-

iment to the rivers. Cataracts (sulas) are formed in the river channel where interglacial incision touches subsurface rock weathering fronts. The absence of bedload forces the Suriname river to avoid the rocky obstacles instead of eroding them away, leading to multi-channel cataracts, which only in plain view resemble braided river patterns. However, they are stable rocky features instead of moving gravel and sand bars. The cataracts represent important knickpoints in the length profiles of the rivers.

In the Suriname River in the Guiana Shield, the presence of several gravel-bearing terrace levels above the present flood plain suggests that in glacial times, in this region, were characterized by semi-arid climatic conditions with savannah-type vegetation, fluvial dynamics differed considerably from the present ones. Three terrace levels at 20, 15 and 5 m above present mean water level were studied in three sectors of the river: an upstream part, a middle part (now submerged below a storage lake), and a lower part. The consistent height difference between these levels and their length profiles being roughly parallel to the present one suggests that they represent major stages in the development of the river basin. The consistent presence of terraces at the 20, 15, and 5 m levels at both the up- and downstream parts of the Suriname River valley can be explained by lowering of long-term eustatic sea level and/or low amount of uplift. As dissection is argued to have started already in the late Pliocene or early Pleistocene, the terrace staircase may represent many more than three climatic cycles. However, because of the absence of datable material individual cycles cannot be resolved as of yet.

The presence of gravel in the fluvial terraces could imply that the role of the knickpoints was less prominent than at present. An island in the northernmost knickpoint, the Brokopondo sula, shows a buried rocky surface under a fining upwards sequence belonging to the 5 m terrace level, suggesting that many cataracts may have suffered bedload erosion indeed during glacial times, becoming covered with so much sediment that their knickpoint function became less effective. As a result, glacial length profiles could be smoother than the present one.

While in the upper part of the river valley the role of upstream controls, notably climatically induced changes in vegetation cover and sediment delivery are obvious, in the lowermost sector of the river the role of downstream controls, especially sea level change must also be discussed. Theoretically, the terraces in this sector could also represent fluvial deposition during sea level highstands and dissection by headward erosion during lowstands. However, even the 5 m terrace levels here are situated at 12 m above present sea level, whereas the oldest marine terrace in the Old Coastal Plain does not reach above 7 m above sea level. Moreover, the distance to the coast of the northernmost terraces is over 100 km, far beyond any evidence of past sea levels. The presence of fluvial deposits on the most downstream knickpoint suggests that the terrace intersection must be situated further north than the present study area.

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