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Client: World Wildlife Fund

Project: Eco-hydrological Assessment of the North Rupununi Wetlands

Date: April 2020

Report: Monitoring and Assessment

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1. SUMMARY

1.1 The North Rupununi Wetlands are situated in the southern interior of Guyana, South America, and support a high terrestrial and freshwater biodiversity. Biodiversity surveys have identified more than 450 fish species, which in turn supply a food chain to endangered species such as the black caiman (*Melanosuchus niger*), giant river otter (*Pteronura brasiliensis*), giant river turtle (*Podocnemis expansa*), and recovering populations of the largest freshwater fish in the world, the arapaima (*Arapaima spp.*). These species are not only important for conservation but also supply local people with a range of livelihood activities, including subsistence fishing and ecotourism. There is increasing evidence that the high fish biodiversity of the North Rupununi Wetlands is in part as a result of a hydrological link between the Amazon and Essequibo basins, allowing species from both basins to intermingle in this region. The North Rupununi Wetlands are characterised by low topography and seasonal flooding of this watershed divide, thus allowing the migration of aquatic species, including arapaima and black caiman, which are found in no other watershed of Guyana. However, the precise location of these connectivity and migration corridors have not been studied to date.

1.2 There is economic pressure in Guyana for natural-resource exploitation and foreign pressure to convert natural habitats into industrial farms, logging, mining and oil wells, and associated infrastructure, especially access roads. This increased activity is having an impact on the North Rupununi Wetlands in terms of pollution, over-harvesting, irresponsible hunting, and unregulated or poorly regulated mining and logging that are resulting in the loss of species in general and habitat connectivity in particular. This has the potential to further deteriorate sustainable traditional livelihoods, already under pressure from globalization and the market economy, forcing many more Indigenous people to migrate to towns and cities in search of often poorly paid work.

1.3 Scientific proof, and detailed mapping, of the precise location and mechanisms enabling the hydrological link between the Amazon and Essequibo basins, would help support appropriate development and conservation in the region. The primary aim of this project is to map the hydrological link and surface water dynamics between the Amazon and Essequibo basins to strengthen the conservation of the North Rupununi Wetlands.

1.4 The project used high-resolution aerial mapping, remote sensing analysis and ground-truthing. This allowed us to precisely identify the spatial and temporal dynamics that allow the waters of the Amazon and Essequibo basins to meet. Our work also produced detailed vegetation, elevation and hydrological maps, which can support decision-making with regards to existing and proposed developments.

1.5 This information will support Guyanese conservation organizations, Indigenous communities and government policy makers in their quest for the sustainable management of the North Rupununi Wetlands. The results will also help with the appropriate design of new road infrastructure especially the upgrade to the Georgetown-Lethem road and the Toka to Lethem road, which dissect the watershed. With the establishment of agri-industrial development in the region, there is the urgent requirement to minimise impacts on biodiversity and the Indigenous communities that depend on these for their livelihoods. The results of our work will help inform better decision making regarding agri-industrial development and support an Integrated Land Management Approach in the region.

Project team

1.6 The project team was composed of the following:

- Project manager - Dr. Matthew Simpson, The Cobra Collective and 35percent Ltd (UK);
- Technical expert - Dr. Andrea Berardi, The Cobra Collective and The Open University (UK);
- In-country coordination - Dr. Deirdre Jafferally, The Cobra Collective;
- Community researcher and coordinator: Felix Holden, Rupununi Wildlife Research Unit, Yupukari, North Rupununi, (Guyana);
- Community researcher and coordinator: Anthony Roberts, Rupununi Wildlife Research Unit, Yupukari, North Rupununi, (Guyana);
- Community Researcher and transportation: Kamal Khan, Rupununi Wildlife Research Unit, Yupukari, North Rupununi, (Guyana);
- Transportation and logistics: Lakeram Haynes, North Rupununi, (Guyana); and
- Satellite radar analyst – Javier Ruiz-Ramos, Open University (UK).

2. INTRODUCTION TO THE NORTH RUPUNUNI WETLANDS

Geography and ecology

2.1 The North Rupununi Wetlands are situated in south-west Guyana (04º N 05', 59º W 02') (Figure 1). The region straddles the watershed divide between the Amazonian basin and the Essequibo River catchment. The area is dominated by three large rivers: the Rupununi, the Takatu, and its tributary, the Ireng. In this area, the three rivers pass within approximately 30 km of each other, separated by savanna, crisscrossed by a network of wetlands, small rivers, creeks, and lakes. The Rupununi River drains the central and eastern parts of the savannas and flows east into the Essequibo River, which drains into the Caribbean Sea. The Takatu and Ireng Rivers drain the western portion of the savannas and flow west into what is eventually the Amazon via the Rio Branco and Rio Negro (Figure 2).

Figure 1 - Map showing the location of the North Rupununi Wetlands (red box) adjacent to the Guyana-Brazil border.

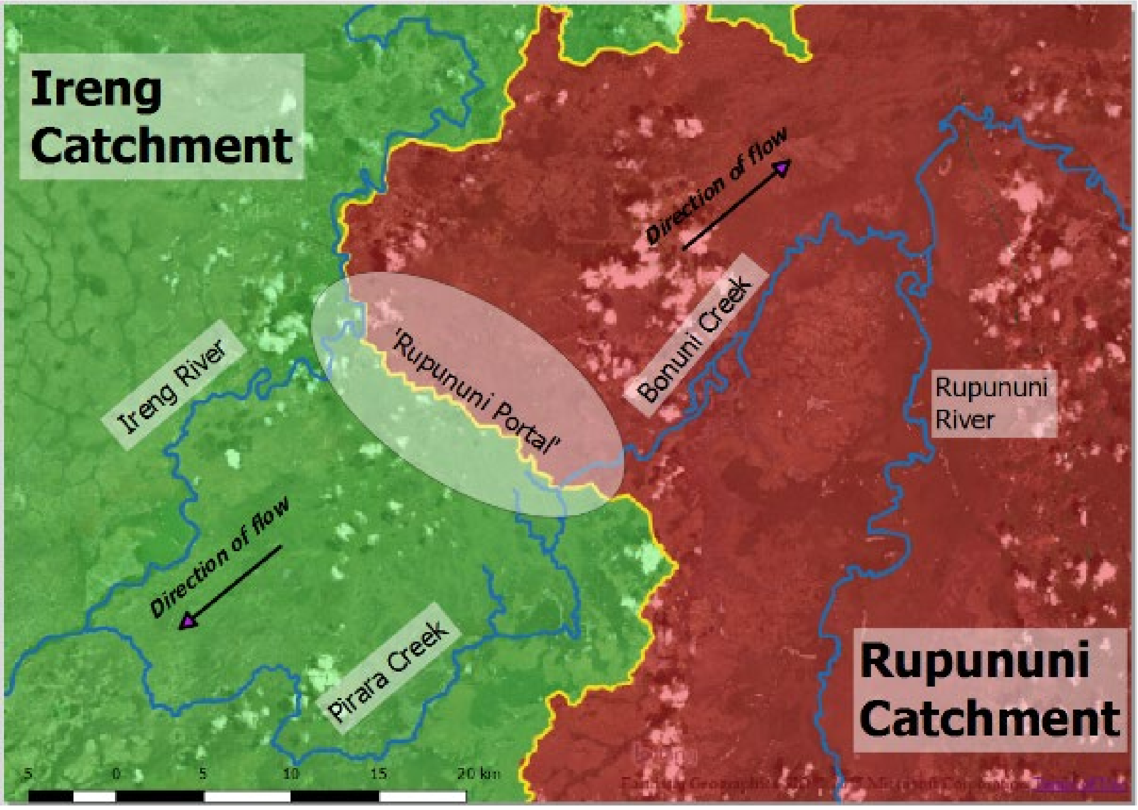

Figure 2 - Map showing the watershed divide between the Ireng River (part of the Amazon basin) and the Rupununi River (part of the Essequibo basin). The 'Rupununi Portal' region indicates where the waters between the two basins can intermix

2.2 The geology of North Rupununi region is complex due to its age. Early plutonic (a body of intrusive igneous rock) and volcanic rock formation, regional metamorphism, rifting, uplifting, and oscillating periods of sedimentary deposition and erosion have shaped the area into a patchwork landscape of varying geological characteristics. These processes have fundamentally influenced topography, soils, water flow, as well as the potential for commercial activities such as mining, agriculture and timber production. The close association between the Essequibo and Amazon basins in the region has ancient geological origins. 30/25 million years ago, an ancient river basin, called the 'Proto-Berbice' drained the Branco, Takutu, Ireng, Rupununi, Essequibo, Demerara and Berbice rivers into the Caribbean Sea. Over time, the Amazon basin gradually captured some of these rivers: the Branco 5 million years ago, and then the Takutu and Ireng 2 million years ago. Some researchers believe that the Rupununi will also be eventually 'stolen' by the Amazon from the Essequibo. These ancient geological shifts may have significantly contributed to the spectacular species richness currently present in this region.

2.3 Contemporary geological attributes also play a major role in creating a rich diversity of habitats, which in turn provides the opportunities for a great variety of species to thrive. Geology contributes significantly towards soil profile and structure. This has a key role in determining what vegetation is dominant and where they are distributed in the Rupununi. Soil profile takes into account several factors such as decaying matter, which determines how rich the soil is in terms of nutrients, and secondly the type of soil composition (i.e. sand, silt or clay) which has a role to play in the soil's ability to absorb and also retain water. The soils of the savannas differ from that of the rainforest region of the Rupununi in that they show low mineral/nutrient retention and water storage. Flora found in the North Rupununi are, therefore, specifically adapted for surviving in these conditions.

2.4 The geology also contributes to great variation in waterbody characteristics, including white, black, and clear water streams, foothill and mountain streams, dissected river systems and ox-bow lake formations. These wetlands are dominated by the Rupununi, Rewa, Essequibo rivers, and a tributary of the Ireng River (Pirara Creek), and include over 750 lakes, ponds and inlets covering approximately 22,000 ha. The hydrology of the area is directly influenced by the Rupununi, Essequibo, Ireng and Takutu river catchments. However, it is the Rupununi River and Ireng catchments that are mostly responsible for the North Rupununi's unique transformation during the wet season (Figure 2).

2.5 The principal rainy season is from May to September, but with substantial year to year variation depending on the position of the Inter-tropical Convergence Zone (ITCZ) which meanders between northern Brazil and the Caribbean (Figure 3). During severe El Nino years, the ITCZ may not even reach Guyana, thus subjecting the region to severe drought, as occurred in 2015 and 2016. The total annual rainfall varies from 1,400 – 3,000mm of which 50 to 70% falls during the main wet season. Approximately 8,000km^2 of the North Rupununi savannas form a seasonally flooded plain during the wet season (the site of the legendary lake of El Dorado), rimmed on the north-west by the Pakaraima mountains, in the north by the Iwokrama mountains and in the south by the Kanuku mountains, allowing the Amazonian and Guianan Shield waters to mix, and effectively creating a water bridge between the two basins – the 'Rupununi Portal'. However, in 2015 and 2016, the rains were late, and no extensive flooding occurred, with severe impacts on biodiversity as aquatic fish species were limited in their spawning, and the resulting fry had a reduced area within which to feed and grow, with consequent impact on the local populations that depend on fishing.

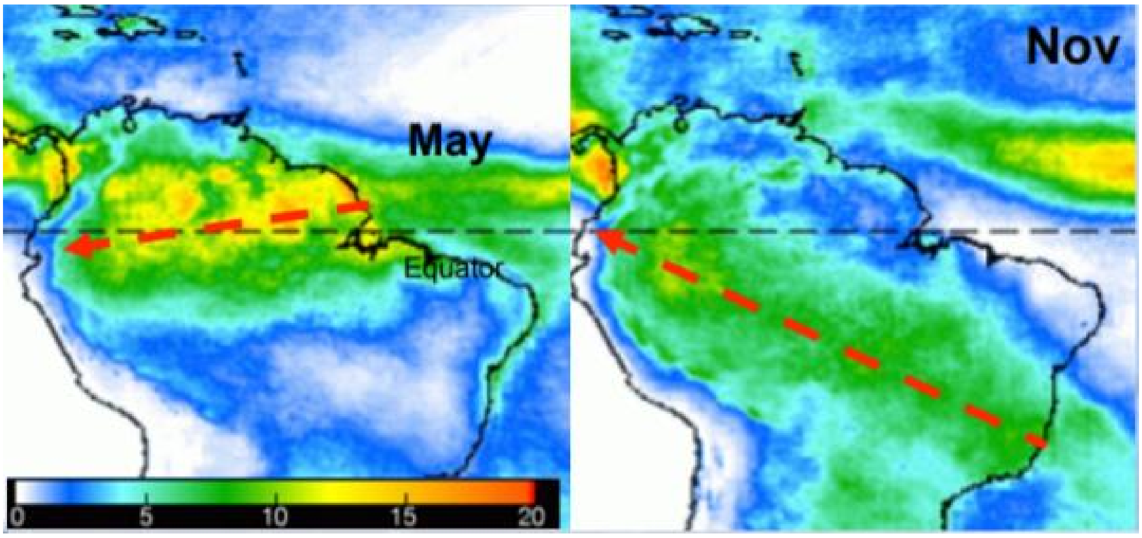

Figure 3 - Position of the Inter-tropical Convergence Zone (dotted red line) in May (wet season) and in November (dry season). The map shows monthly average precipitation (mm/day) for 1998-2008 (after Bovolo et al, n.d.)

Flora and Fauna

2.6 The range of rainforest, savanna and wetland ecosystems present in the North Rupununi provide a unique and diverse selection of habitats for a rich biodiversity. It has been argued that the seasonal water bridge between the Amazonian and Guiana Shield basins represent a link for species and biodiversity, and is thus a key site for species migration, as well as providing an abundance of food, breeding grounds, and diverse habitats. Fishes, turtles and many native birds feed, breed and live in the wetlands all year round. At the same time, many species of migratory birds rely on the wetlands as feeding and breeding grounds. Flooding of these wetlands provides the opportunity for migration for fishes and other species of fauna that would have been otherwise isolated for parts of the year. Similarly, plant species are assisted by seasonal flooding by permitting seed dispersal.

2.7 Generally speaking, forest ecosystems support a higher abundance of plants and animals as compared to the savanna ecosystem. There have been over 1200 plant (Clarke et al., 2001, 141 amphibian and reptile (Donnelly et al., 2005) and 130 mammal (Lim et a.l, 2005) species documented in the Iwokrama Rainforest. The forested region of the North Rupununi area is generally mixed forest with no particular species dominance. These vary from tropical moist forest, tropical dry forest and at higher altitudes (on mountains and hills), tropical montane forests. These forests include important non-timber product species such as crabwood (*Carapa guianensis*) which is well known for the oil that is produced from its seeds used for medicinal and industrial purposes. Some common timber species include wallaba (*Eperua spp.*), mora (*Mora excelsa*), silverballi (*Ocotea spp*.), bullet wood (*Manilkara bidentata*) and greenheart (*Chlorocardium rodiei*). Kokrite (*Attalea regia*) and ite palm or tibisiri (*Mauritia flexuosa*) are also prevalent and serve as thatching materials for the Amerindian communities. Small-scale clearing of forested areas for subsistence farming through shifting cultivation methods has been the culture for many years and is still undertaken.

2.8 Forested areas gradually give way to extensive savannas. The savanna is a rolling grassland scattered with shrubs and isolated trees and interspersed with wetlands. Unlike the soils found in the forested areas, soils in the savannas are generally nutrient poor. Plants that are prevalent here are those that are specially adapted for drought conditions. They may have long tap roots which will enable them to reach the deep water table, drop their leaves in the dry season to avoid evapotranspiration and/or have underground storage organs to conserve water. Ranching has historically been the dominant human activity in the savannas, with the wide use of fire as a management tool, although in recent years ranching has subsided.

2.9 With regard specifically to the fauna of the North Rupununi, it has been estimated that this region supports populations of over 65% of the species of wildlife found in Guyana (Iwokrama and NRDDB, 1998) and it is a known fact that Amerindian communities have coexisted with such wildlife for thousands of years (Forte, 1996). The North Rupununi is home to many species of endangered animals and including those that have come to be known as the ‘Giants of El Dorado’. These include the harpy eagle (*Harpia harpyja*), capybara (*Hydrochaeris hydrochaeris*), jaguar (*Panthera onca*) and giant anteater (*Myrmecophaga tridactyla*). The Rupununi, Rewa, and Essequibo River systems are home to over 450 species of fish, including the arapaima (*Arapaima spp*), the world’s largest freshwater fish. Interestingly, comparable wetlands in South America such as the Varzéa of Mamiraua and the Pantanal wetlands, indicate records of only 400 and 200 species of fish respectively. In addition, there are healthy populations of internationally endangered species such as the giant river turtle (*Podocnemis expansa*), black caiman (*Melanosuchus niger*), and giant river otters (*Pteronura brasiliensis*).

2.10 Overall, it is important to recognize and appreciate the functions of the many unique ecosystems that are part of the North Rupununi both individually and as one large interconnected system, which is ultimately responsible for the health and productivity of all the biodiversity found within it.

The People

2.11 The North Rupununi Wetlands and the surrounding region is the traditional home of the Makushi people. Although the Makushi are still the primary ethnic group in the area, many communities contain a mixture of other indigenous groups and immigrants from the more populated coast. The primary livelihood activities in the area are subsistence farming and fishing, with some amount of hunting and gathering, trapping, brick making, and cattle ranching. The main local crop is cassava (*Manihot esculenta*), of which several varieties are grown to produce *farine* (roasted cassava grains), cassava bread, tapioca, and various beverages. There is also some local commercial exploitation of wildlife for the meat and pet trades. Wildlife represents a major local food source in the North Rupununi. Mammals and fish, in particular, provide the majority of the protein intake for villagers (Watkins et al., 1999). According to a study by the Makushi Research Unit (Forte, 1996) over 100 species of fish are eaten by the Makushi. As such, fishing is an extremely important subsistence activity. Aside from subsistence and economic value, the North Rupununi Wetlands also feature prominently in indigenous culture and folklore, and have significant aesthetic value, serving as a primary place of recreation for local residents.

2.12 The residents of the North Rupununi are distributed among twenty primary communities, consisting of approximately 9000 people. Although sixteen of these communities have legal title to some of their traditional lands, all of the communities currently practice customary user rights to their surrounding land and resources. The villages are represented by elected Toshao or Captains. These leaders came together in 1996 to establish the North Rupununi District Development Board (NRDDB), a regional, community-based NGO, which currently acts as the coordinating body for conservation and development initiatives in the area.

Challenges

2.13 The extreme remoteness and wilderness of the North Rupununi and the isolation of its people make it vulnerable to illegal and poorly managed resource extraction, pressure to convert natural habitats, and climate change impacts, with limited oversight and support from statutory agencies, situated hundreds of miles away on the coast. Direct threats include the growing global demand for commodities and processed products such as gold, cocaine, palm oil, soy, rice, meat, aluminium and petroleum. Other threats are highlighted in a recent study on the interaction between deforestation, fire and drought in the Amazon potentially leading to losses of carbon storage, and changes in regional precipitation patterns and river discharge (Davidson et al., 2012). The same study concludes that the increase in droughts associated with climate change is likely to worsen changes in these precipitation patterns, thus further exacerbating the direct impacts of land-use change on remaining wilderness areas.

2.14 Small-scale and large-scale mining activities, oil prospection and extraction, dam building, and large-scale agriculture all have impacts on complex and fragile tropical environments. For example, the impact of the mining sector on the environment is profound and durable. It is responsible for the clearing of forests and the pollution of rivers and soil. The dispersion of chemicals in water and air contaminates the food chain and has an impact on biodiversity. Gold mining is an increasing presence in the region with concessions to major international corporations having recently been issued in the headwaters of the Rupununi and Rewa rivers (Guyana Goldstrike, n.d.).

2.15 With a population density of fewer than three people per square kilometre and largely concentrated in the town of Lethem on the Brazilian border, the North Rupununi is amongst one of the least populated areas on Earth. Despite the existence of legally recognized Indigenous lands, this remote region is attractive to illegal activities such as drug trafficking and gold mining, as has been documented in nearby regions (Phillips 2011). Its strategic location and troubled history may also raise questions of national security (Butler 2012). Consequently, there are social and environmental impacts associated with regards to foreign owned and/or funded large-scale infrastructure projects such as road-building, dams, and mega-farms, with associated peopling, including on Indigenous lands (MacDonald, 2014; 2016).

2.16 All tropical ecosystems are sensitive to land-use and climatic change, but wetlands are particularly sensitive. It is therefore imperative to establish the eco-hydrological mechanism for maintaining the North Rupununi Wetlands and determine a baseline, so as to inform appropriate and sustainable development strategies while monitoring the impacts of current and emerging developments in the region.

Research on the Rupununi Portal to-date

2.17 Much has been speculated about the ecological significance of the 'Rupununi Portal'. Lowe-McConnell (1964) provides one of the first comprehensive list of fish species present in the region. More recent studies have gone beyond a straightforward identification of fish species, to focus on understanding their genetic diversity (de Souza 2012). These various studies have identified over 450 distinct fish species in the region, placing the North Rupununi Wetlands as one of the most biodiverse aquatic ecosystems in the world, as far as fish are concerned. These studies have also provided proof of a significant overlap in fish species composition between the rivers and water bodies of the Amazonian and Essequibo basins. However, all of these studies have not determined the exact location and dynamics of the hydrological connectivity. For example, Figure 4 is an extract from a map published in Lowe-McConnell (1964) indicating a number of creeks from the Ireng and Rupununi rivers converging towards 'Lake Amuku' – the site of the 'Rupununi Portal'.

2.18 In-text descriptions within various publications also limit themselves to one-sentence statements without detailed maps or information regarding the seasonal dynamics of the North Rupununi Wetland system:

- "As the Rupununi savannas are extensively flooded in the rainy season the Amazon and Essequibo drainage systems are here in contact in wet years, meeting in the vast flooded plain known as Lake Amuku." (Lowe-McConnell, 1964, P. 105);
- "Pirara head, which is the exact site of the Takutu connection to the Rupununi portal" (de Souza, p.46); and
- "During this research, it was possible to identify and confirm that the Bononi Creek represents the link between the Essequibo watershed and the Amazon watershed"(Ingwall-King, 2013, p.204).

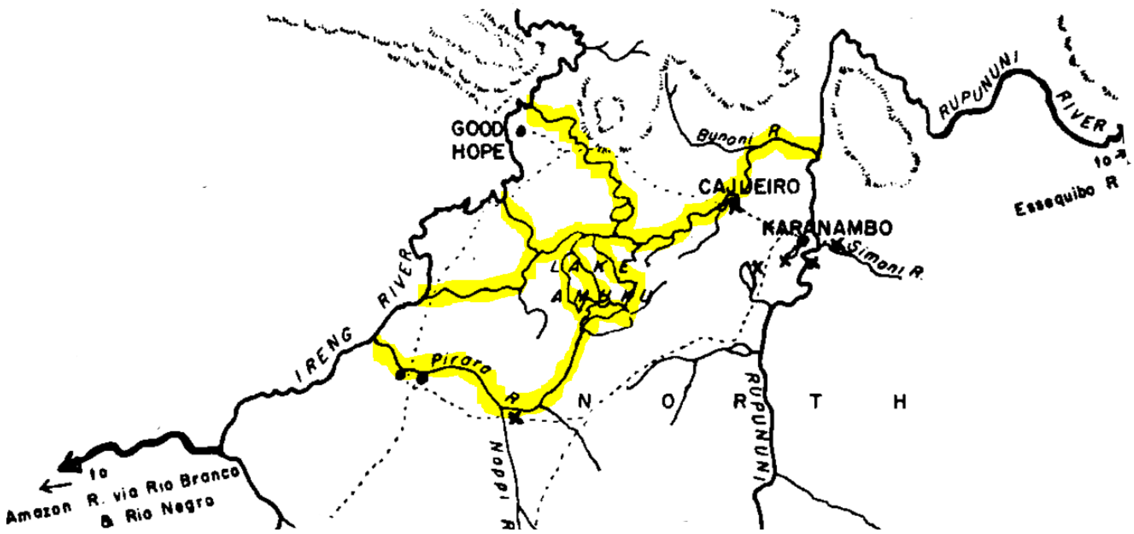

Figure 4 - Map extract from Lowe-McConnell (1964) indicating at least five distinct hydrological connections between the Ireng and Rupununi rivers (our highlighting in yellow)

2.19 Since there is an increasing number of diverse threats that may affect the connectivity and dynamics of the hydrological links between the Ireng and Rupununi rivers, there is, therefore, an urgent need to precisely map and characterise the dynamic nature of the hydrological connectivity.

3. AIMS AND OBJECTIVES

3.1 The aim of this project is to undertake mapping of topographic levels across the North Rupununi Wetlands and through modelling and interpretation provide an analysis of flood dynamics and ecological sensitivity in relation to the hydrodynamics.

3.2 To deliver this aim the following objectives were completed:

- To undertake SENTINEL-1 radar analysis of 29 May, 10 June, 22 June, 04 July, 16 July, 28 July, 09 August, 21 August, 02 September, 14 September, and 26 September surveys to accurately map surface water dynamics during the 2019 wet season and compare this to 2017 and 2018 flood seasons;
- To undertake precise drone surveys to provide 10cm resolution topographic mapping of key surface water flooding areas, existing and planned road networks, habitats of major conservation significance and areas undergoing or planned for development;
- To produce a digital elevation model of the North Rupununi Wetlands;
- To develop a flood dynamics model for the North Rupununi Wetlands;
- To produce a report on the most sensitive conservation sites and corridors of the North Rupununi Wetlands; and
- To train relevant staff in survey and analysis techniques.

4. METHODOLOGY

4.1 The following methods were used to develop an overall understanding of the eco-hydrological processes responsible for the link between the Amazon and Essequibo basins within the North Rupununi Wetlands.

Satellite imagery and radar image analysis

4.2 To determine large-scale, landscape analysis of the North Rupununi Wetland system remotely sensed satellite imagery was used. The joint NASA/ U.S. Geological Survey LANDSAT series of Earth Observation satellites was used to determine a habitat classification as it provides optimal ground resolution and spectral bands for this type of analysis. The classification was carried out using the only two LANDSAT images taken of the North and South Rupununi in the last 6 years that are not obstructed by cloud cover. This was a set of images taken on September 11th 2015. The processing of these raw images into a land cover classification of the North Rupununi involved selecting typical regions for five important land cover types:

1. Open Water – characteristic of the main river systems (Rupununi, Ireng, Takutu) and some large ponds not covered in any wetland vegetation (e.g. Awarikuru);
2. Wetland – characteristic of permanently wet habitats dominated by wetland species, such as water lilies and rushes (e.g. Lake Amoko)
3. Grassland – characteristic of habitats that are covered in water for most of the wet season, and that only completely dry out for a short period during the dry season (e.g. along the Pirara and Bonuni creeks). To note that the classification is not able to distinguish between natural wet grassland from cultivate rice fields due to very similar spectral signatures;
4. Savanna – characteristic of habitats that are dry for most of the year, with some lower lying areas only occasionally being inundated during peak flooding;
5. Forest – characteristic of both floodplain forests that are inundated during the wet season, and higher regions that never gets flooded but nevertheless has a closed canopy of trees.

4.3 The resulting classification map of the North Rupununi is at a resolution of 30m and has been validated through comparisons with the drone orthomap images which shows an excellent match.

4.4 Satellite imagery analysis and drone surveys were used to produce Digital Elevation Models (DEM) for the region. This allowed the production of DEMs at 30m resolution using the Shuttle Radar Topography Mission data, collected from the Space Shuttle Endeavour, 12m resolution using WorldDEM Airbus data and 20cm resolution using the drone surveys described in the section below. To note that the WorldDEM data was obtained as a result of a data sharing agreement with colleagues within the Field Museum, USA.

4.5 To understand the drainage flow pathways slope analysis of the DEM was also undertaken.

4.6 A challenge of using remotely sensed satellite imagery for exploring flooding regimes within tropical contexts is that the extensive cloud cover during the wet season obscures what is going on at ground level. However, radar imagery is able to penetrate cloud cover, and since 2014, researchers have been able to freely download imagery taken by the European Space Agency's Sentinel-1 Synthetic Aperture Radar. Coverage of the

Rupununi region is available from late 2015, but the effects of a severe El Nino during the 2015 and 2016 years meant that the North Rupununi Wetlands only experienced significant flooding in 2017, when the El Nino abated. Radar image analysis from Sentinel-1 was carried out for images taken in 2019 using a unique orbit, with a revisit time of 12-day. This produced 19 radar acquisitions (from 05th May 2019 until 07th December 2019). A specific 'Surface water' and 'Flooded vegetation' analyses were computed for each date and exported to GeoTIFF at 20m spatial resolution.

4.7 The 2019 data was then compared to flooding in 2017 and 2018 to allow the determination of a flood dynamics conceptual model for the North Rupununi Wetlands and the hydrological mechanisms maintaining the ecosystem. The landscape scale analysis also allowed the identification of key sites for more accurate mapping using drones.

Drone surveys

4.8 Drones enable real-time, aerial photographs to be taken. The purpose of the drone surveys was to produce a high-resolution three-dimensional map of elevation, water bodies, vegetation cover and roads of the watershed divide. This allowed the determination of the eco-hydrological characteristics in key areas where the watersheds have hydrological connections, and therefore, species movement and exchange. This involved pre-programming survey missions on the drone software which then allowed the drone to autonomously fly a series of transects. Communities were fully informed of the drone operation and demonstrations took place within villages so that they were aware of drone operation and purpose. An intensive training programme was also carried out so that the Community Researchers could co-design survey missions (Figure 5) and operate the drone (Figure 6).

Figure 5 - Mission planning

Figure 6 -Drone training at Caiman House, Yupukari

4.9 Advanced fixed-wing drones were deployed to survey 2km by 2km blocks at a time (Figure 7). In total, 33 blocks, of key locations, were flown resulting in drone surveys covering 132km^2 (Figure 8). Additional drone survey data taken in 2017 was also used to provide supplementary data for a further 6 blocks. These blocks have been used to determine the eco-hydrological mechanisms in key locations, such as Pirara Creek confluence with the Ireng River, Bonuni Creek confluence with the Rupununi River, the Rupununi Portal area, the Ireng River flood input location to the North Rupununi Wetlands and key development infrastructure locations. They have also provided a baseline assessment which can allow a determination of eco-hydrological changes and impacts through regular monitoring.

4.10 Full approval from the Guyana Civil Aviation Authority (GCAA) was gained for the surveys after a 40-page operations manual was produced in preparation for the missions which included pre-flight risk assessments and checks. Approval was also given from Guyana's Environmental Protection Agency (EPA), Ministry of Indigenous Peoples' Affairs and the local communities before undertaking the surveys.

Real-Time Kinematic surveys

4.11 Real-Time Kinematic (RTK) positioning is a satellite navigation technique used to enhance the precision of position data derived from satellite-based positioning systems (global navigation satellite systems, GNSS) such as the US Global Positioning System (GPS). RTK surveys involve establishing a 'base' unit at a fixed point (usually a point of higher elevation, Figure 8). A second unit, the 'rover', is then used to carry out the survey. The rover measures its position relative to the base unit to an accuracy of several centimetres. This allowed correction of the elevation maps produced by the drone surveys and to have instant high precision data on the elevation of areas that were surveyed, thus allowing development of the conceptual hydrological model of connectivity on the ground.

Figure 7 -Anthony Roberts launching a fixed wing drone in the North Rupununi Portal

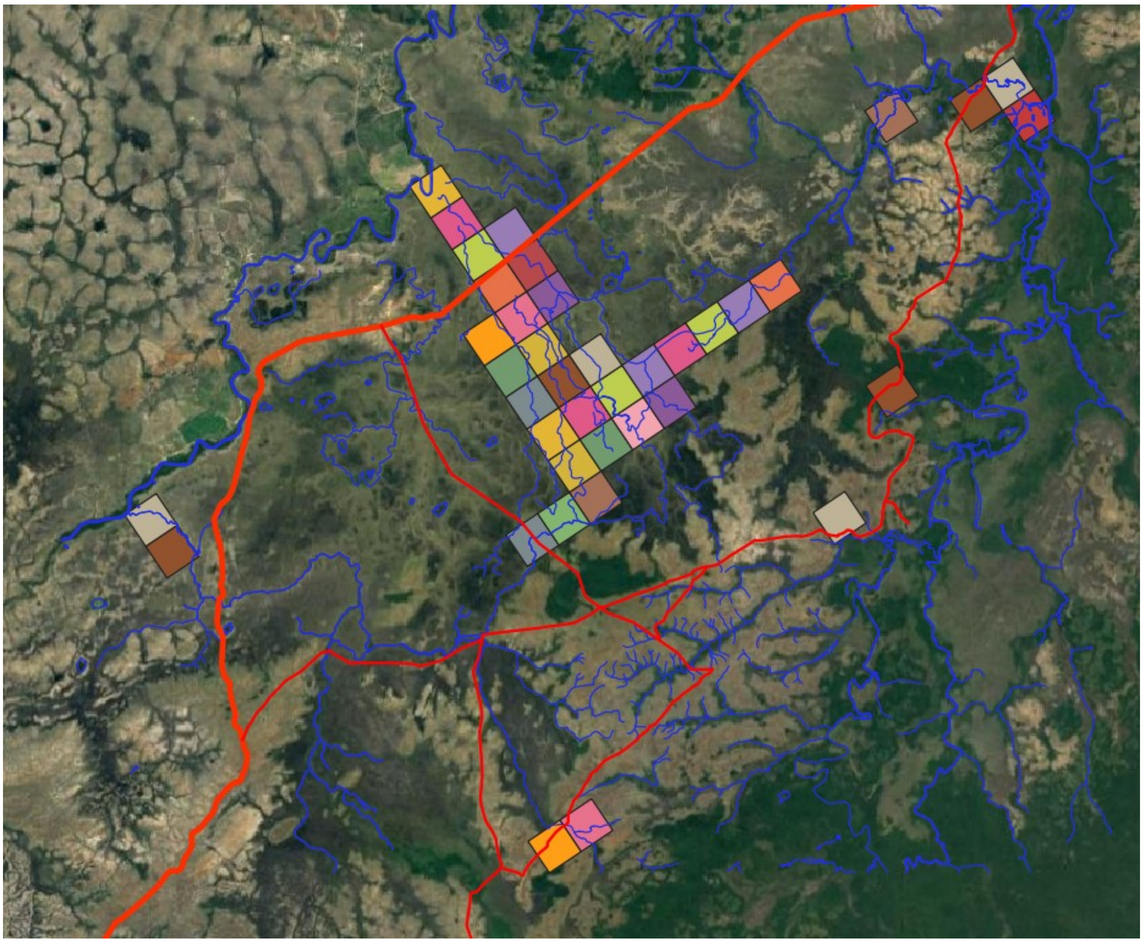

Figure 8 - Drone survey mission areas completed

Figure 9 - The RTK base station positioned at a point of high elevation overlooking the Rupununi Portal region

5. RESULTS

Remotely sensed satellite image analysis

Habitat classification

5.1 Analysis of Landsat data allowed the determination of a landscape scale habitat map which is shown in Appendix I, page 33.

5.2 It illustrates that permanent wetlands are distributed throughout the region and are connected to the Pirara Creek and Bonuni Creek drainage systems. It should also be noted that the grassland areas are seasonally flooded, along with much of the savanna areas found adjacent to the wetland areas.

Digital elevation models

5.3 The DEM, using the satellite data at 30m resolution, is shown in Appendix II, page 34, the 12m resolution in Appendix III, page 35, and an example of the 10cm resolution from a drone survey in Appendix IV, page 36. Appendix V, page 37, provides a comparison when all three resolutions are put together into a composite image.

5.4 The DEMs demonstrate that the Ireng River is at a higher elevation than the Rupununi River and the wetland areas are found at lower elevations. The analysis also demonstrates that although much of the North Rupununi Wetlands area is relatively flat there is great variation at the micro-topographical level.

Drainage pathways

5.5 Appendix VI, page 38, illustrates the slope analysis for the region and demonstrates the dominant flow pathways. In general, across the region, there is a topographic fall from the Ireng River in a southerly and south easterly direction but there is significant variation in pathway direction at a micro-topographical level. This demonstrates that as floods overtop the banks of the Ireng River and flow downslope, depending on the scale of the flooding, the water can move in multiple directions before it eventually reaches the Bonuni and Pirara Creek drainage systems. The micro-topographical variation, particularly areas where you have a break of slope, explains why you have pockets of permanent wetlands distributed throughout the area.

5.6 The analysis has also indicated that the 1968 Ordnance Survey maps of the area are incorrect in where they plot the drainage network. The errors are found in the area between the main road and the North Rupununi Wetlands. Within this gently sloping area, the stream network is incorrectly mapped on the higher ridge areas not the lower drainage areas as illustrated in drone data shown in Appendix VII, page 39.

Radar image analysis of flood dynamics

5.7 Figure 10 illustrates the backscatter detected from the Sentinel 1 satellite data. It illustrates the rise in water levels during the 2017 to 2019 period within the North Rupununi Wetlands. The graph corresponds well with local community observations of flooding. For example, Rupununi communities reported distinct periods of heavy rainfall in October, November and December 2019, and this peak (disrupting the general drying trend of this period) was also picked up by the radar image analysis.

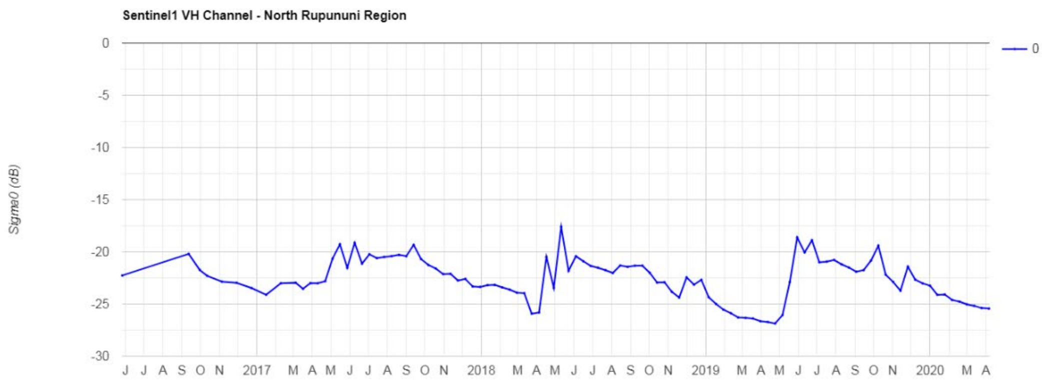

Figure 10 - Sentinel 1 VH channel backscatter time series

5.8 Appendix VIII, page 40, provides the 19 radar images analysed for surface water and flooded vegetation over the 2019 flood season (5th May to 7th December). It illustrates two major flood events (approximately 29th May and 22nd June), where water from the Ireng River overtops its banks and flows downslope (northwest to southeast) into the main North Rupununi Wetlands portal region. This is illustrated by extensive flooded vegetation and surface water expanding out southeast, across the main road and down to the low lying surface water areas. In 2019, hydrological inputs to the North Rupununi Wetlands come directly from precipitation and from surface water inundation and downslope runoff from the Ireng River. The radar analysis, for 2019, does not show flooding back up the Pirara Creek or the Bonuni Creek. This is despite some flooding along the Rupununi River being apparent on 14th September radar image. Although some localised flooding is identified near the confluence with the Bonuni Creek it does not demonstrate a flood pulse back up the Bonuni Creek into the main North Rupununi Wetlands area from the Rupununi River flooding. However, it should be noted that when the Rupununi River is high then it would hold back the drainage from the North Rupununi Wetlands via the Bonuni Creek, prolonging surface water across a more extensive area.

5.9 Appendix IX, page 59, shows the peak flood event for 2018 which demonstrates a similar flooding mechanism with inundation from the River Ireng flowing downslope to the North Rupununi Wetlands. Appendix X, page 60, shows the 2017 flood patterns. In May 2017, the picture was similar with limited flooding occurring from the Ireng River. However, in 2017 later in July and August, the flooding dynamic was different with rainfall in the south flooding the Nappi Creek and lower Pirara Creek areas rather than the dominant input coming from the Ireng to the north.

Drone survey and RTK analysis

5.10 Figures 11 to 14 show close up views of key monitoring areas surveyed with drones in February 2020. The high-resolution images allow identification of individual plants and features within the landscape. This will allow detailed analysis to be undertaken if proposed developments occur in these locations and will allow future monitoring to detect and record change.

Figure 11 - Bonuni Creek confluence with Rupununi River

Appendix XI, page 64, provides further image examples captured during the drone surveys and illustrates the digital elevation models that can be produced in these key areas. Key locations illustrated in Appendix XI, are the confluence of Bonuni Creek and the Rupununi River, the River Ireng overbank flooding location, the confluence of Pirara Creek and the Ireng River and the North Rupununi Wetlands portal area between the Bonuni Creek and Pirara Creek catchments. A DEM for 3 Mile Bush is also provided to show how habitat monitoring can be undertaken from these type of images.

Figure 12 - Pirara Creek confluence with Ireng River

Figure 13 – Rupununi portal wetlands

Figure 14 – Turtle pond

Conceptual flood dynamics model

5.11 The multiple analysis techniques have identified five hydrological mechanisms that influence water levels within main wetland area. The first is through direct precipitation on the wetland area resulting in standing surface water. The second, and most important, is overbank flooding from the Ireng River downslope from the north and northwest to the south and southeast. This flooding can have negative impacts on the main road that links Lethem (on the Brazilian border) to Georgetown (on the Caribbean coast) as shown in Figure 15. This is rapidly flowing, sheet flow of water across a large, gently sloping area.

Figure 15 -Flood damage to the Lethem-Georgetown Road in July 2017

5.12 This flooding mechanism is shown in Figure 16. It also shows a third hydrological contribution to water levels in the North Rupununi Wetlands via the Pirara Creek. During high stage levels in the Ireng River, water can potentially flow back up the Pirara Creek or act to hold water back that would normally drain through the Pirara Creek. This would result in backing up of water and a raising of water levels within the main wetland area as drainage would be restricted.

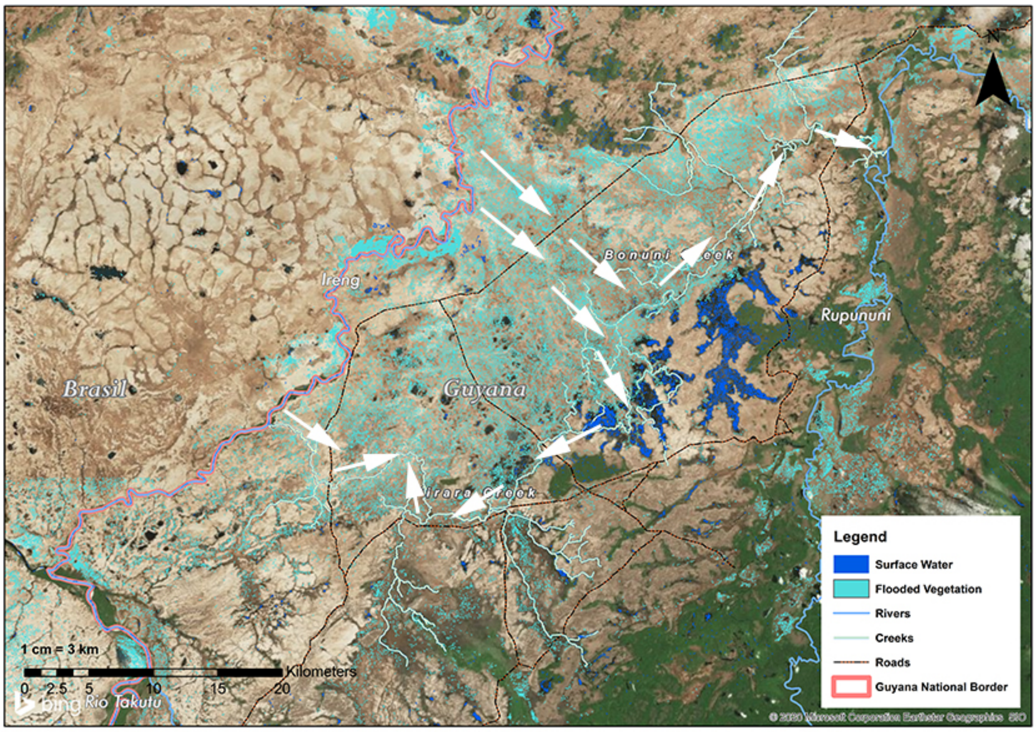

Figure 16 -Flooding into the North Rupununi Wetlands from the Ireng River

5.13 A fourth hydrological input, is a similar mechanism to that of Pirara Creek. If stage levels in the Rupununi River are high then flow and levels in the Bonuni Creek are impacted. Anecdotal evidence has suggested in these conditions flow direction in the Bonuni is reversed (Figure 17). The radar evidence suggests that this effect is limited but high water levels in the Rupununi River would also cause water in the Bonuni Creek to back up and levels to rise in the main wetland areas as drainage would be restricted.

5.14 The fifth, and final, hydrological mechanism influencing water levels within the North Rupununi Wetlands is flow from the south through creeks such as Nappi Creek which ultimately flow into Pirara Creek. Intense rainfall in the south can result in increased discharge via these creeks and result in flooding in the southwestern end of the North Rupununi Wetlands. This hydrological mechanism would also act to back water up that is draining from the northeastern portion of the wetland area via Pirara Creek.

Eco-hydrological sensitivity analysis

5.15 Information from the hydrological conceptual model, flood dynamics analysis, the habitat classification and the digital elevation models have been combined to develop an eco-hydrological sensitivity map for the North Rupununi Wetlands, Figure 19, which illustrates different conservation zones. The first conservation zone covers the main drainage network shown in blue and the flow pathway areas shown in white. Key to the survival of the wetlands is the maintenance of the flow pathways described in the conceptual hydrological model as the flow pathway areas are essential for water supply but also for species migration, fish spawning and exchange of species across the two major catchments.

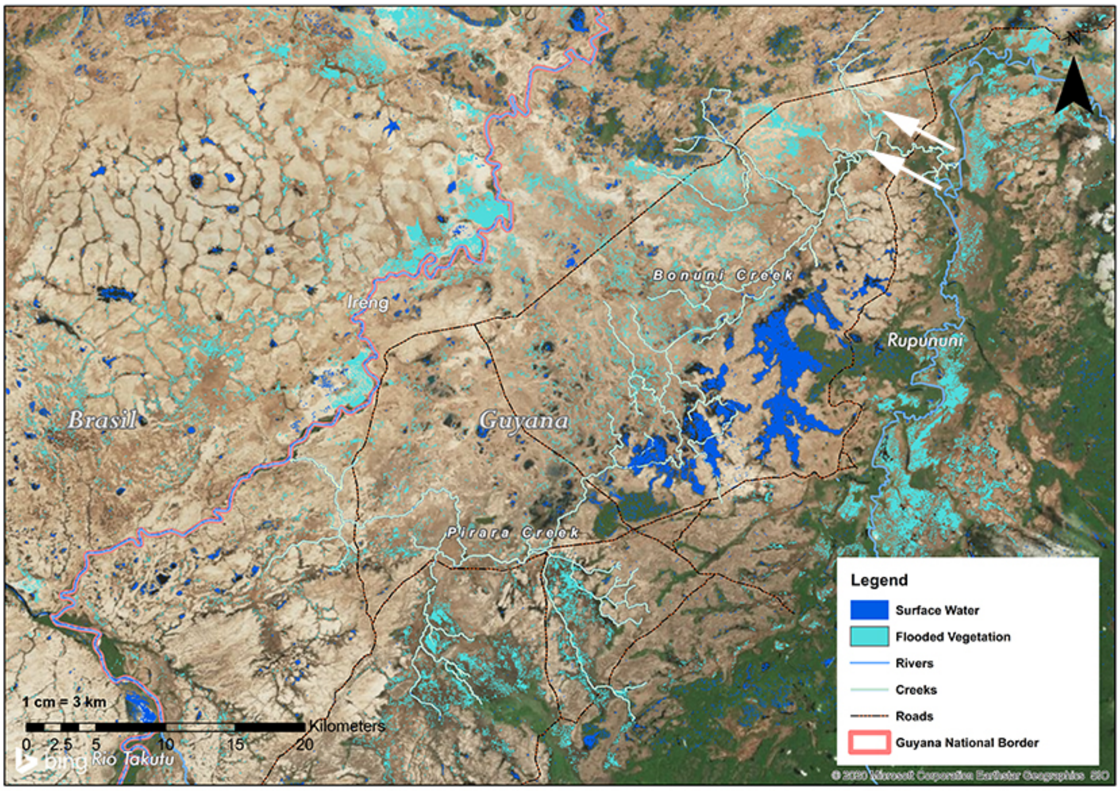

Figure 17 -Flooding into the North Rupununi Wetlands from the Bonuni Creek

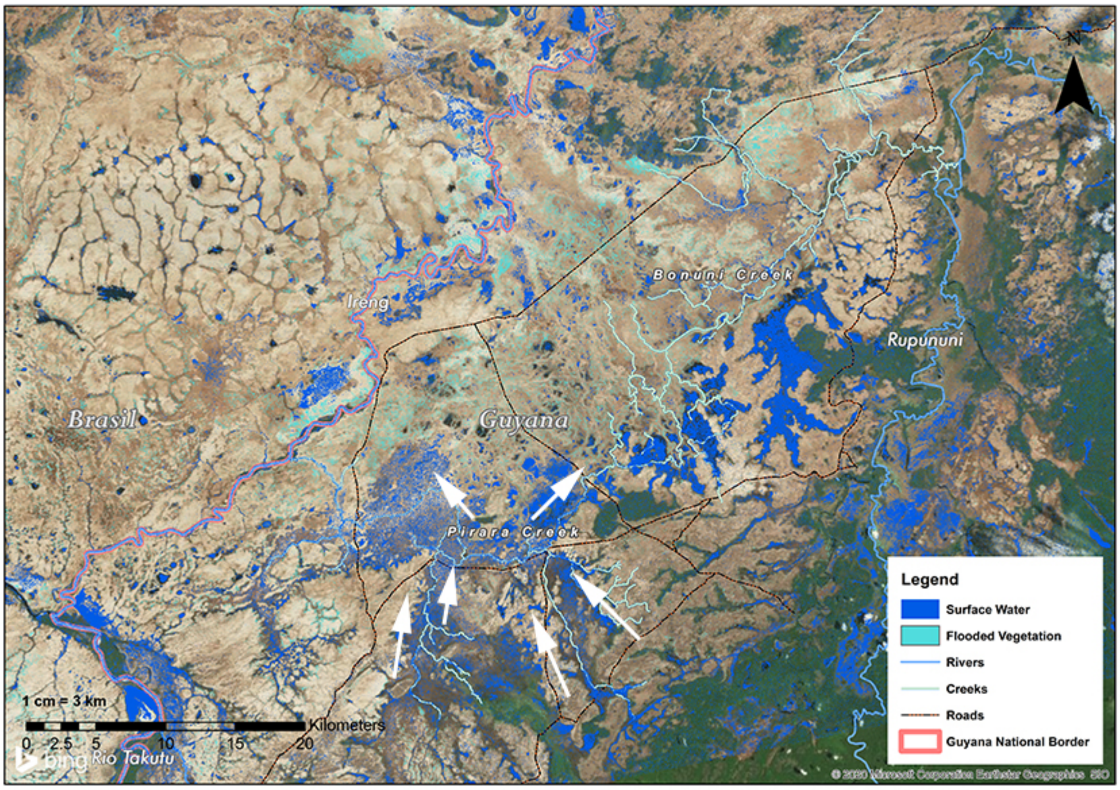

Figure 18 -Flooding into the North Rupununi Wetlands from the south

5.16 The other key conservation zone in terms of eco-hydrological sensitivity are illustrated as red in Figure 19. These identify the mosaic of wetland habitats that make up the North Rupununi Wetlands as they are important for maintaining the diverse animals and plants found in the region and the communities that rely on them.

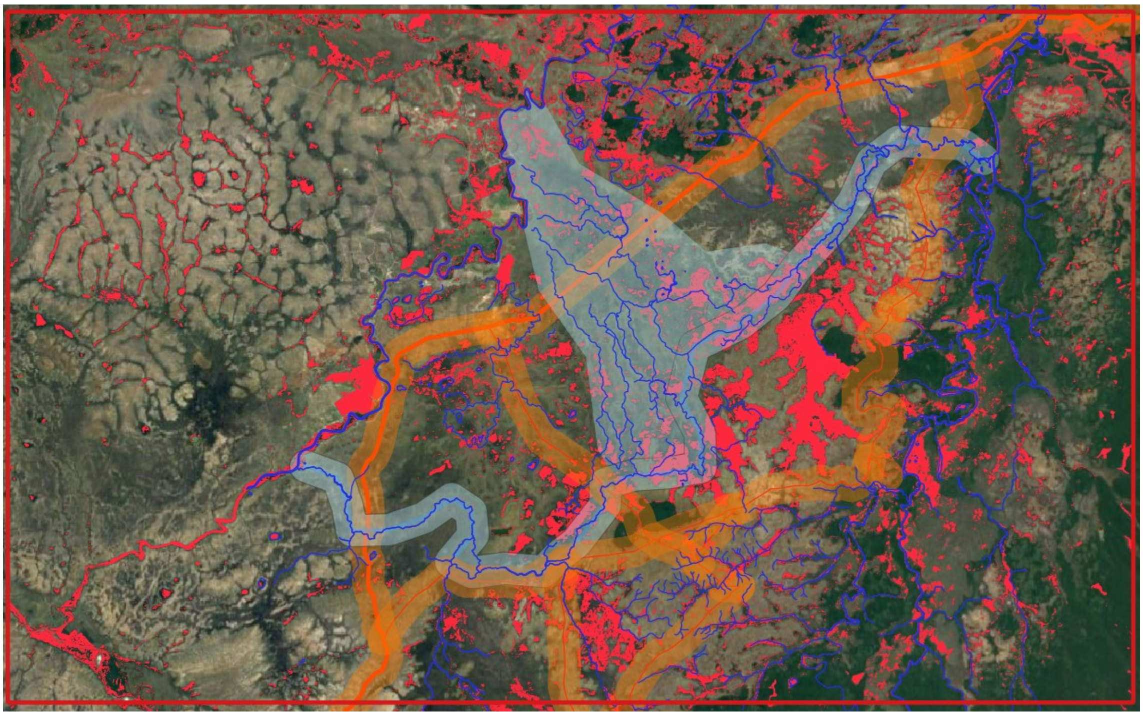

Figure 19 - North Rupununi Wetlands eco-hydrological sensitivity map

5.17 Figure 20 illustrates how the eco-hydrological sensitivity map could be used to support decision making in the North Rupununi. In this example, a road crosses the red zones comprising wetland habitat of key conservation importance so would require culverts and bridges to maintain habitat and hydrological connectivity.

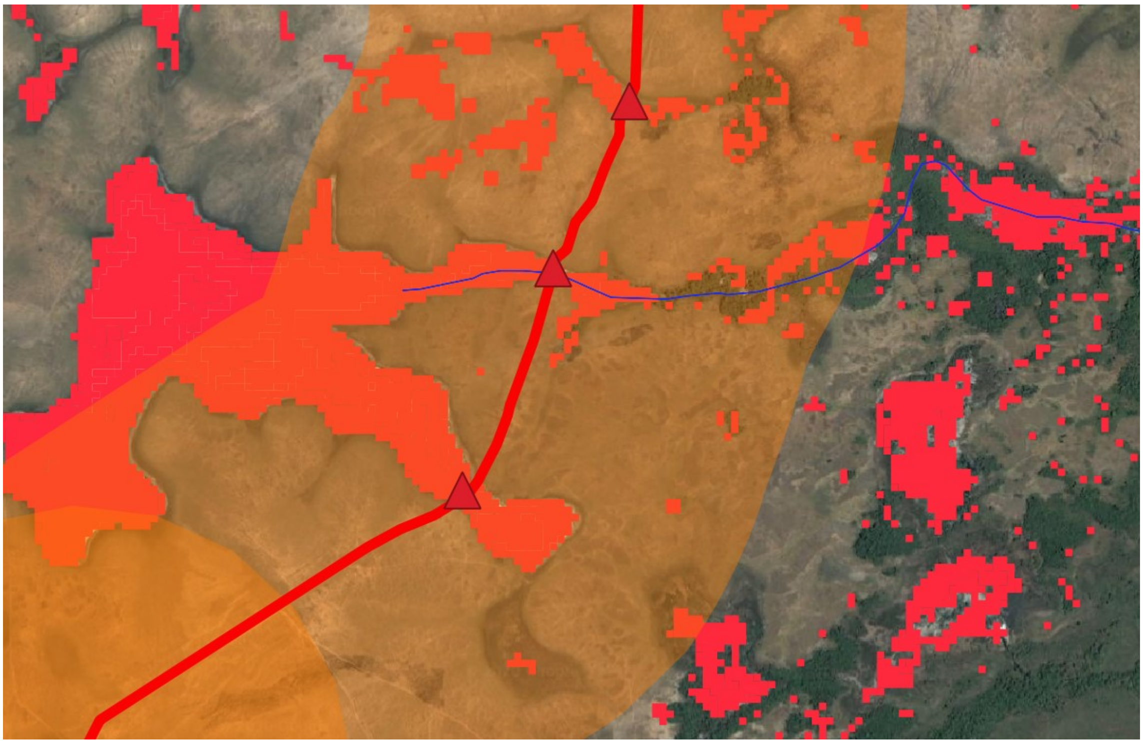

Figure 20 – Example management use of the eco-hydrological sensitivity map along the new road currently being built potentially disrupting wetland habitat surrounding Airstrip Pond

6. DISCUSSION

6.1 This analysis, undertaken within this project, has demonstrated that there is no singular 'neat' hydrological connection between the Ireng and Rupununi rivers, as has been stated in previous studies. The Bonuni and Pirara creeks are important hydrological conduits, but what has not been documented previously is the importance of direct overtopping from the Ireng River into the North Rupununi Wetlands. In the 2017, 2018 and 2019 wet seasons, this direct overtopping was the single most important source of water to the North Rupununi Wetlands.

6.2 Currently, the hydrological input from the Ireng River is being impeded by the Lethem-Georgetown road as the culvert capacity during larger flood events is too low. This impacts the important environmental flows that spread out across the North Rupununi Wetlands. This barrier to flow results in lower volumes of water reaching the wetlands, thus affecting the wetland habitat and fish spawning grounds. This is also an issue for road integrity as significant flood volumes result in major damage to road infrastructure disrupting the road link between Lethem and Georgetown. It is therefore imperative that these water flows are not further impeded to maintain the important environmental flows and to protect road transportation in the region.

6.3 Our findings also indicate that all low-lying wetland areas within the region have the potential to play an eco-hydrological role, especially in support of spawning fishes. The eco-hydrological sensitivity map that illustrates key conservation zones, Figure 19, can be an important tool when assessing future developments. For example, in the past an agricultural project was proposed for the lower catchment area of Pirara Creek involving the damming and extensive flooding of one of its major tributaries, Nappi Creek (Figure 21).

Figure 21 -A plan for a proposed agricultural centre, showing the extensive area of flooding which will result from the damming of Nappi Creek. Note also the location of the agricultural area (in green and light blue)

6.4 The analysis of the proposed agricultural research station location with the satellite interpretation data indicates that it would be within the July 2017 floods in the lower Pirara catchment (Figure 22). Damming the Nappi Creek and converting the natural habitat of a significant proportion of Pirara creek into industrial agriculture, would prevent fish from accessing a key spawning area. This is especially important in years, such as 2017, when only part of the North Rupununi Wetlands was flooded.

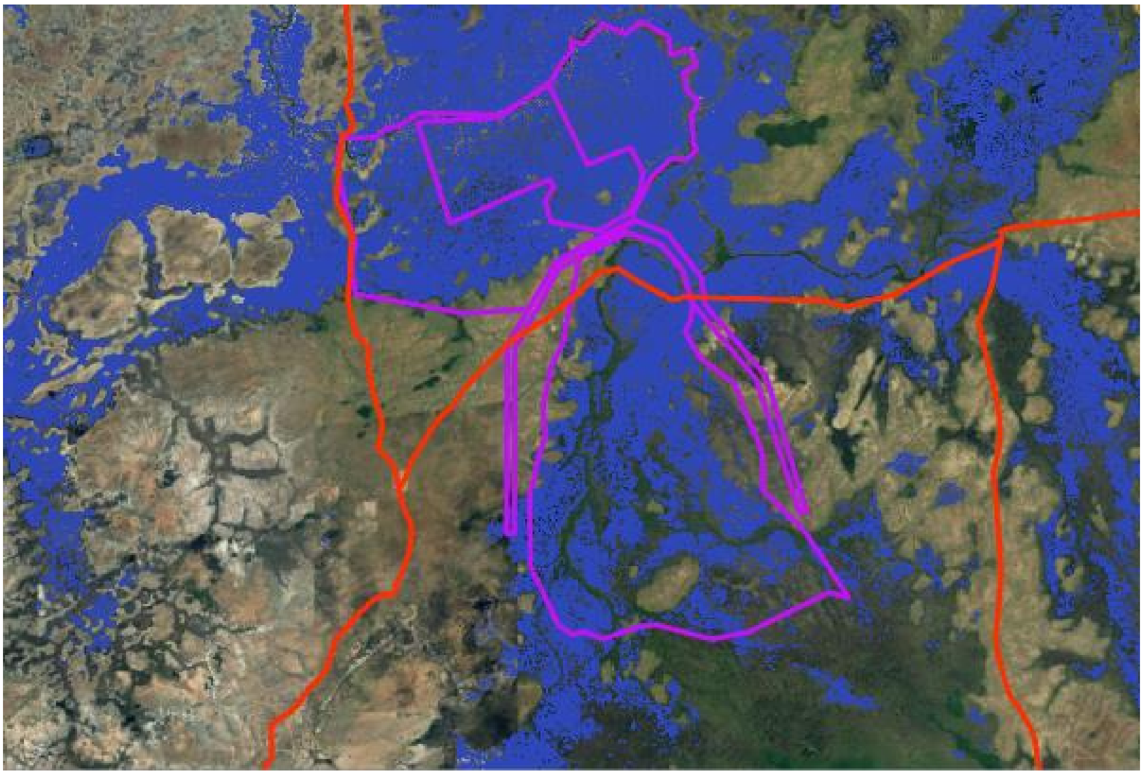

Figure 22 -Footprint of the proposed agricultural centre and associated reservoir on the 2017 flood extent

6.5 Another new regional development has been the construction of a new road from Toka to Lethem, improving access for villages such as Yupukari. This road was under construction during the drone surveys in February 2020. This, like the main Lethem to Georgetown road, has the potential to become a hydrological barrier to the key flow pathways sustaining the North Rupununi Wetlands. Figure 23 illustrates the route of the road in purple and where the potential barriers to flow could occur. The project team has previously advised that six bridges across major creeks, including Bonuni and Pirara tributaries, are required and a minimum of 57 smaller bridges or culverts are required to maintain flow pathways and habitat connectivity. The drone data collected, in February 2020, now provides the ability to determine in detail where eco-hydrological barriers could occur and to illustrate these in detail (Figures 24 to 25). Figure 26, was provided in the past, to give guidance on culvert and bridge design for proposed road construction that would cut across key eco-hydrological connection areas.

6.6 The data collected in this project now provides the ability for future developments to be assessed for their potential impact on the North Rupununi Wetlands. The eco-hydrological sensitivity map provides a straightforward resource to judge whether proposed developments would occur within conservation zones. The drone data, collected in key areas, provides a resource to accurately assess and monitor the impacts of developments on important eco-hydrological flow pathways and the wetlands themselves.

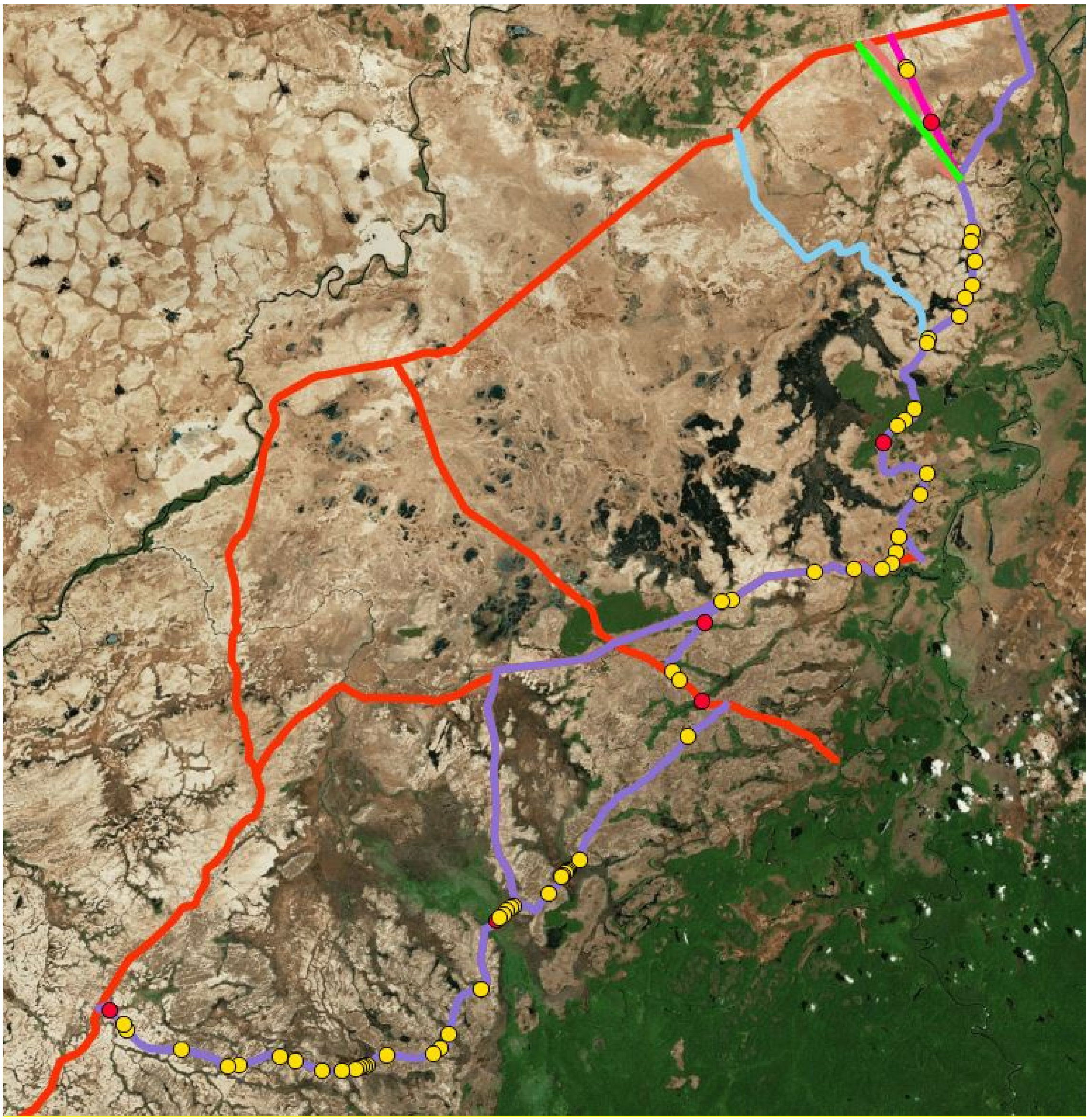

Figure 23 -Path of proposed road in purple across the Rupununi Portal Region. Yellow dots indicate locations required for culverts and red dots indicate bridge locations

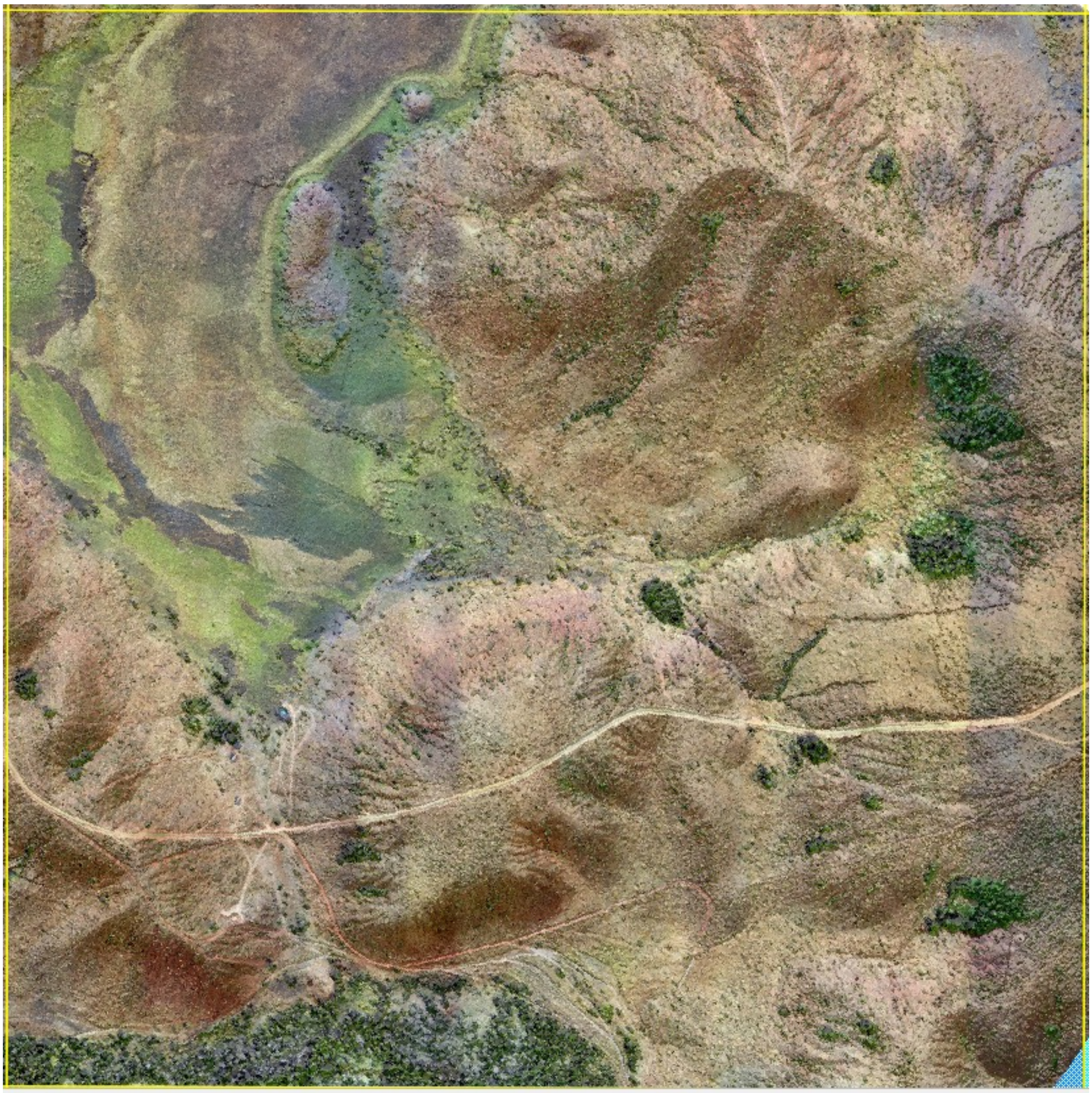

Figure 24 - Aerial image of road construction across eco-hydrological connection

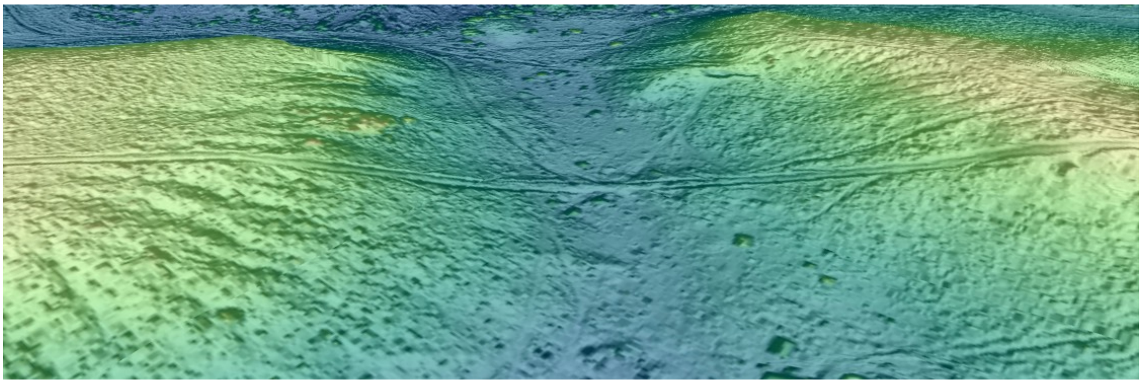

Figure 25 - Oblique view of road construction across eco-hydrological connection

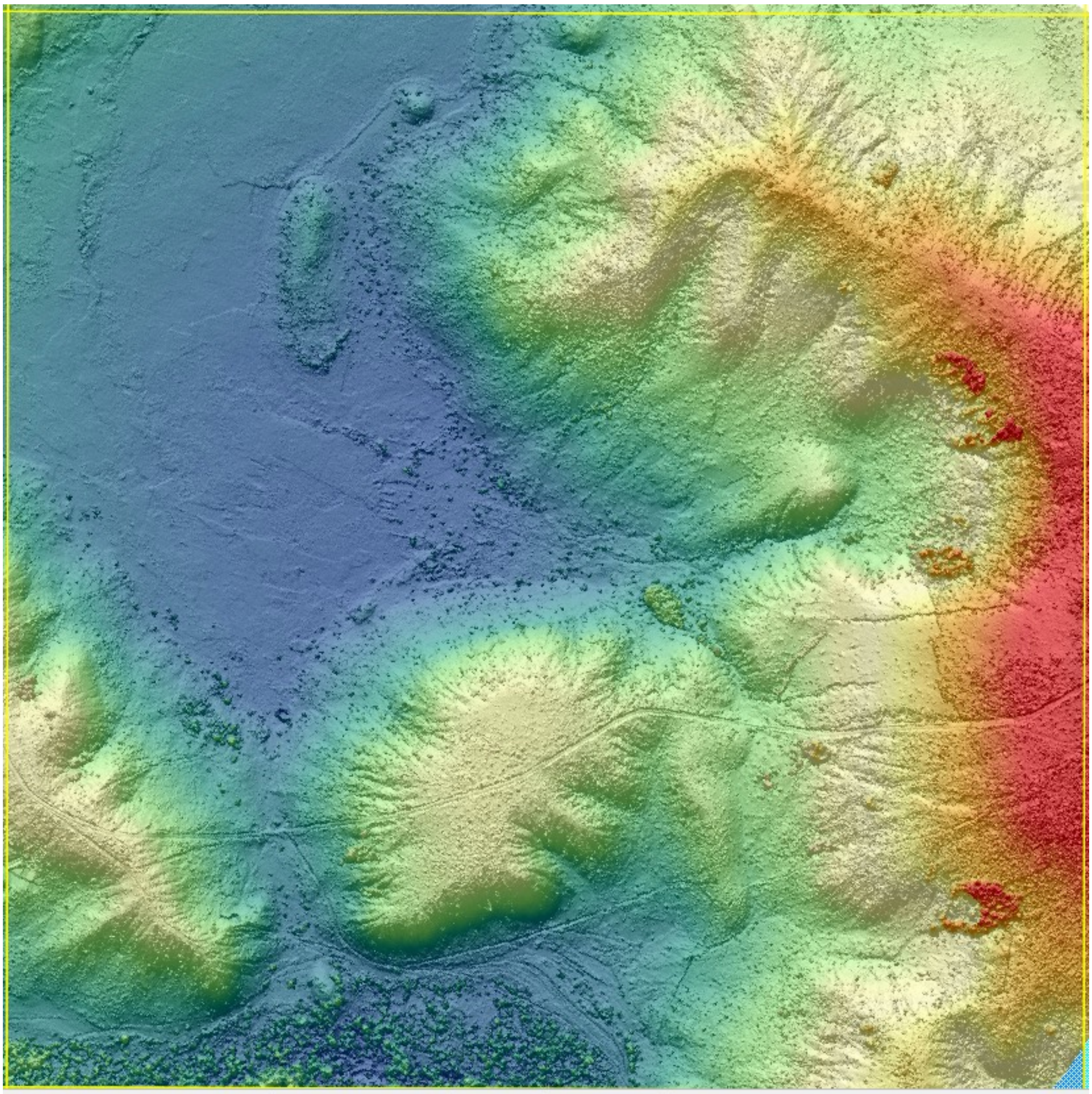

Figure 26 - Digital elevation model of road construction across eco-hydrological connection

Figure 27 -Road design and construction advice

The design and construction of a road when it crosses low elevation areas should never just be an elevated, embanked road. It is vital that bridges and culverts are used in these areas to prolong the life of the road, reduce flood risk and maintain ecological connectivity. The design of individual bridges and culverts is important to reduce the potential flood risk associated with these structures and is essential to maintain hydrological connectivity and ecological integrity. It is important to consider the size, slope, and route of the existing flowing water when installing a culvert or bridge as:

- Wetland, creeks and rivers are dynamic with some features having periods of no flow, low flows and flood flows. Road design but particularly bridge and culvert design has to allow for all of these flow conditions. Often focus is on the high, flood flow conditions but the construction should also ensure that low flow connections are still maintained and the slope and gradients of wetland depressions, creek and river channels, after construction, are restored to the original condition to maintain hydrological connection during low flow conditions. These low flows are essential for all biodiversity but particularly for invertebrates and fish migration.

- It is important to avoid using culverts as much as possible as these can become blocked easily. Bridges should be the preferred option and culverts only used as a last resort.
- Under-sizing a bridge or culvert can restrict river flow and increase flood levels locally on the upstream side. Water backing up behind a structure can also bypass the channel and travel down alternative flow paths e.g. roads, creating flood risk to other areas. All designs should demonstrate that they can accommodate a flood flow comparable to a 1 in 200 year flood event as a minimum.
- The chance of failure increases if the bridge or culvert is poorly designed. It needs to have adequate erosion protection so that it does not erode or collapse. Bypassing can be a particular problem with culverts if they are not sealed and protected correctly. Poor design and installation can rapidly lead to the water flows eroding around culverts, undermining the road and leading to failure.

The following basic design principles should be used for bridge design:

- The structure should be designed to convey peak flood flow (1 in 200 year flood event as a minimum) and maintain low flows.
- A suitable freeboard should be included to allow for extra capacity during extreme floods and potential blockage from debris.
- The design of any in-stream structures e.g. piers; should not encourage the deposition of sediment or debris. A clear span bridge is recommended where possible.
- The design of any in-stream structures should not cause erosion to the bed or banks or direct flows towards the banks thus causing erosion as the additional sediment can be deposited downstream thus increasing flood risk.
- The design of the structure should not result in any narrowing of the channel or the floodplain of the channel's width.
- The provision of a safe overland flow path, should be part of the design, should the bridge capacity be exceeded.

The following basic design principles should be used for culvert design:

- The structure should be able to convey peak flood flow (1 in 200 year flood event as a minimum) and maintain low flows.
- A suitable freeboard should be included to allow for extra capacity during extreme floods.
- A safe overland flow path should be designed so that if the culvert capacity is exceeded water is directed away from damaging the road.
- There should be no hydraulic drop at the culvert inlet or outlet as this encourages sediment deposition and increase the risk of blockage to the culvert and flood water bypassing the structure.
- The culvert base shall be below the natural bed level, and the natural bed level maintained. Placing a culvert on top of the natural bed level could result in the structure being undermined and flood water bypassing the structure.
- The approach channel to the culvert (and outlet) should be suitably straight to reduce the risk of blockage and sediment deposition.

7. NEXT STEPS

Developing an Integrated Landscape Management Plan

7.1 Multiple organizations have initiated a process to develop an integrated landscape management plan for the North Rupununi Wetlands. After consultation with key stakeholders, the following sections have been determined with respect to governance, detailed survey and capacity building requirements that would assist in the development of an integrated landscape management plan.

Adaptive management planning

7.2 Adaptive management planning - Ideally an adaptive management plan would be developed using a participatory approach, representing all stakeholders. A nested approach that has multiple scales included within it from village plans to regional plans covering sectors such as community livelihoods, conservation, tourism, agriculture, mining, aquaculture etc. would be required. Following an adaptive approach, it would then be implemented, monitored, evaluated and updated on a regular basis to respond to internal and external drivers such as climate change etc. Before the plan can be developed certain baseline technical information needs to be collected (see below). These data could then inform a plan development process.

Planning principles and guidelines

7.3 To support the integrated landscape management plan a set of planning policies and guidelines would ideally be established to set the boundaries for decision making. These help regulate development, ensure sustainability, and would help speed up planning decision making.

North Rupununi Wetlands Planning Committee

7.4 A committee or set of committees would need to be established to review planning decisions. Ideally these have representatives from all stakeholders – this committee(s) could then provide recommendations to government. Ideally the committee(s) also adopt an adaptive management approach that monitors and reviews decisions with full evaluation so that lessons can be learnt for the future. It is important that this is not undertaken in the traditional EIA approach with token consultation with communities. Communities need to be fundamentally part of decision making within these committees.

Capacity requirements

7.5 The following technical skills and experience are required to ensure success of a plan for the North Rupununi Wetlands:

- Trained facilitators that can develop an integrated landscape management plan with multi-stakeholders through a participatory approach
- Technical and legal expertise to develop and draft planning guidance
- Trained facilitators that can deliver planning decisions through an adaptive management, participatory approach
- Trained technical staff that can undertake drone surveys, differential GPS surveys, satellite interpretation and GIS analysis to develop digital terrain models and hydrological drainage plans
- Trained technical staff that can undertake water level and water quality monitoring and analysis. This type of monitoring can be undertaken at a community level as well as via government staff
- Trained technical staff that can undertake ecological surveys. This type of monitoring can be undertaken at a community level as well as via government staff

- Trained technical staff that undertake socio-economic surveys. This type of monitoring can be undertaken at a community level as well as via government staff

Data requirements

7.6 To support the development of an integrated management plan, the evaluation of any proposals and the monitoring of impacts a set of baseline information is required. This project helped initiate data collection but the following is still required.

7.7 **Hydrological monitoring** – The current project has further refined understanding of the hydrological mechanisms for flooding and water movement across the North Rupununi Wetlands. Extent of inundation and flow pathways have been determined but understanding is still required in terms of hydrodynamics of water levels and flow volumes and relate this to the hydrological mechanism model that has been developed. Water level fluctuations are key to allow species movements and, in particular, are a trigger for fish spawning. Relating flood levels in the main rivers to water levels in different areas of the North Rupununi Wetlands can only be accurately understood with the installation of real-time water level monitoring devices.

7.8 The installation of a network of piezometers that measure shallow groundwater levels and surface water monitoring devices would provide hourly data of water levels to enable an analysis of flooding patterns in the portal area so they can be related to flooding in the various river systems. Installing a network of piezometers, along a series of transects, allows the peizometric head of water to be determined and therefore the direction of sub-surface flow to also be understood. This is important in the North Rupununi Wetlands as many of the soils are highly permeable which indicates that groundwater and surface waters will meet during flood event periods. However, at low flow periods surface water will disappear underground, flowing downslope and connecting to ponds, lakes, and rivers, but crucially also entering the aquifers that many communities rely on for drinking water. The installation of water level monitoring equipment and analysed in relation to the data collected, within this project, would allow the determination of the impacts land use change and climate change will have on the hydrodynamics of the region. It would also improve culvert and bridge design because actual water levels and discharge could be modelled.

7.9 **Baseline water quality data** – Changing land use in the North Rupununi Wetlands and in the wider catchment, that are the hydrological source areas of floodwater, has the potential to impact on surface water and groundwater quality. Land use change includes agricultural expansion, reservoir construction, road improvements, logging, and mining. These all have the potential to impact negatively on the flora and fauna of the region and for the local communities that rely on river water and groundwater to directly impact negatively on their drinking water source. To understand the potential impact of changing land use in the region water quality assessments of key surface water inflows to the North Rupununi Wetlands and community groundwater wells is required. This would provide a baseline of surface and groundwater quality, with threshold levels, to review proposals and projects against. This is potentially expensive if done to a high standard and accredited laboratories are usually required. However, in the short term mobile kits could be used to provide basic information for pH, dissolved oxygen, hydraulic conductivity etc.

7.10 **Baseline ecological data** – Ideally there would be the development of a set of aquatic and terrestrial ecological indicators, with corresponding thresholds, that can be monitored to assess the impacts of any proposed projects. These data would also be useful in promoting tourism. Using the drone surveys of key sites, regular monitoring of habitat extent and changes can now also be undertaken. Regular monitoring of species on the ground can be expensive but it could be a planning requirement for certain projects.

7.11 **Baseline socio-economic data** – There should also be a set of socio-economic indicators, with corresponding thresholds, that can also be regularly monitored to ensure any proposals or projects do not have negative impacts. This can also be expensive and time consuming but it would be important to regularly monitor basic parameters such as health, well-being, livelihoods etc.

8. CONCLUSION

8.1 This report summarises the survey work undertaken using satellite interpretation, drone photo capture and ground-truthing, and analysis used to determine the landscape topographical characteristics, flood dynamics and ecological sensitivity in relation to the hydrodynamics of the North Rupununi Wetlands.

8.2 It has indicated the complex interactions of five hydrological mechanisms supporting water levels within the North Rupununi Wetlands and the importance of overbank flooding from the Ireng River into the wetland area.

8.3 The analysis has allowed the determination of an eco-hydrological sensitivity map to support proposed development planning decisions. In addition, the capture of drone data for key wetland sites allows monitoring and development impact analysis to take place.

8.4 Finally, this report has provided guidance for how an integrated landscape management plan for the North Rupununi Wetlands could be realised.

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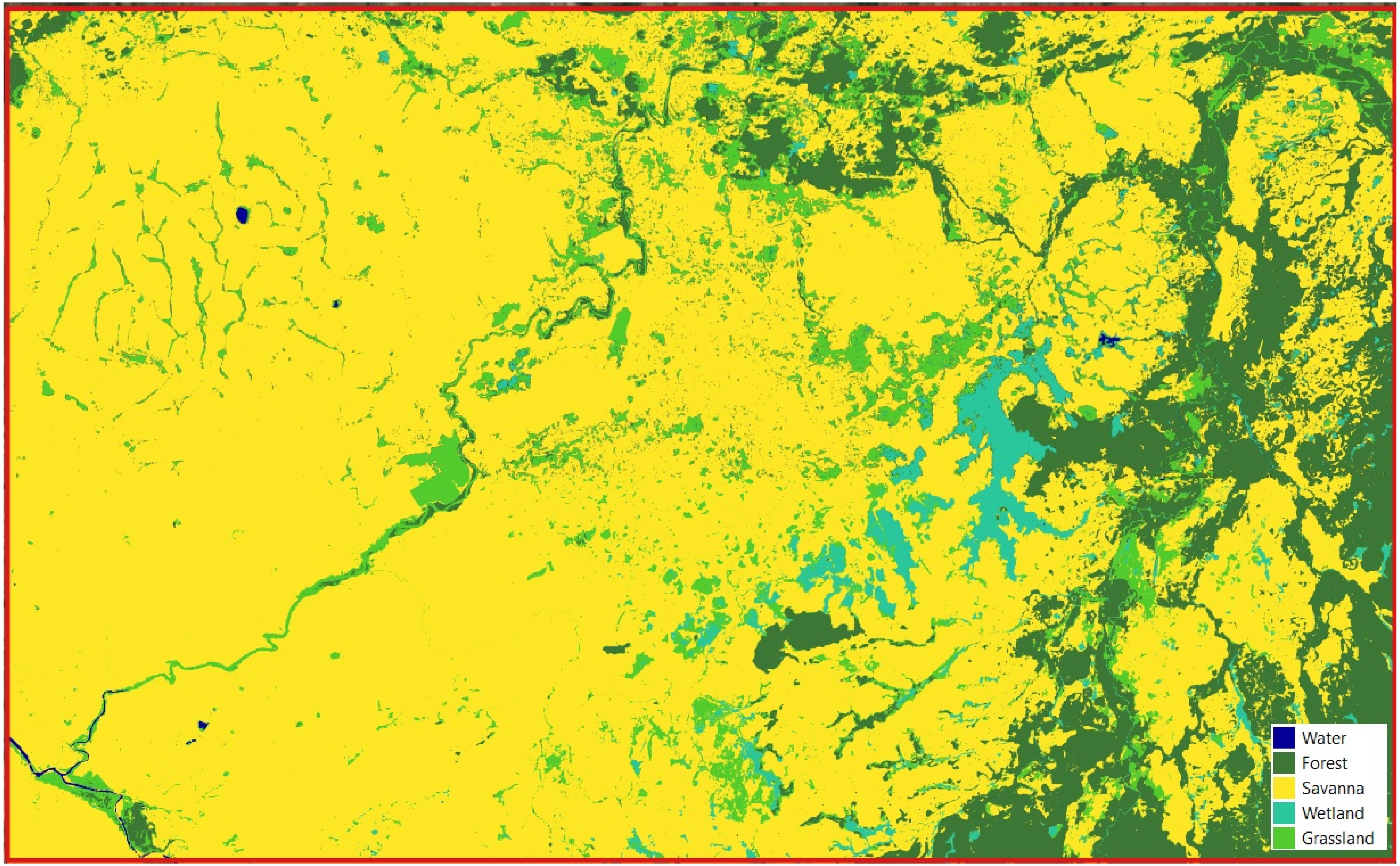
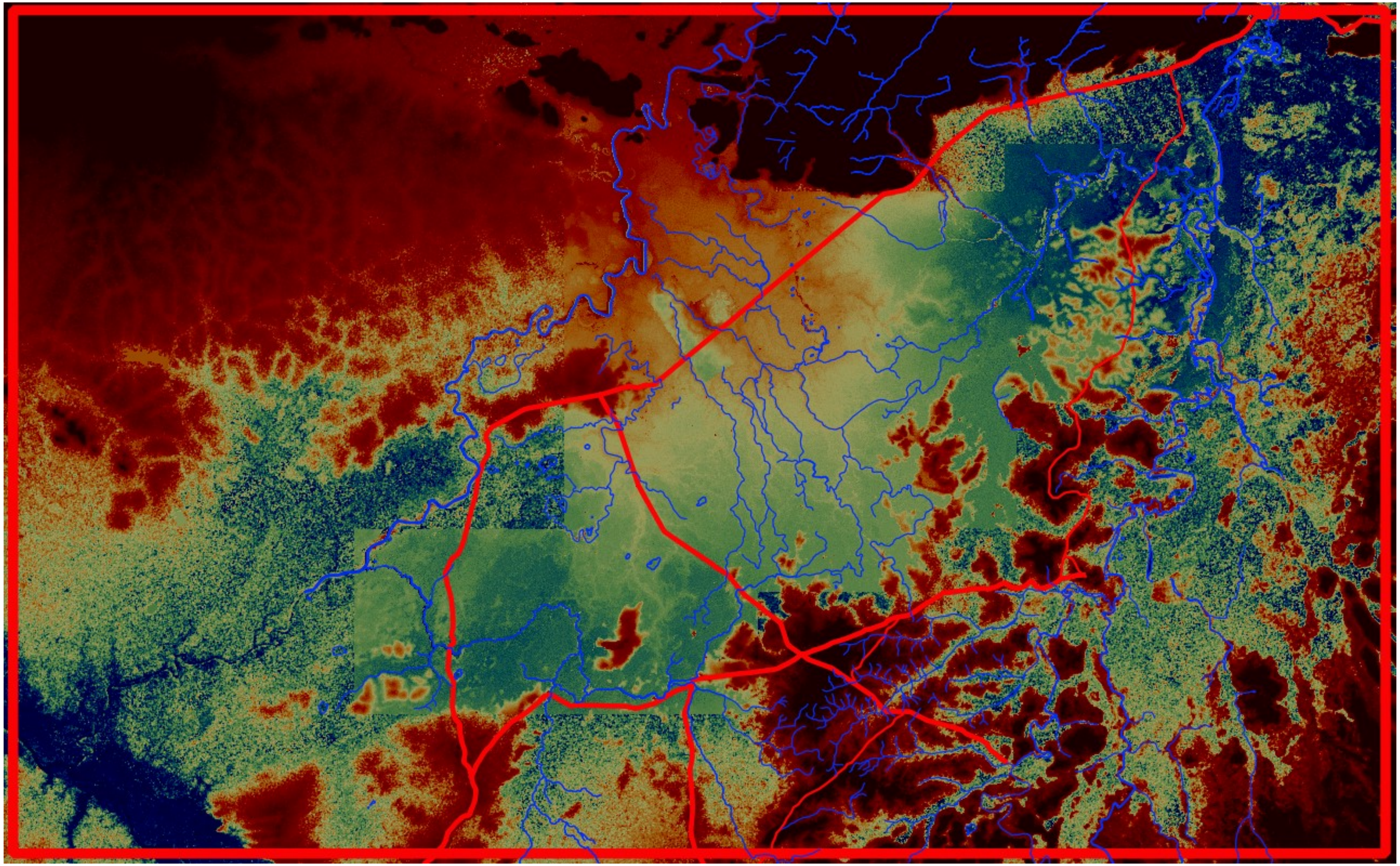
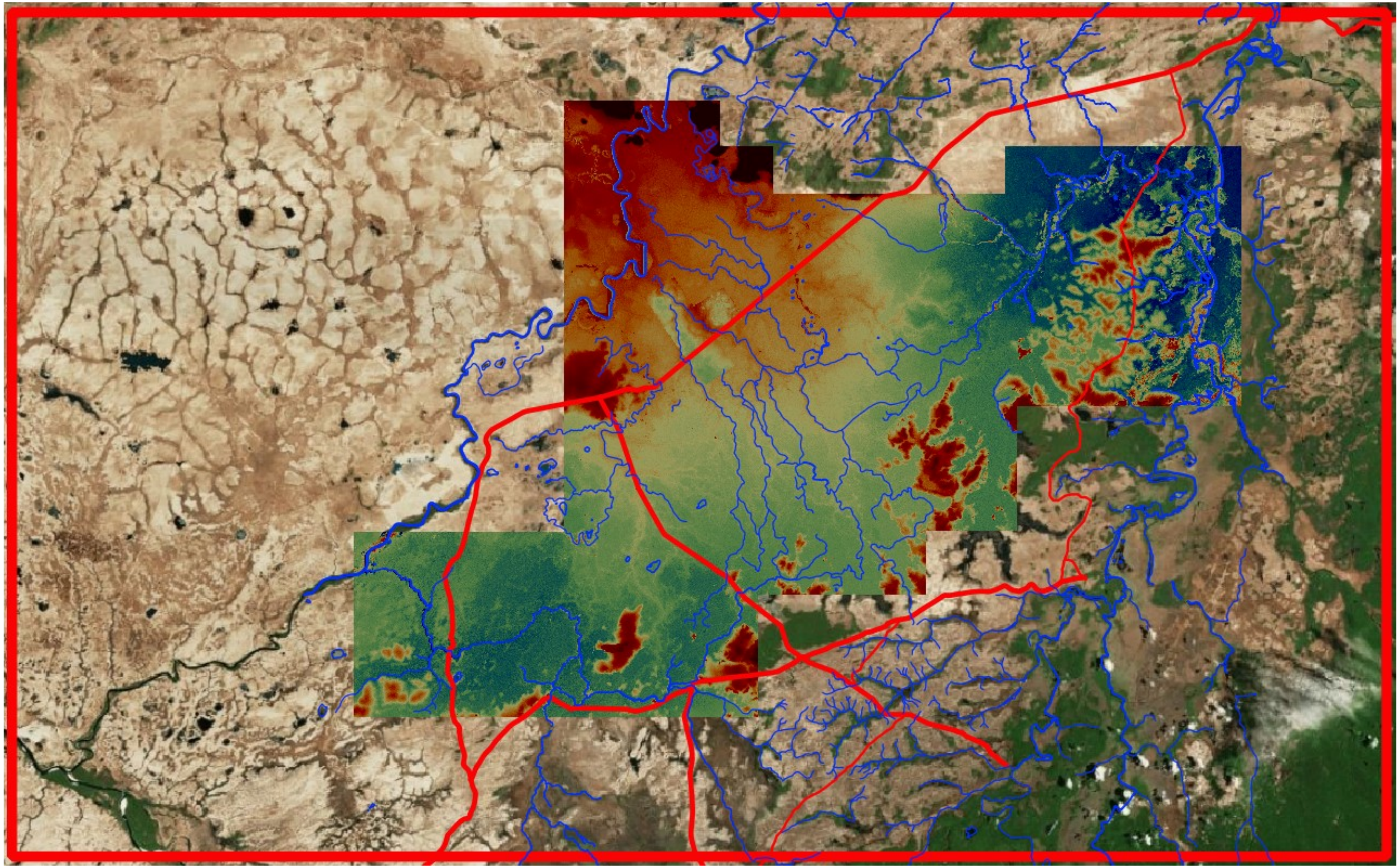
APPENDIX I. Habitat classification



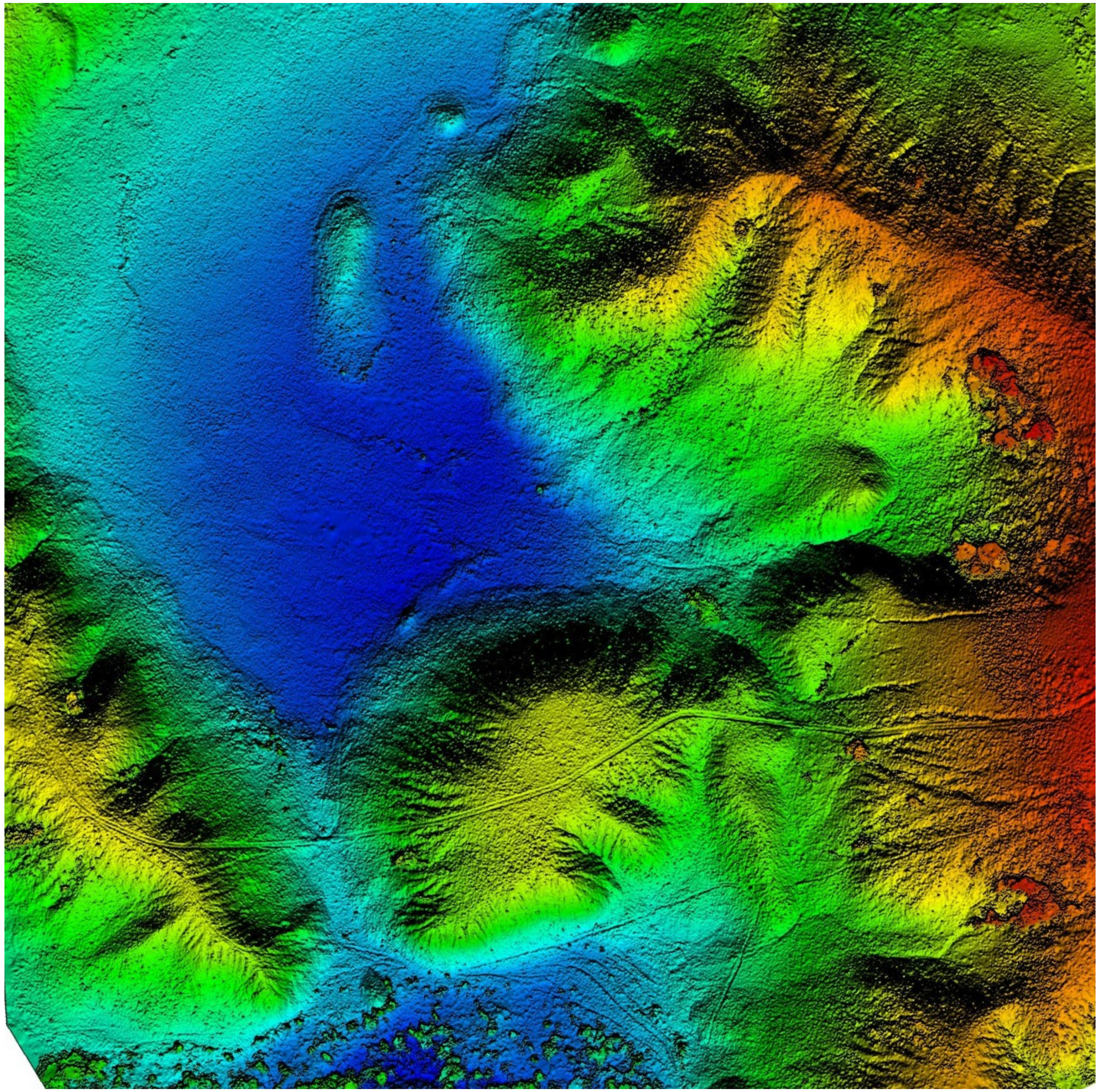
APPENDIX II. Digital elevation model – 30m resolution



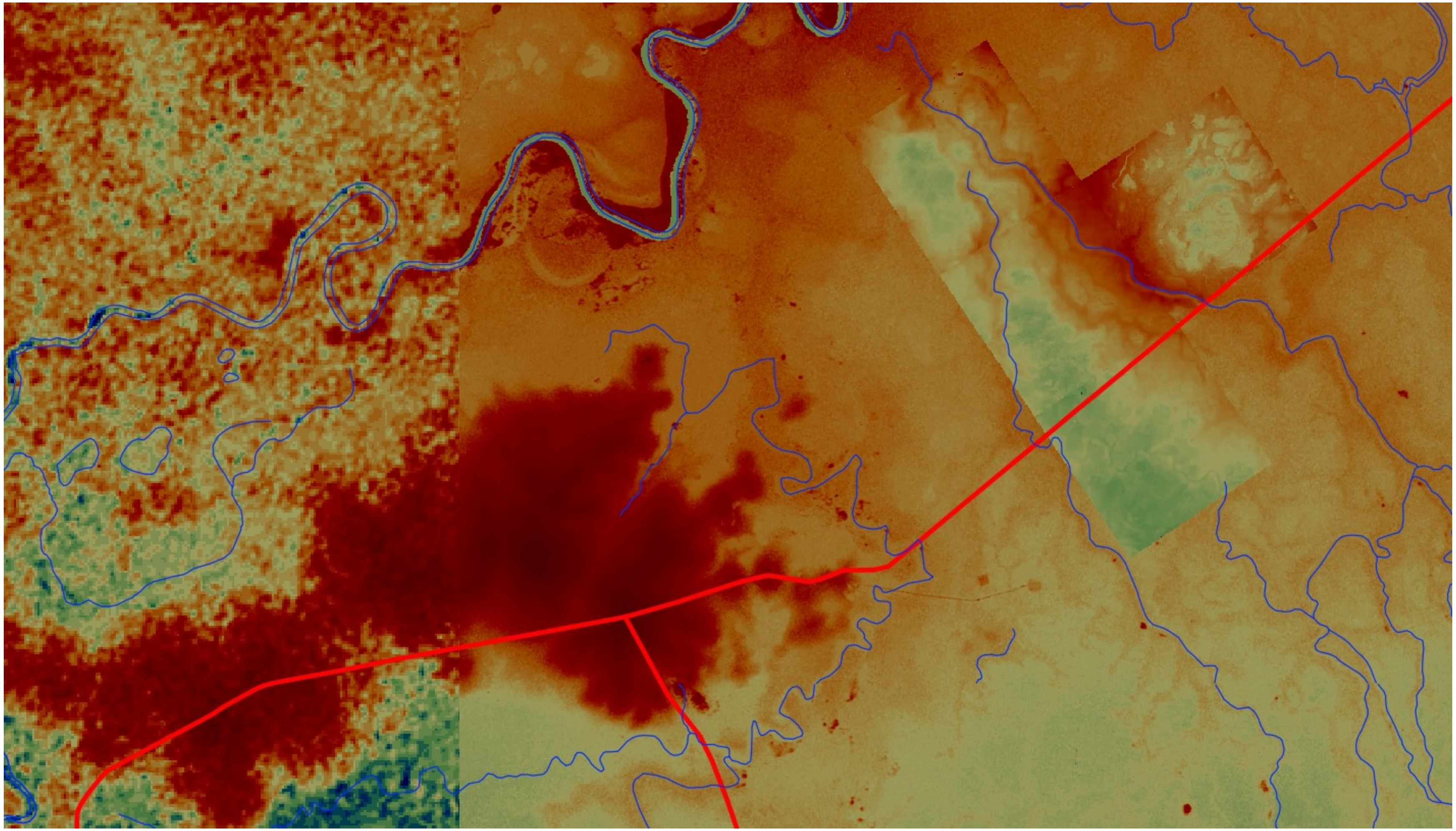
APPENDIX III. Digital elevation model – 12m resolution



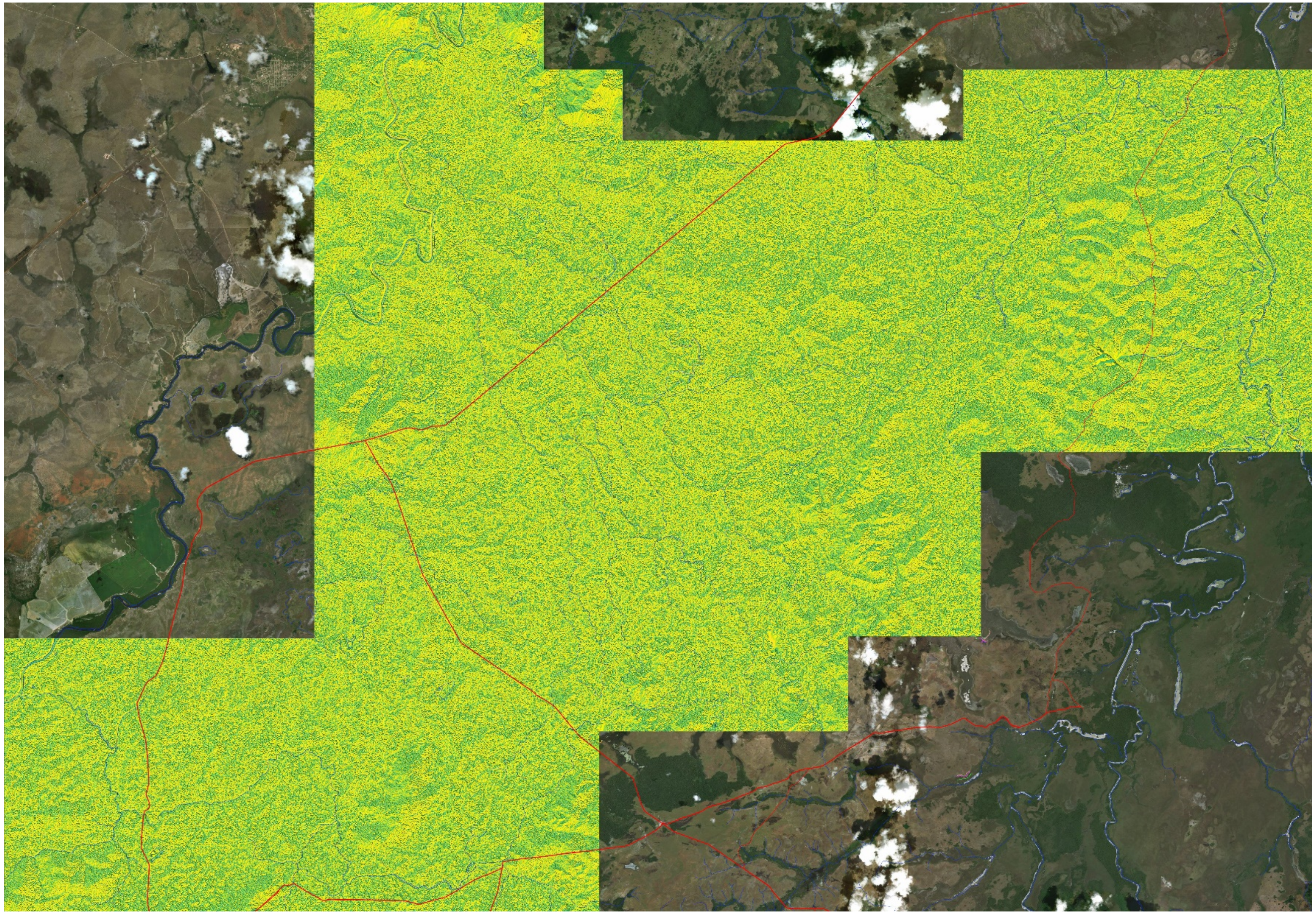
APPENDIX IV. Digital elevation model 10cm resolution example



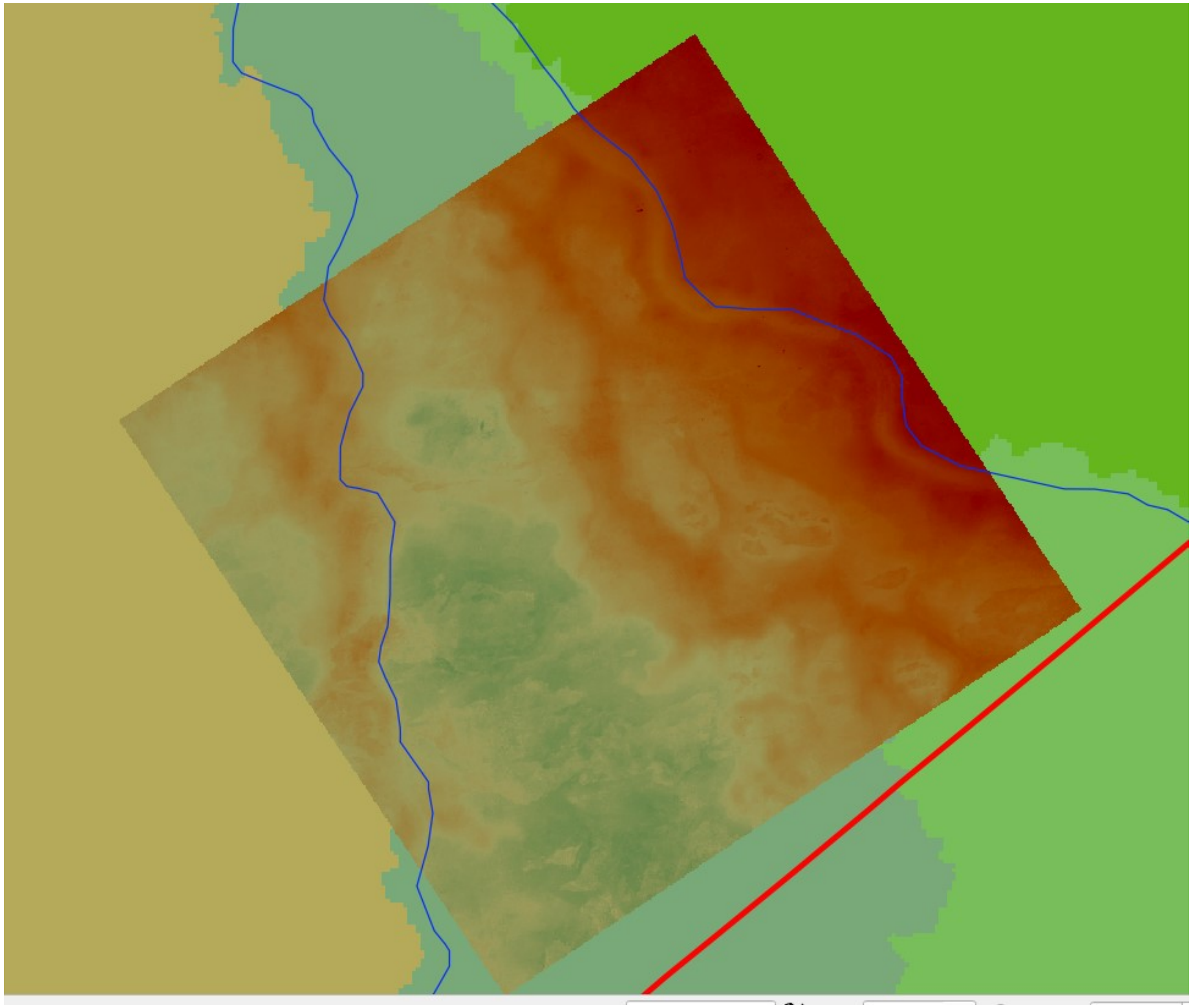
APPENDIX V. Comparison of digital elevation model resolutions



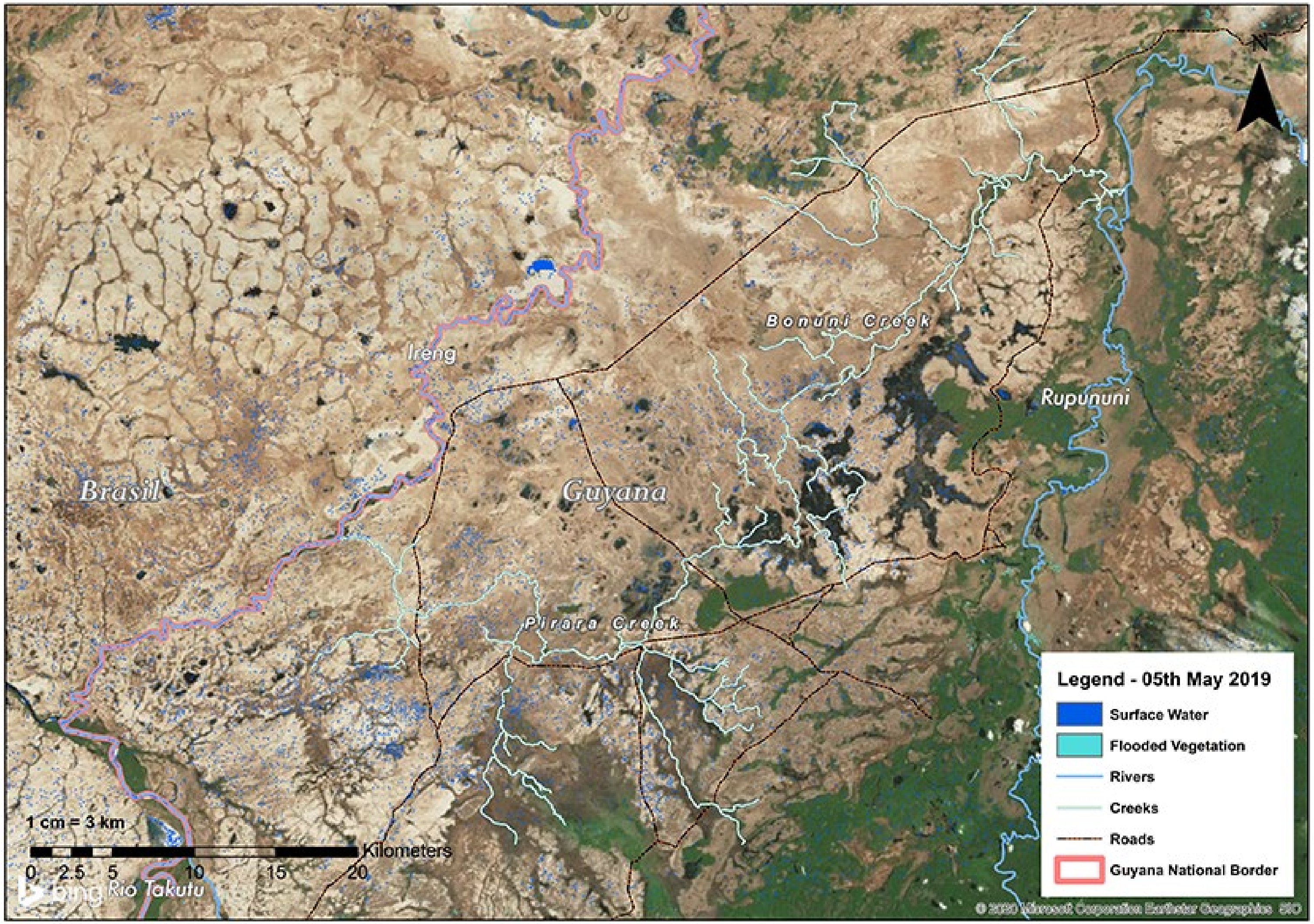
APPENDIX VI. North Rupununi Wetlands slope analysis and drainage pathways

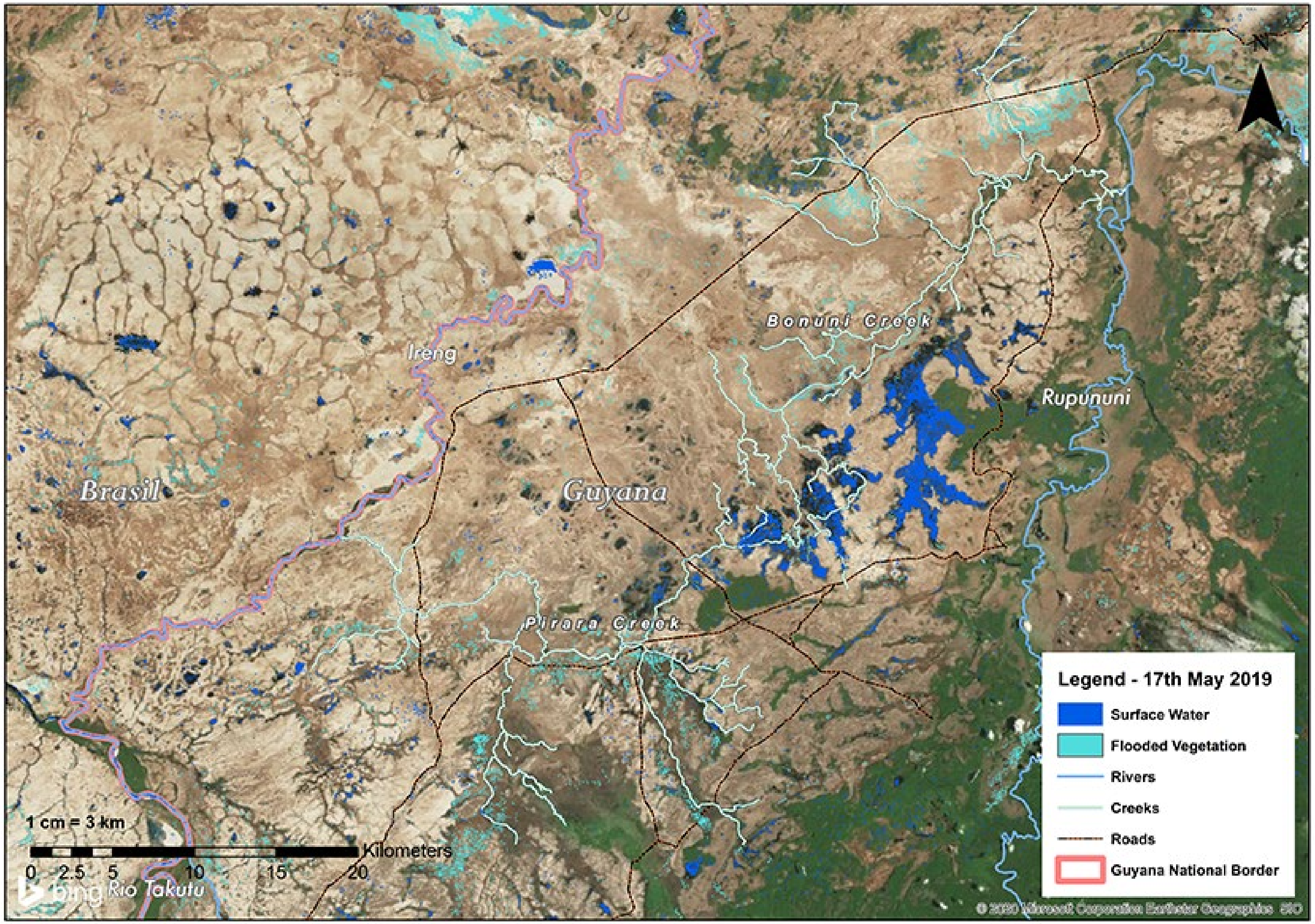


APPENDIX VII. Analysis of 1968 stream mapping

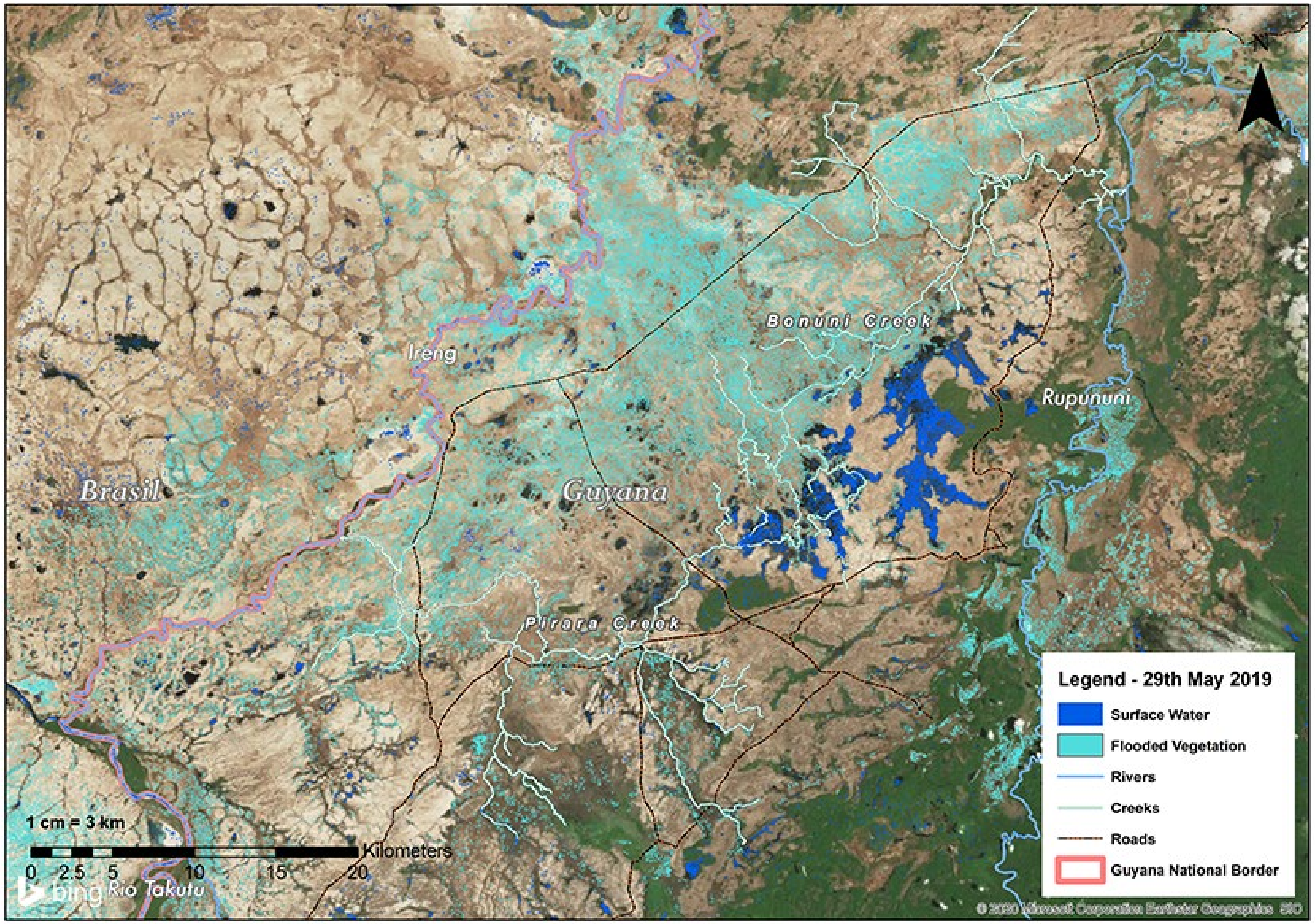


APPENDIX VIII. 2019 flood dynamics of the North Rupununi Wetlands

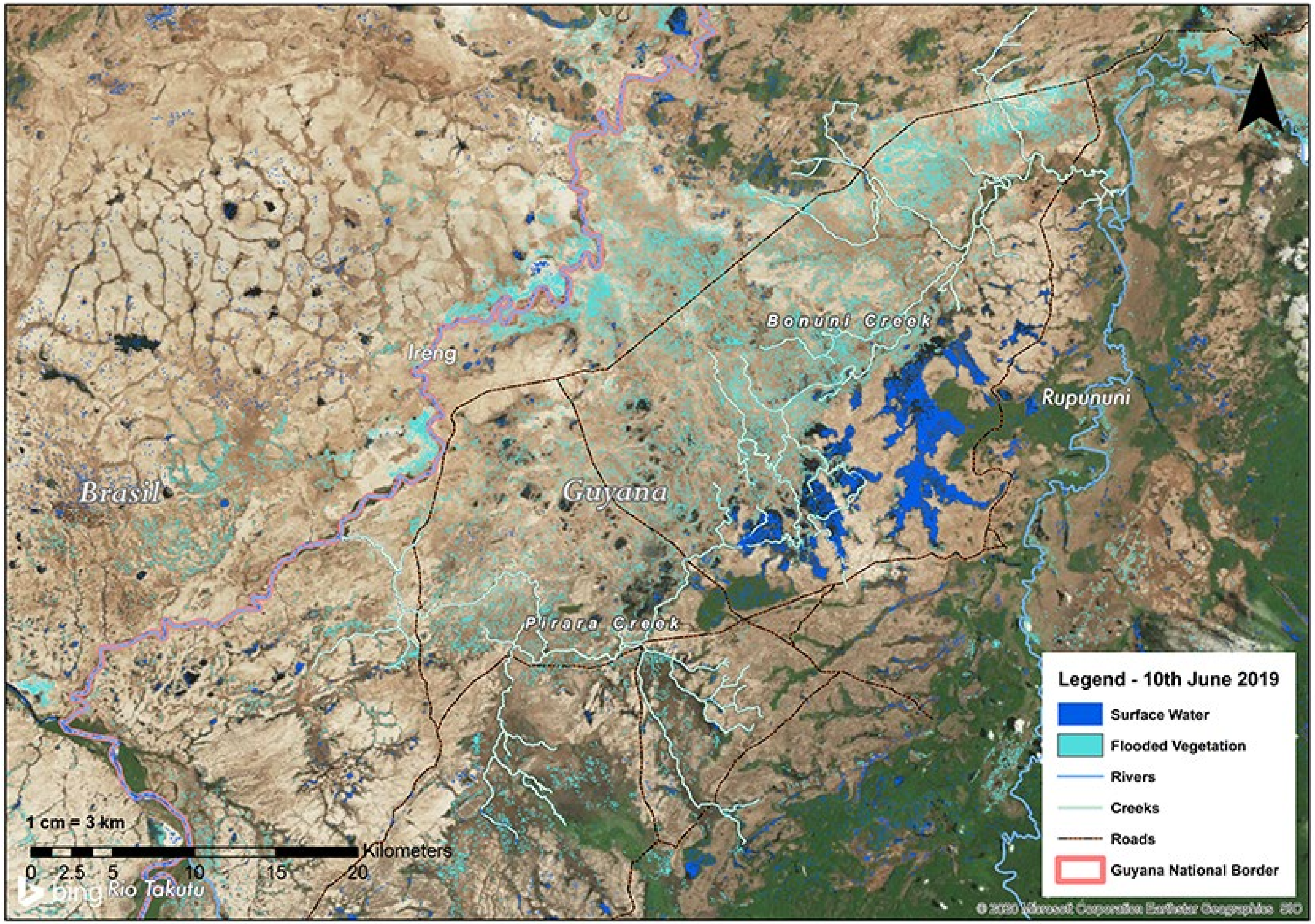


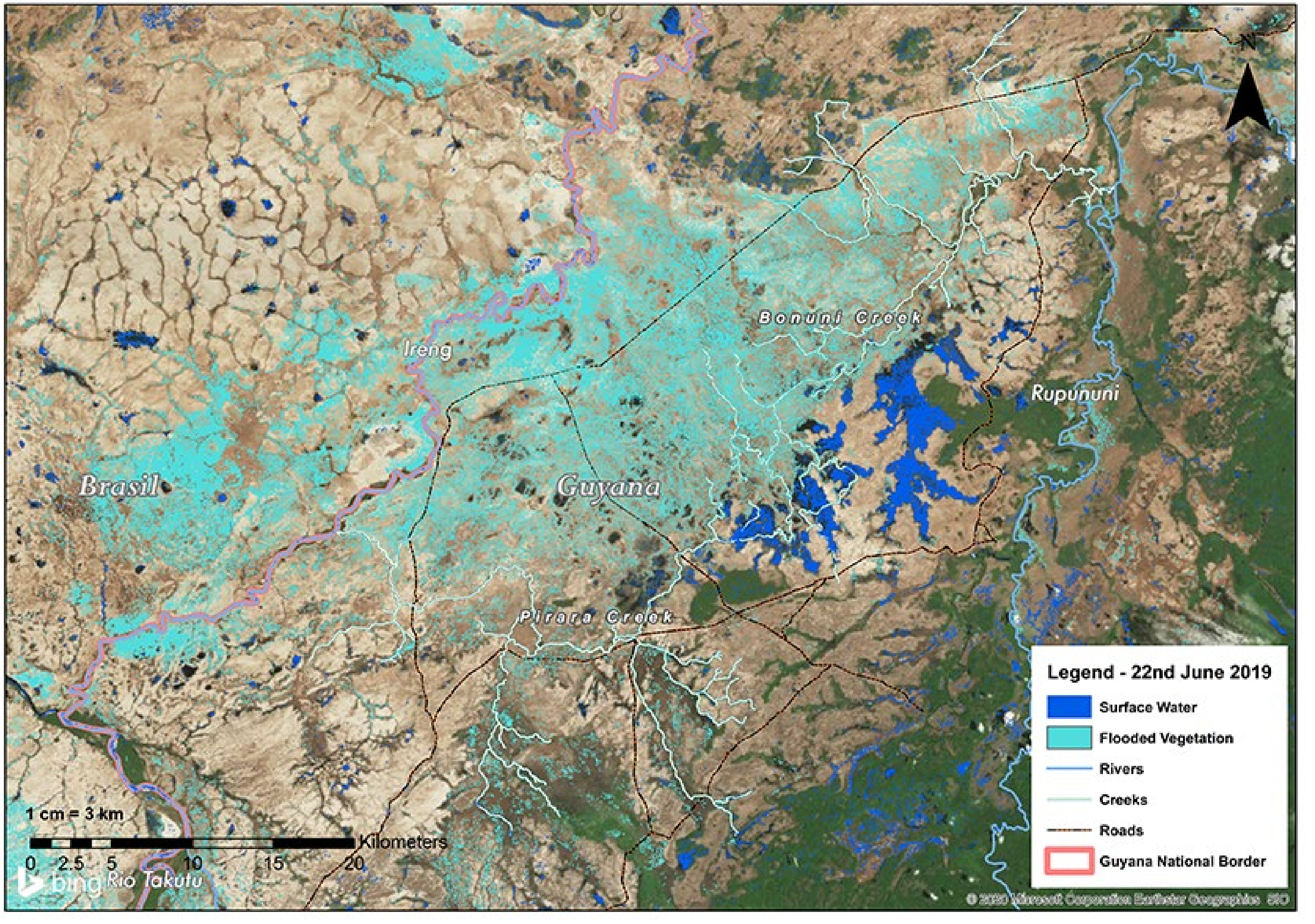


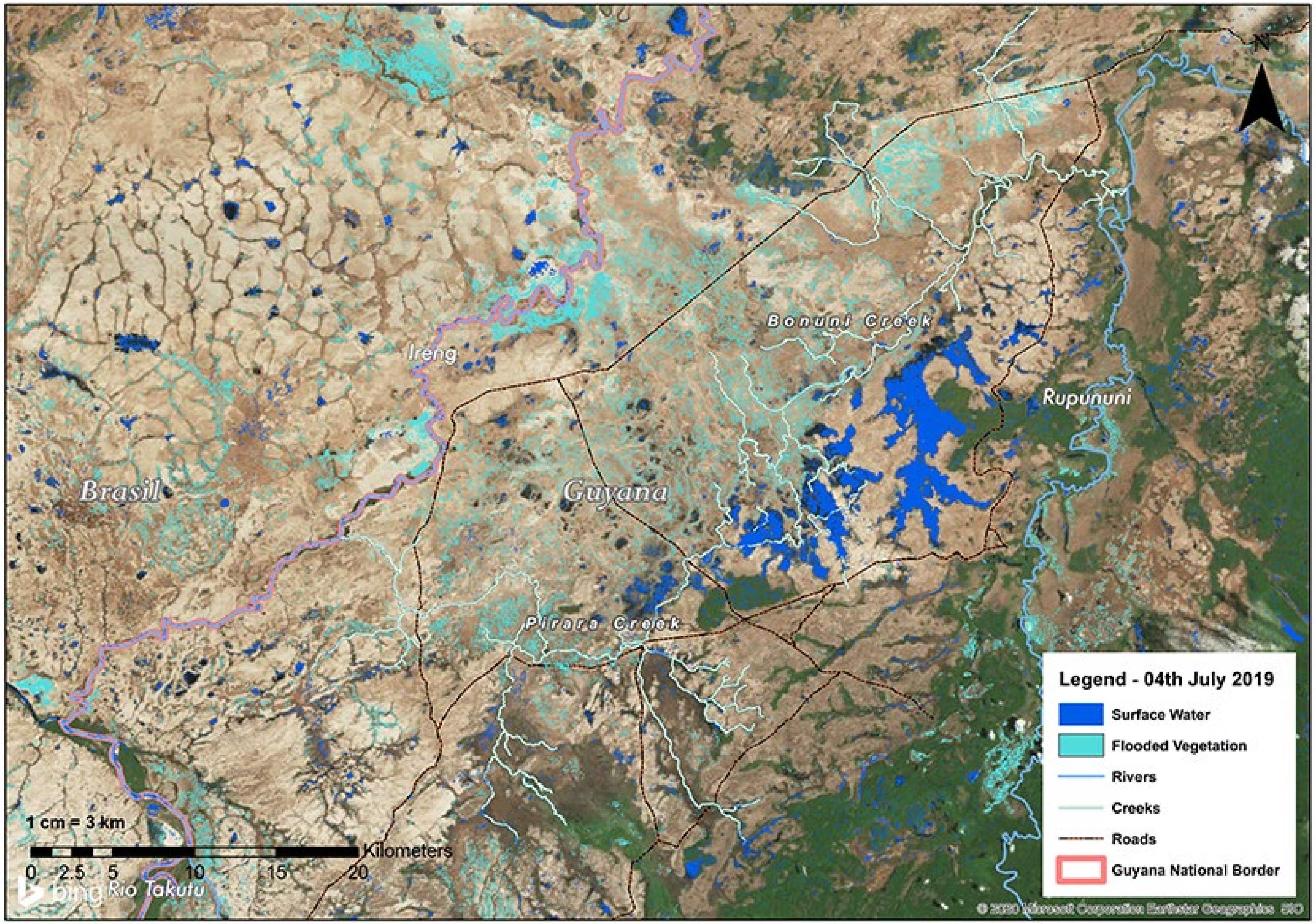
Ireng
Bonuni Creek
Rupununi
Brasil
Guyana
Pirara Creek
Rio Takutu
N
1 cm = 3 km
0 2.5 5 10 15 20
Kilometers
Legend - 17th May 2019
Surface Water
Flooded Vegetation
Rivers
Creeks
Roads
Guyana National Border

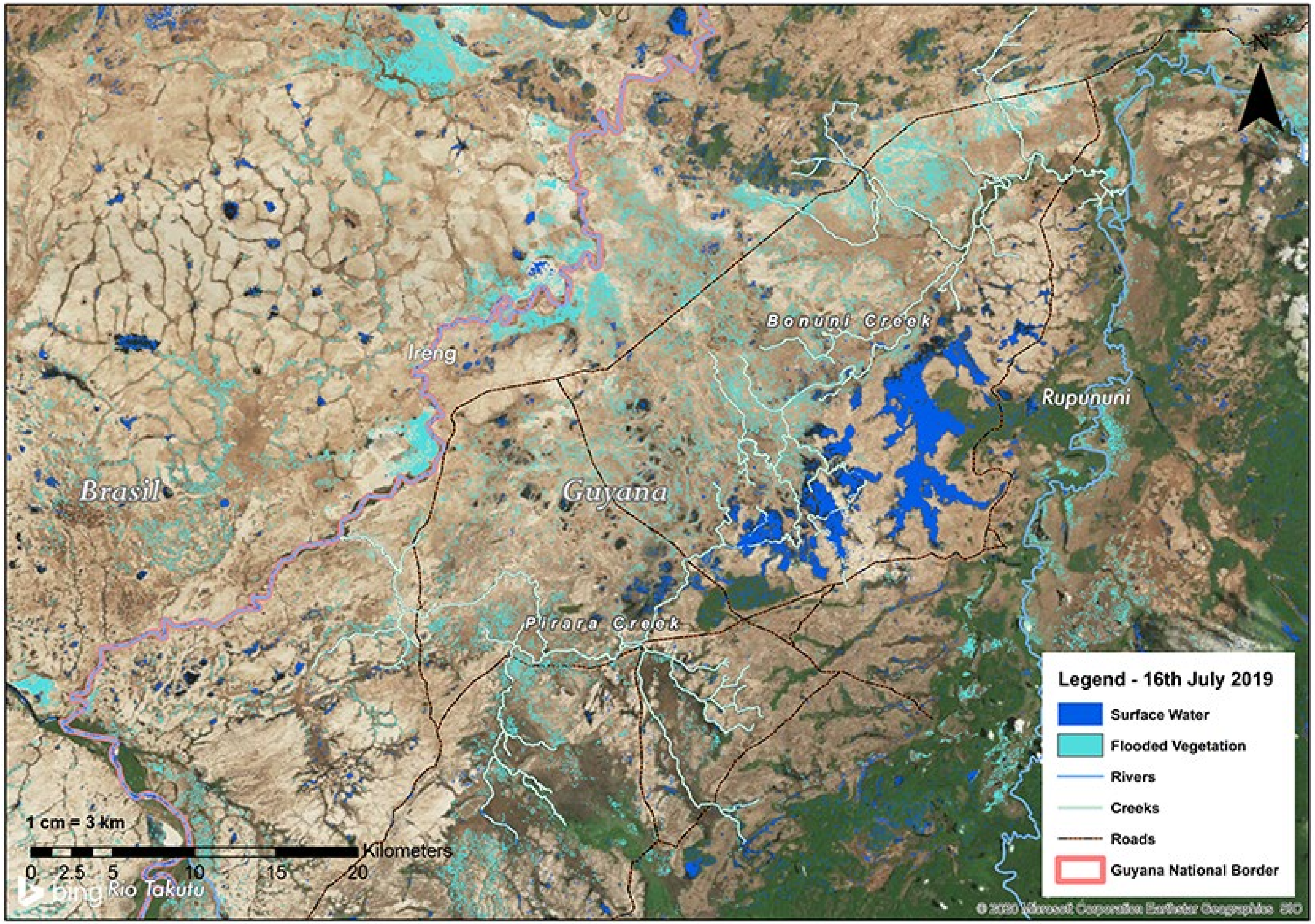


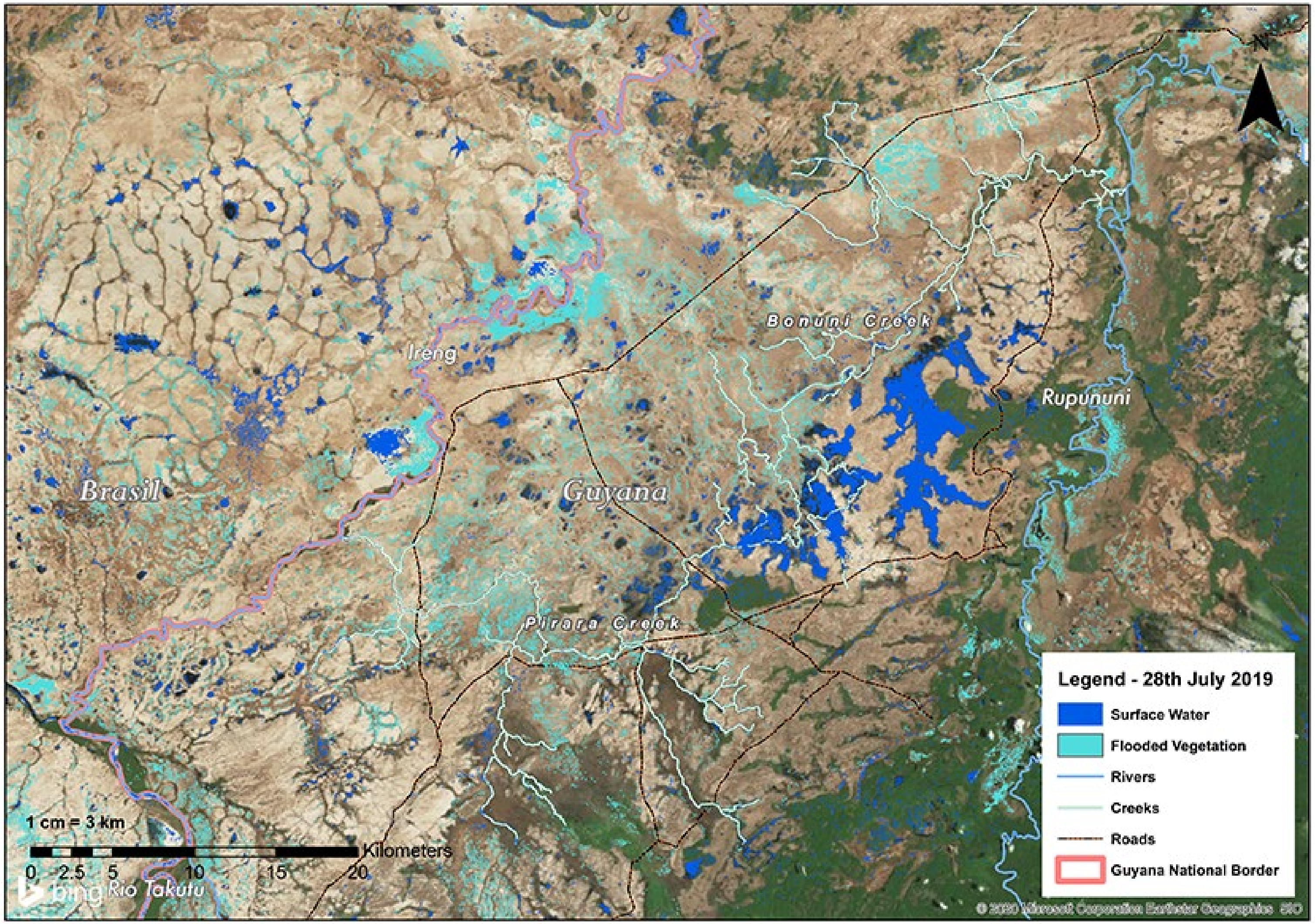
Brasil
Guyana
Ireng
Bonuni Creek
Rupununi
Pirara Creek
Rio Takutu
N
1 cm = 3 km
0 2.5 5 10 15 20
Kilometers
Legend - 29th May 2019
Surface Water
Flooded Vegetation
Rivers
Creeks
Roads
Guyana National Border

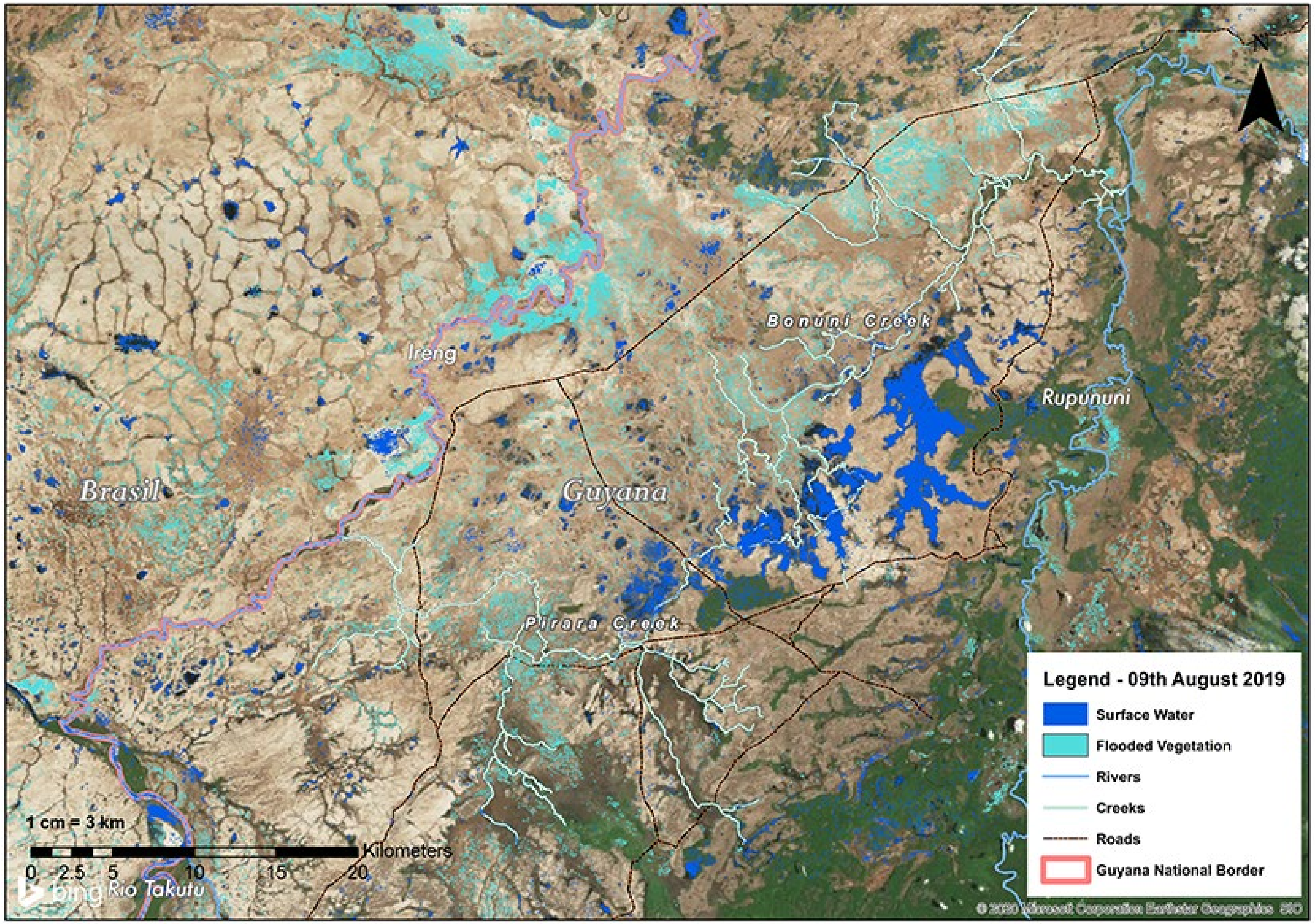

Ireng
Bonuni Creek
Rupununi
Brasil
Guyana
Pirara Creek
Legend - 10th June 2019
Surface Water
Flooded Vegetation
Rivers
Creeks
Roads
Guyana National Border
1 cm = 3 km
0 2.5 5 10 15 20
Kilometers
Rio Takutu
N

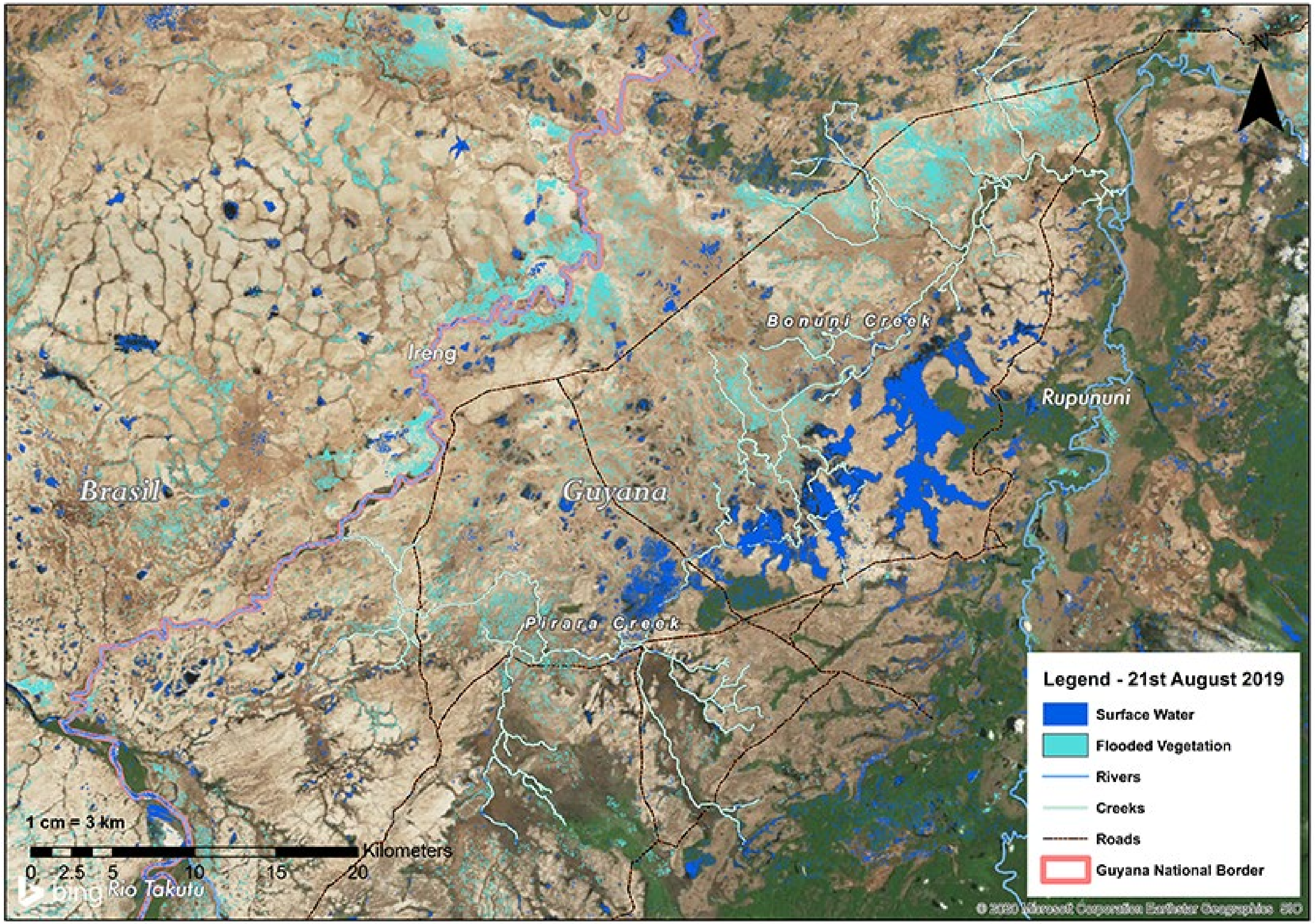

Legend - 22nd June 2019
Surface Water
Flooded Vegetation
Rivers
Creeks
Roads
Guyana National Border
Bonuni Creek
Ireng
Rupununi
Brasil
Guyana
Pirara Creek
1 cm = 3 km
0 2.5 5 10 15 20
Kilometers
Rio Takutu
N

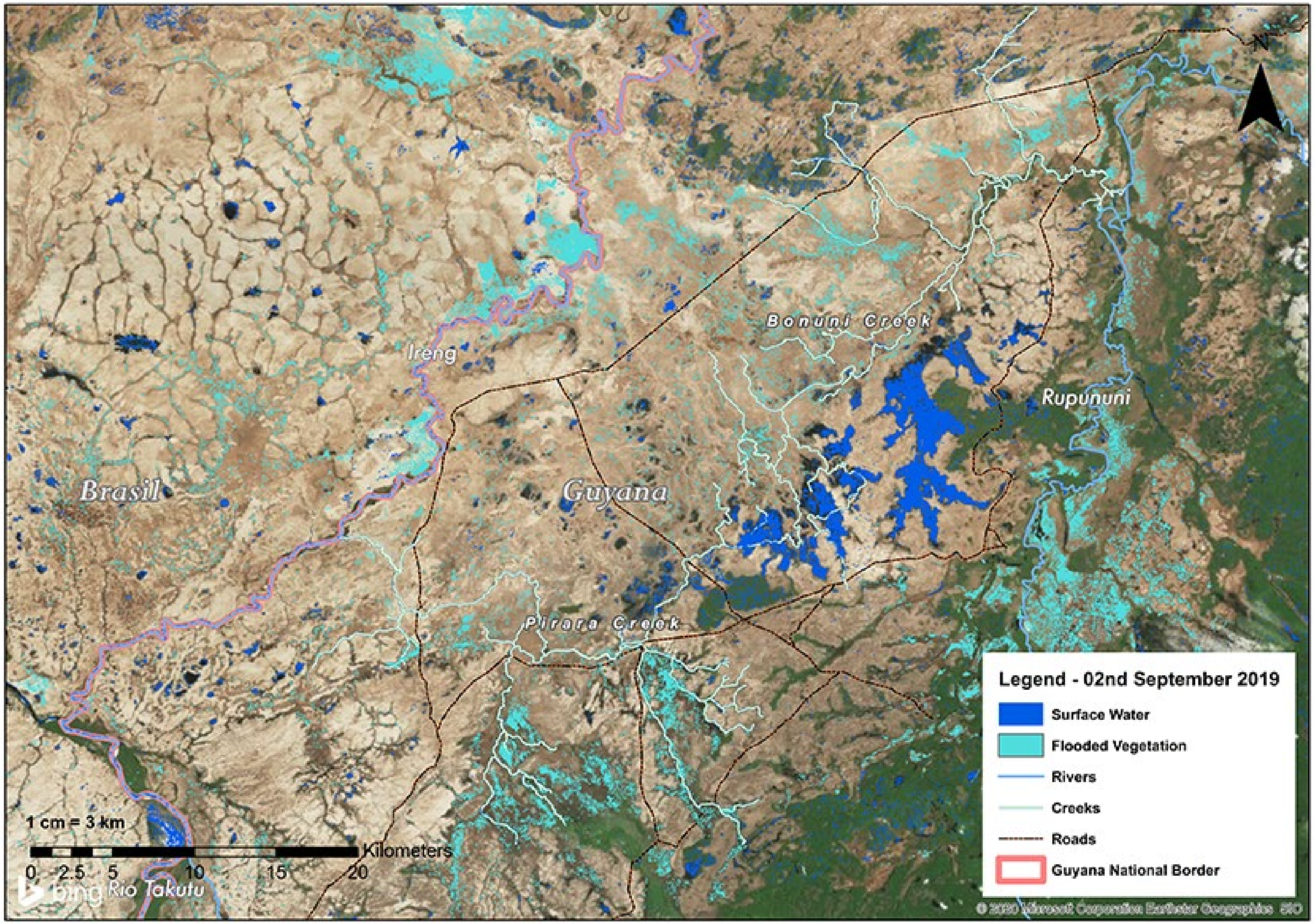

Ireng
Bonuni Creek
Rupununi
Brasil
Guyana
Pirara Creek
Rio Takutu
N
1 cm = 3 km
0 2.5 5 10 15 20
Kilometers
Legend - 04th July 2019
Surface Water
Flooded Vegetation
Rivers
Creeks
Roads
Guyana National Border


Ireng
Bonuni Creek
Rupununi
Brasil
Guyana
Pirara Creek
Rio Takutu
1 cm = 3 km
0 2.5 5 10 15 20 Kilometers
Legend - 16th July 2019
Surface Water
Flooded Vegetation
Rivers
Creeks
Roads
Guyana National Border

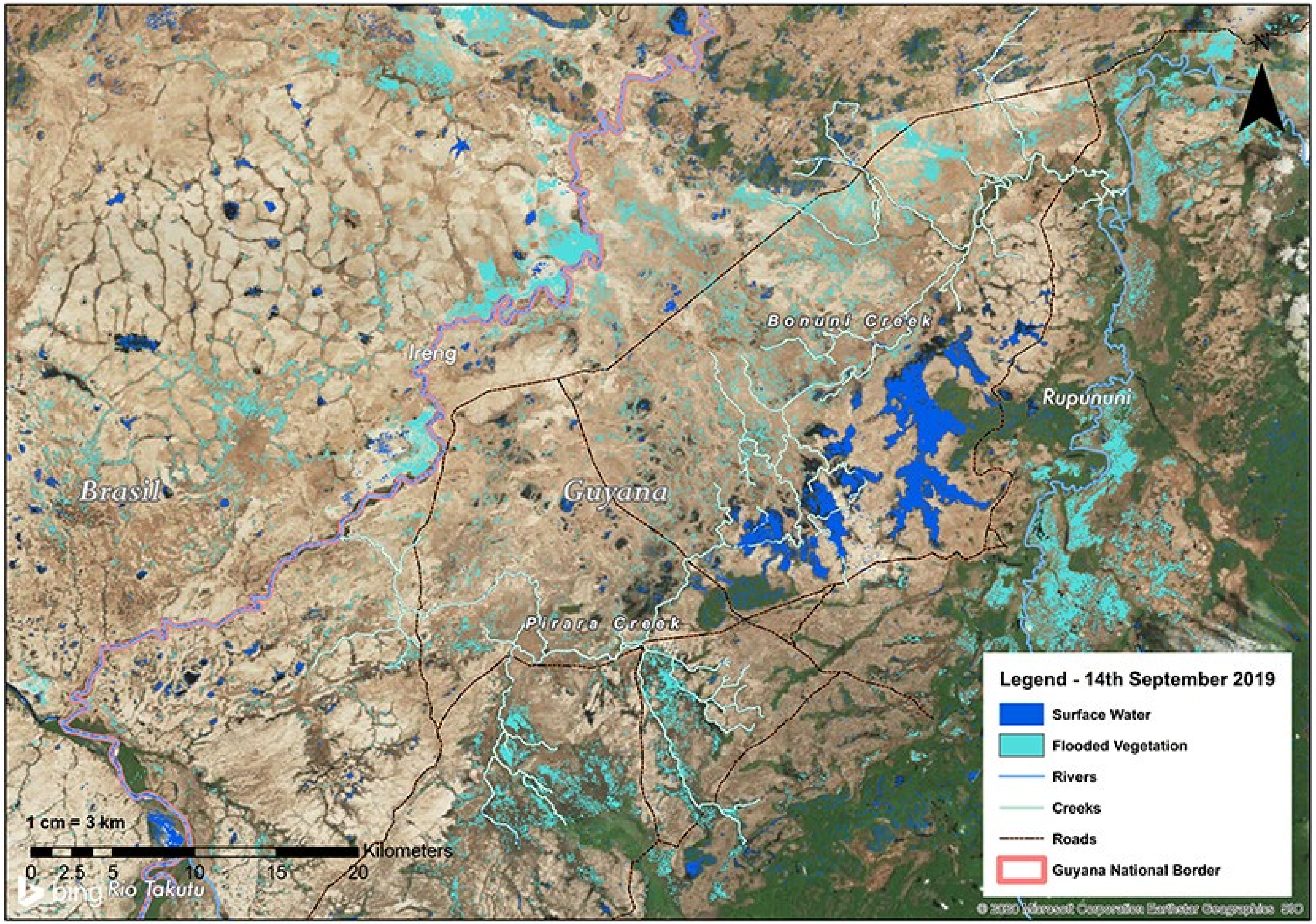

Ireng
Bonuni Creek
Rupununi
Brasil
Guyana
Pirara Creek
Legend - 28th July 2019
Surface Water
Flooded Vegetation
Rivers
Creeks
Roads
Guyana National Border
1 cm = 3 km
Kilometers
0 2.5 5 10 15 20
Rio Takutu

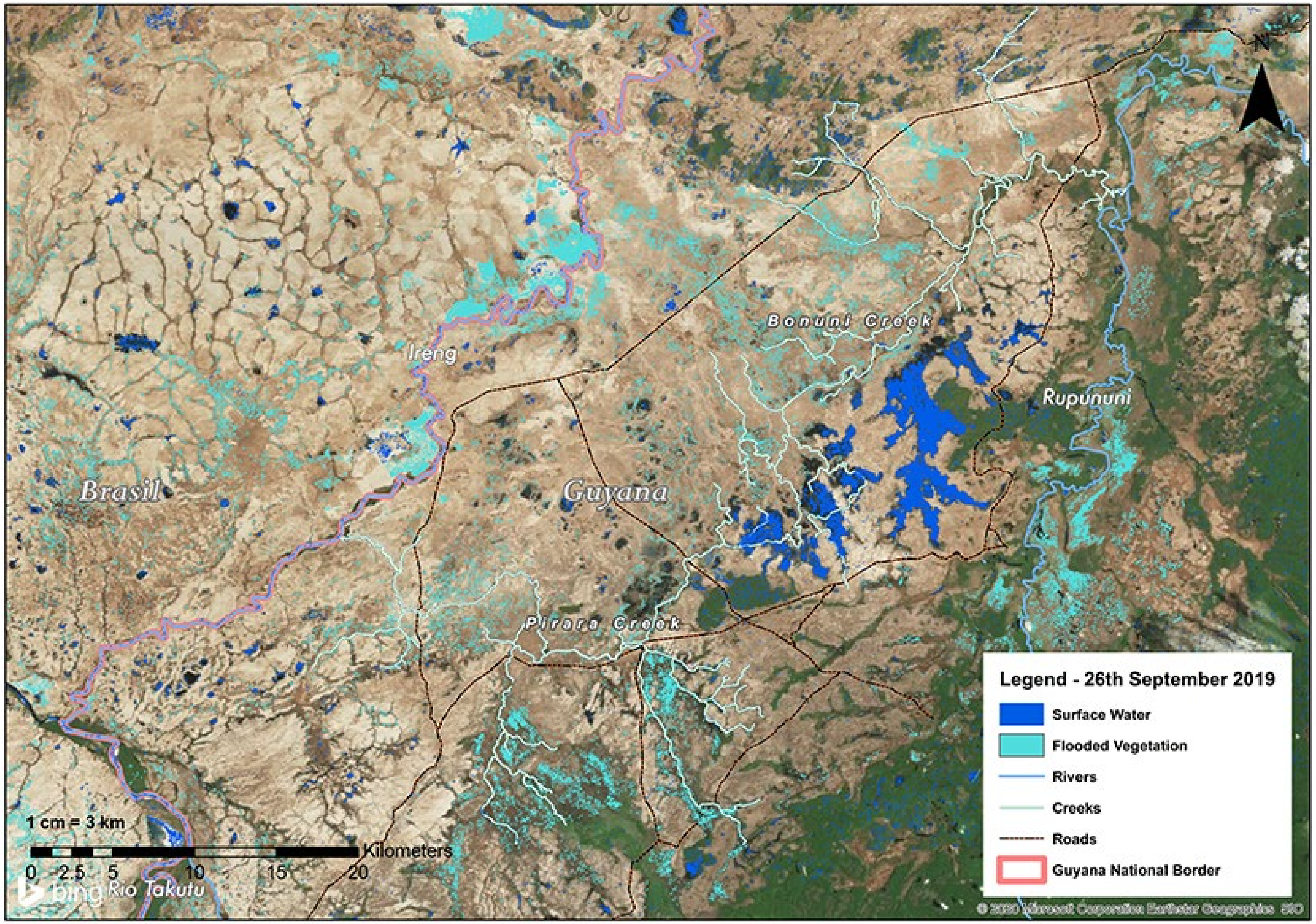

Ireng
Bonuni Creek
Rupununi
Brasil
Guyana
Pirara Creek
Rio Takutu
N
1 cm = 3 km
0 2.5 5 10 15 20
Kilometers
Legend - 09th August 2019
Surface Water
Flooded Vegetation
Rivers
Creeks
Roads
Guyana National Border

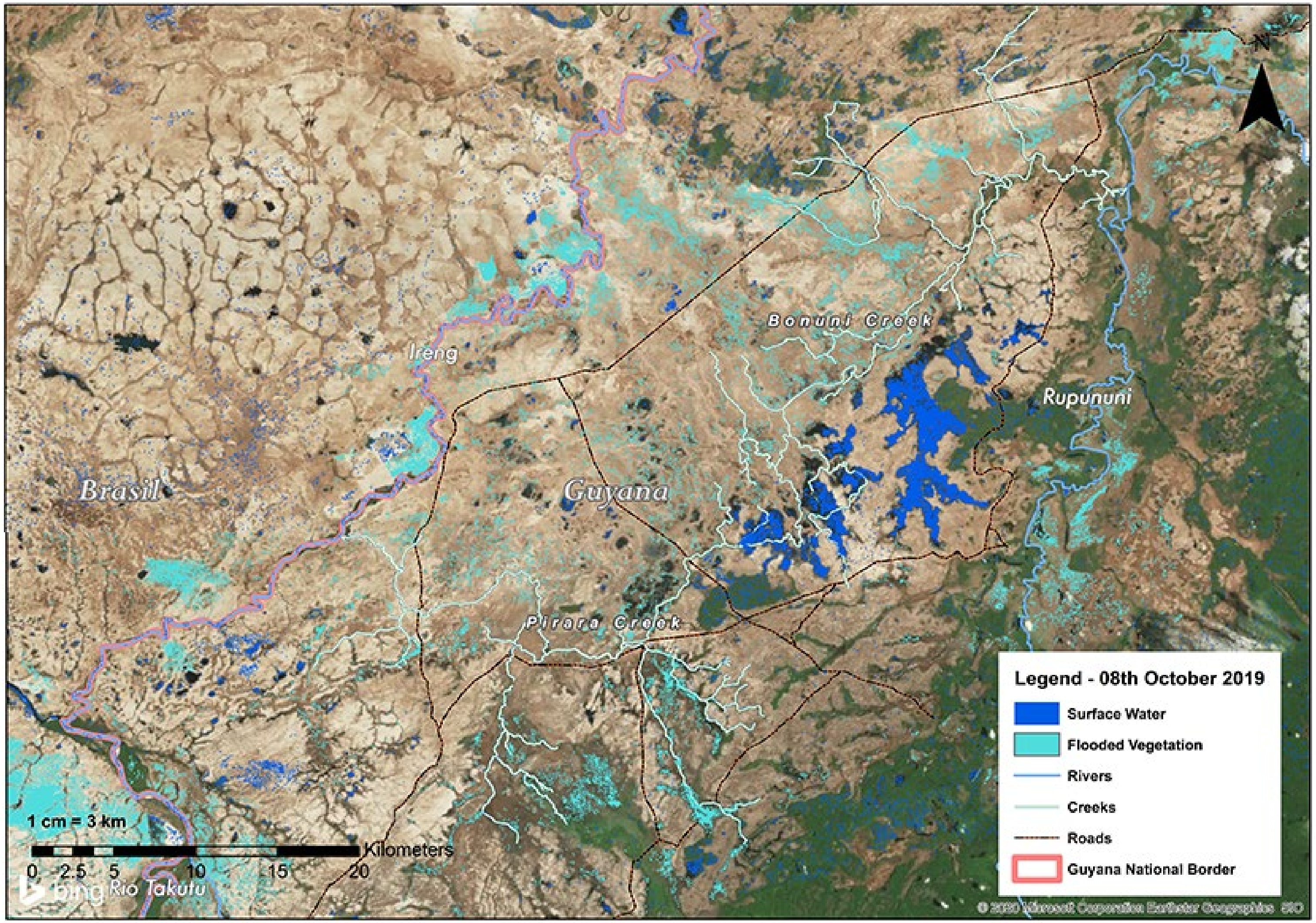

Ireng
Bonuni Creek
Rupununi
Brasil
Guyana
Pirara Creek
Rio Takutu
N
1 cm = 3 km
0 2.5 5 10 15 20
Kilometers
Legend - 21st August 2019
Surface Water
Flooded Vegetation
Rivers
Creeks
Roads
Guyana National Border

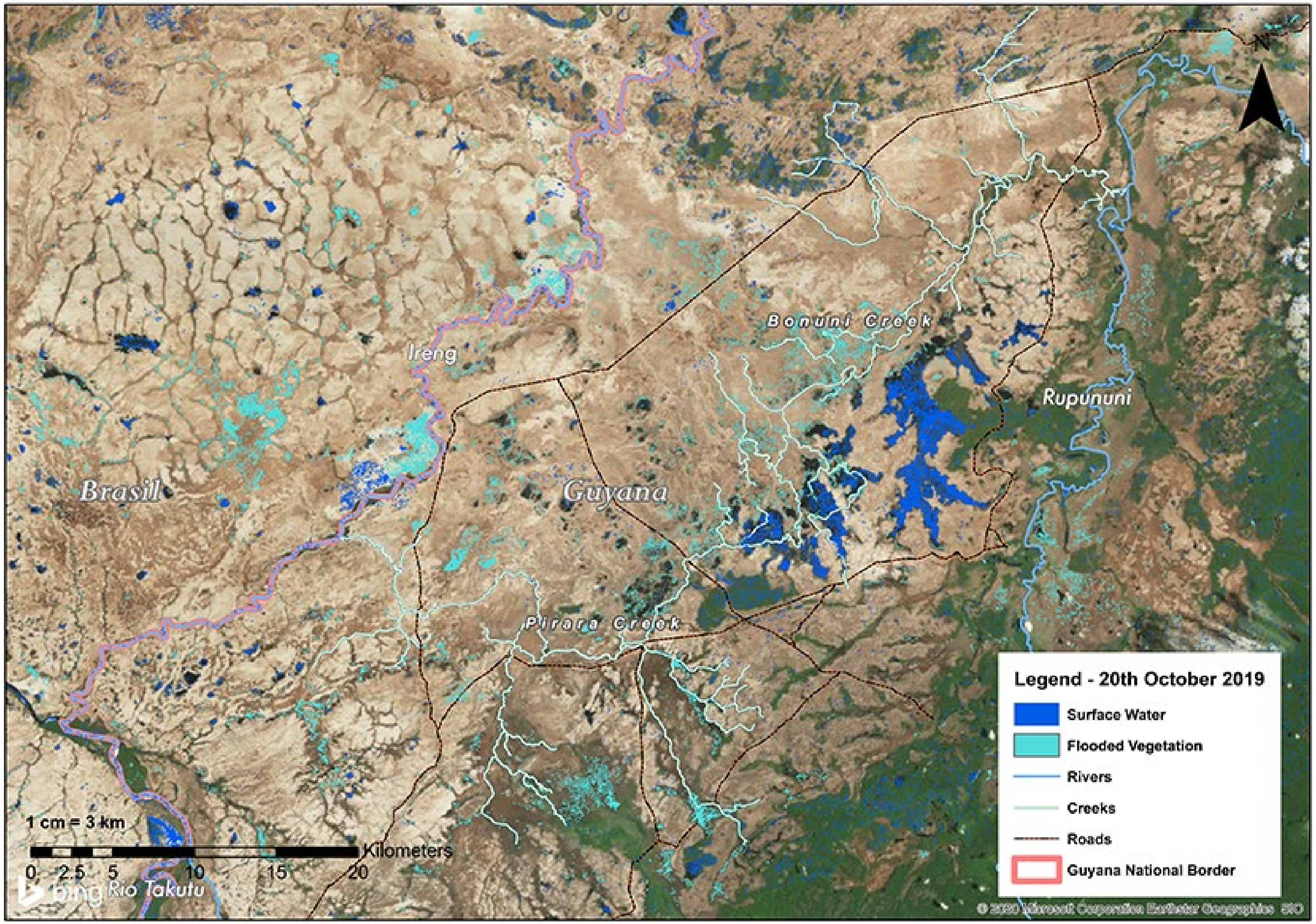


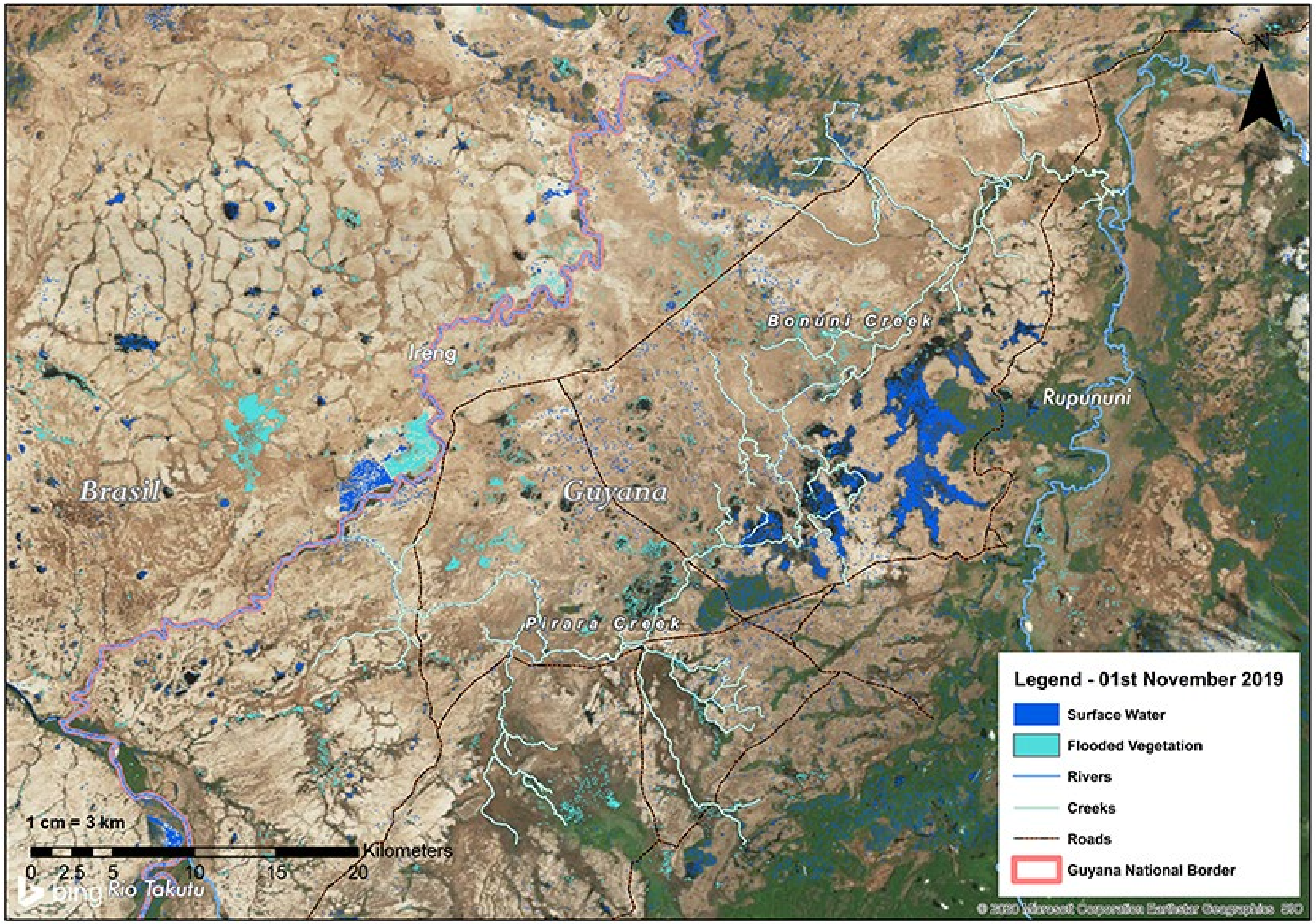
Bonuni Creek
Ireng
Rupununi
Brasil
Guyana
Pirara Creek
Rio Takutu
1 cm = 3 km
Kilometers
0 2.5 5 10 15 20
Legend - 02nd September 2019
Surface Water
Flooded Vegetation
Rivers
Creeks
Roads
Guyana National Border

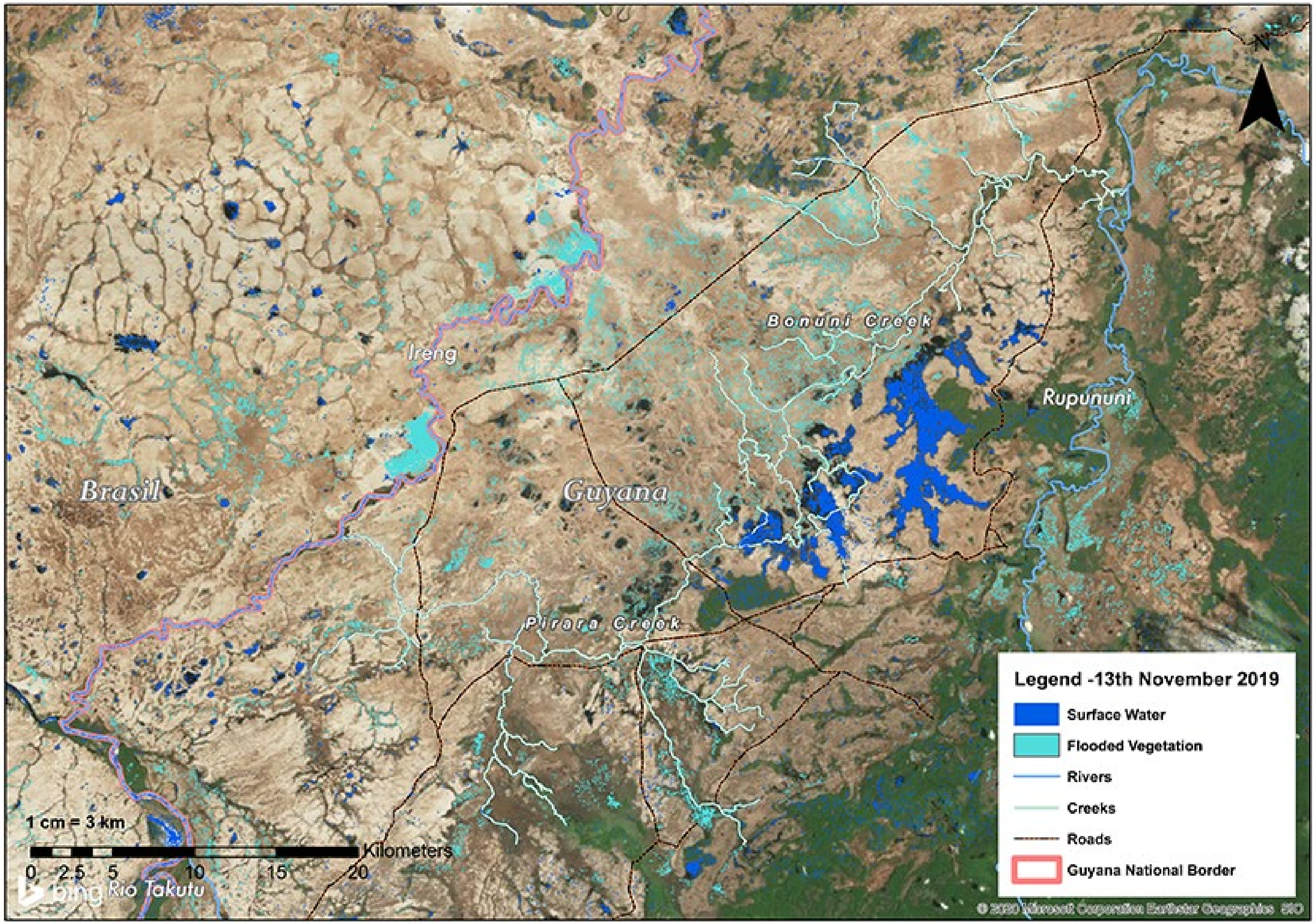

Brasil
Guyana
Ireng
Bonuni Creek
Rupununi
Pirara Creek
Rio Takutu
N
1 cm = 3 km
0 2.5 5 10 15 20
Kilometers
Legend - 14th September 2019
Surface Water
Flooded Vegetation
Rivers
Creeks
Roads
Guyana National Border


Ireng
Bonuni Creek
Rupununi
Brasil
Guyana
Pirara Creek
Legend - 26th September 2019
Surface Water
Flooded Vegetation
Rivers
Creeks
Roads
Guyana National Border
1 cm = 3 km
0 2.5 5 10 15 20
Kilometers
Rio Takutu
N

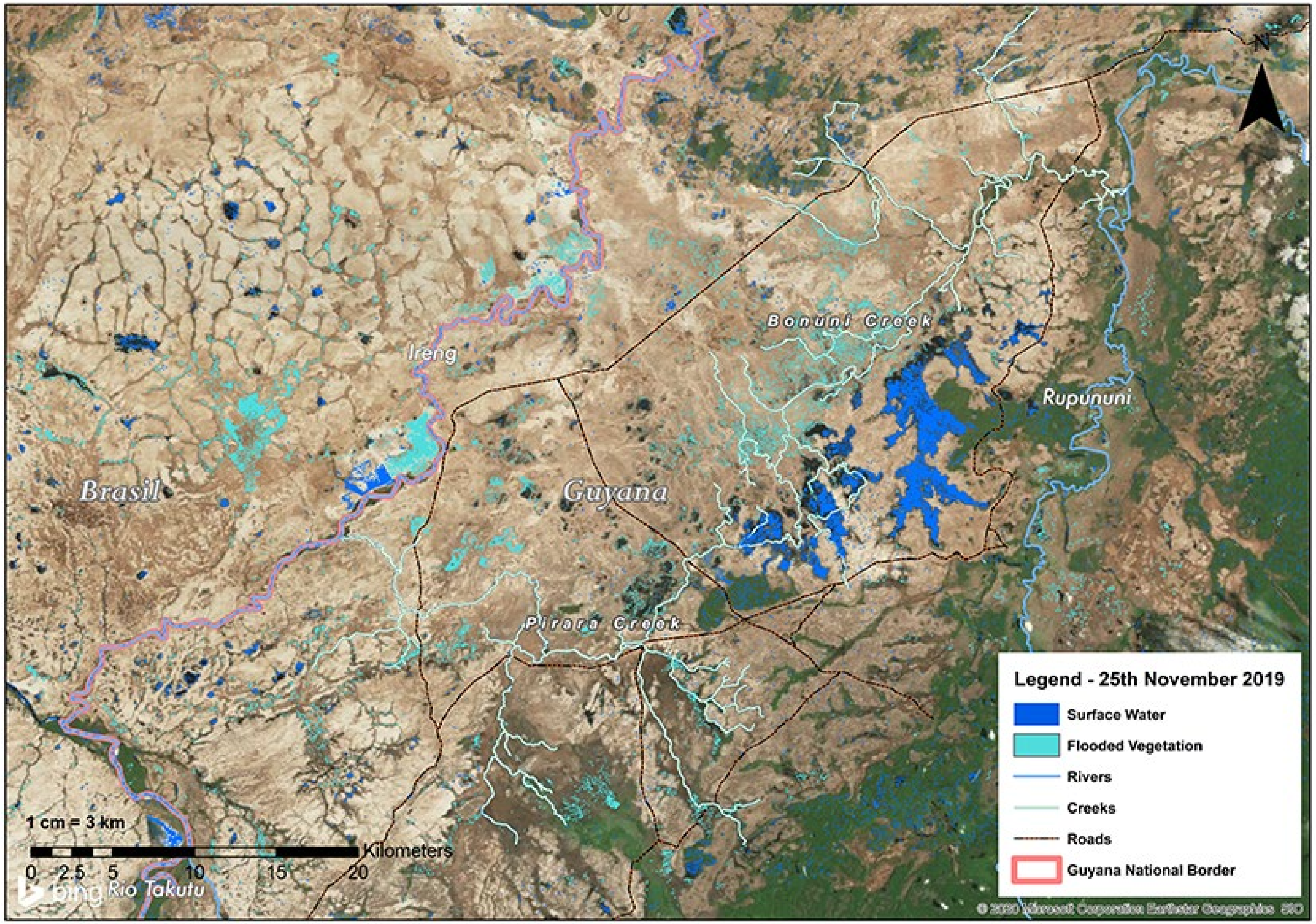

Legend - 08th October 2019
Surface Water
Flooded Vegetation
Rivers
Creeks
Roads
Guyana National Border
Bonuni Creek
Ireng
Rupununi
Brasil
Guyana
Pirara Creek
1 cm = 3 km
0 2.5 5 10 15 20
Kilometers
Rio Takutu
N

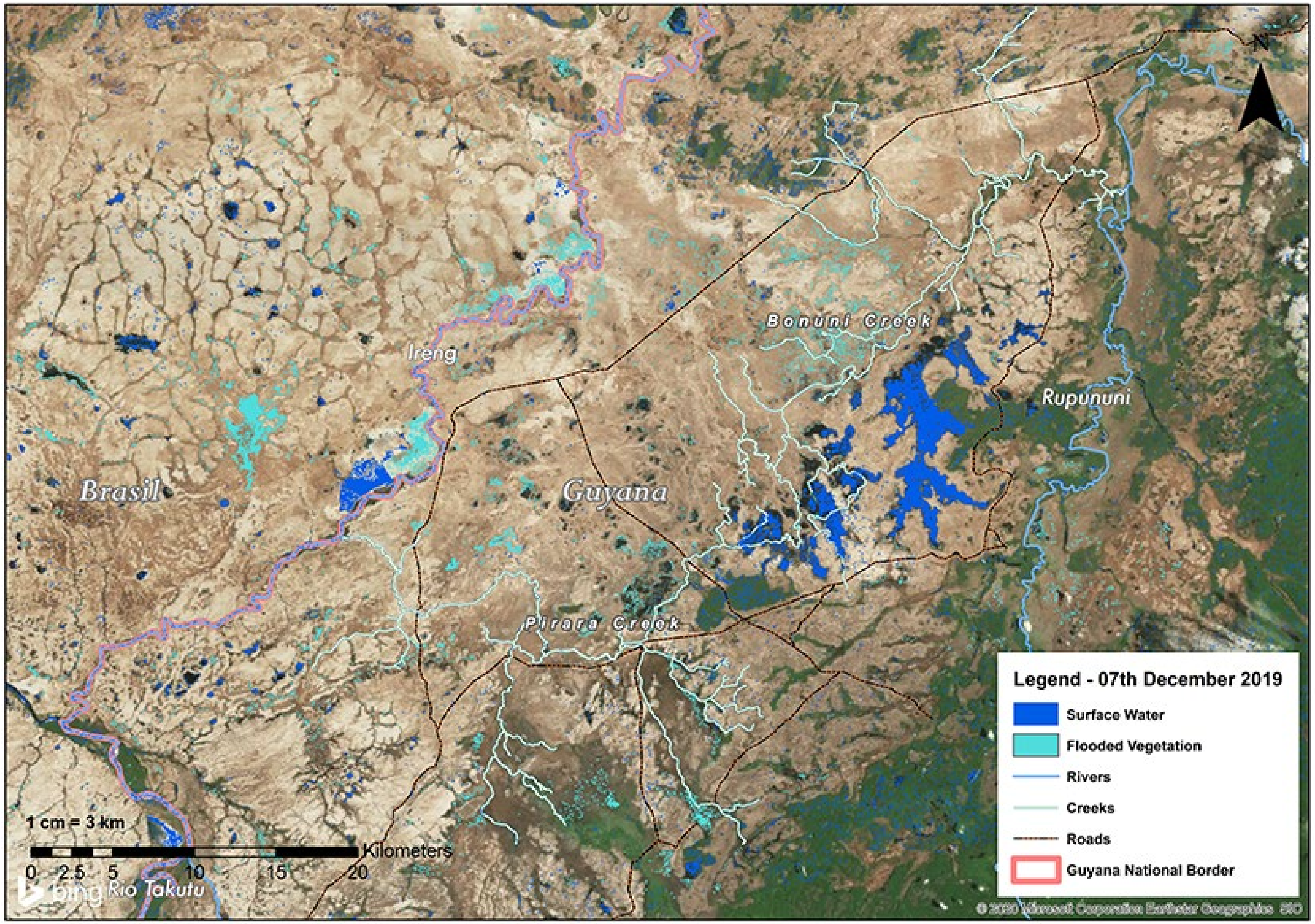

Ireng
Bonuni Creek
Rupununi
Brasil
Guyana
Pirara Creek
Legend - 20th October 2019
Surface Water
Flooded Vegetation
Rivers
Creeks
Roads
Guyana National Border
1 cm = 3 km
0 2.5 5 10 15 20
Kilometers
Rio Takutu
N


Ireng
Brasil
Guyana
Bonuni Creek
Rupununi
Pirara Creek
Rio Takutu
N
1 cm = 3 km
0 2.5 5 10 15 20
Kilometers
Legend - 01st November 2019
Surface Water
Flooded Vegetation
Rivers
Creeks
Roads
Guyana National Border



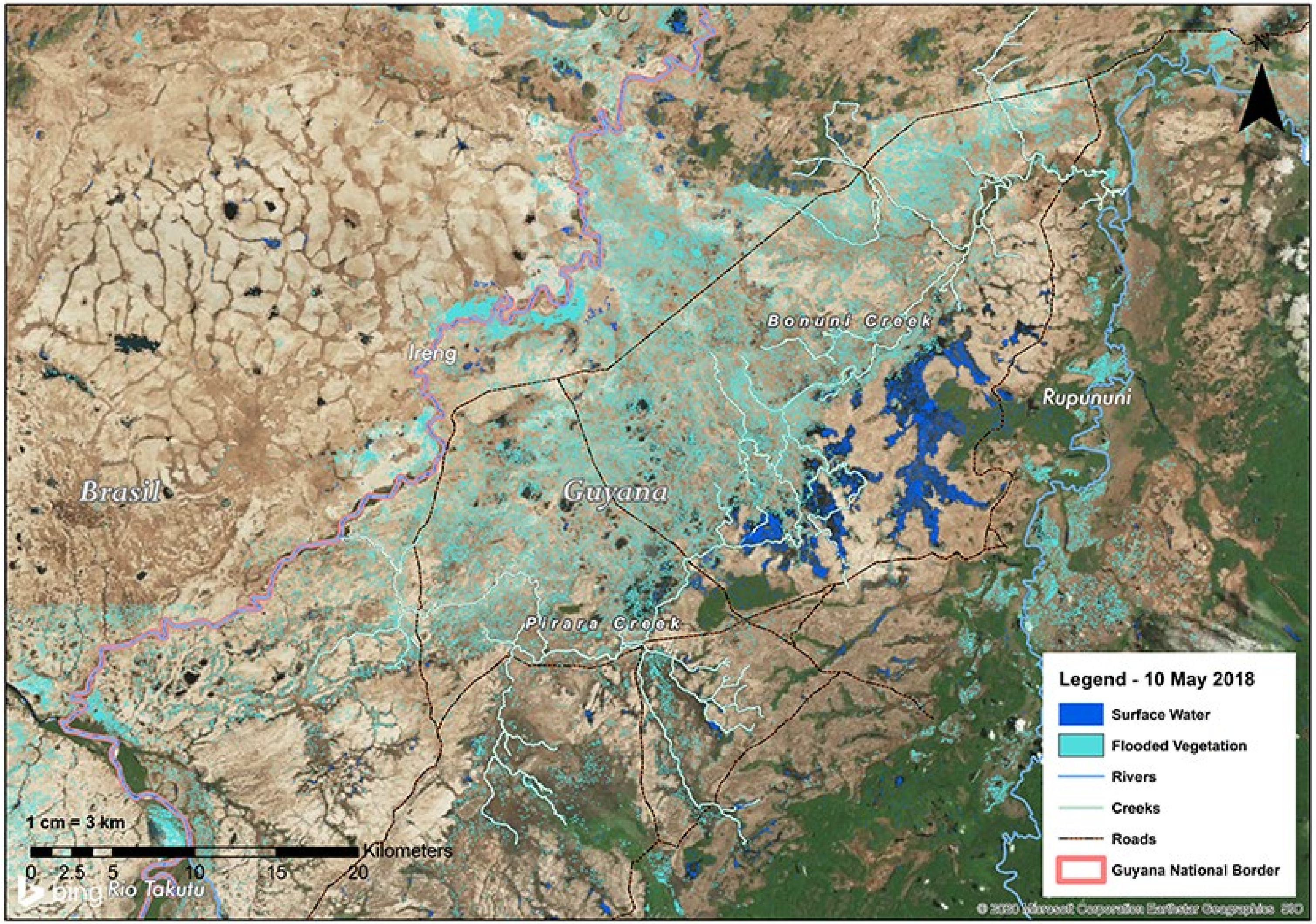
Ireng
Bonuni Creek
Rupununi
Brasil
Guyana
Pirara Creek
Rio Takutu
1 cm = 3 km
0 2.5 5 10 15 20
Kilometers
Legend -13th November 2019
Surface Water
Flooded Vegetation
Rivers
Creeks
Roads
Guyana National Border


Ireng
Bonuni Creek
Rupununi
Brasil
Guyana
Pirara Creek
1 cm = 3 km
0 2.5 5 10 15 20
Kilometers
Rio Takutu
N
Legend - 25th November 2019
Surface Water
Flooded Vegetation
Rivers
Creeks
Roads
Guyana National Border

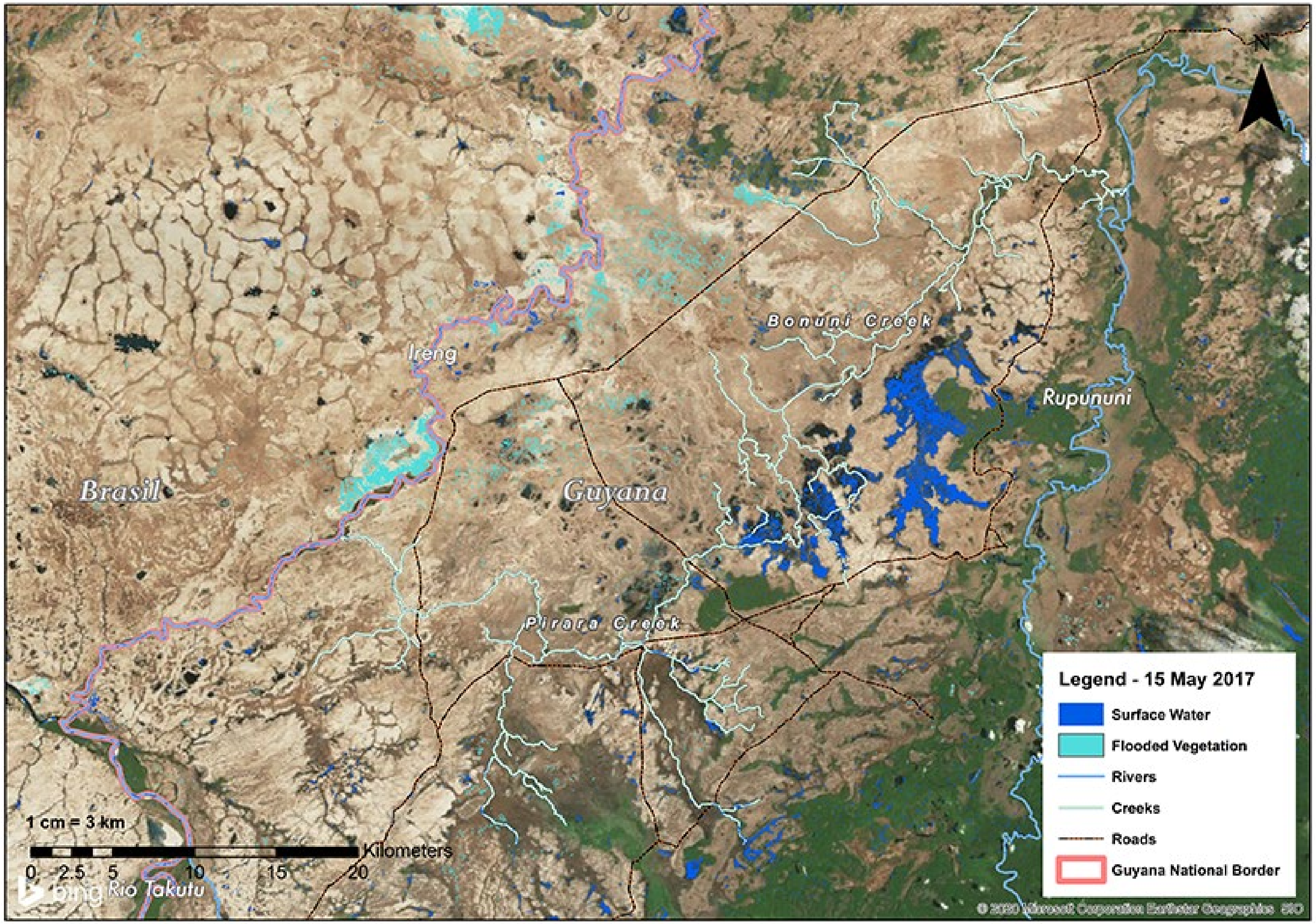


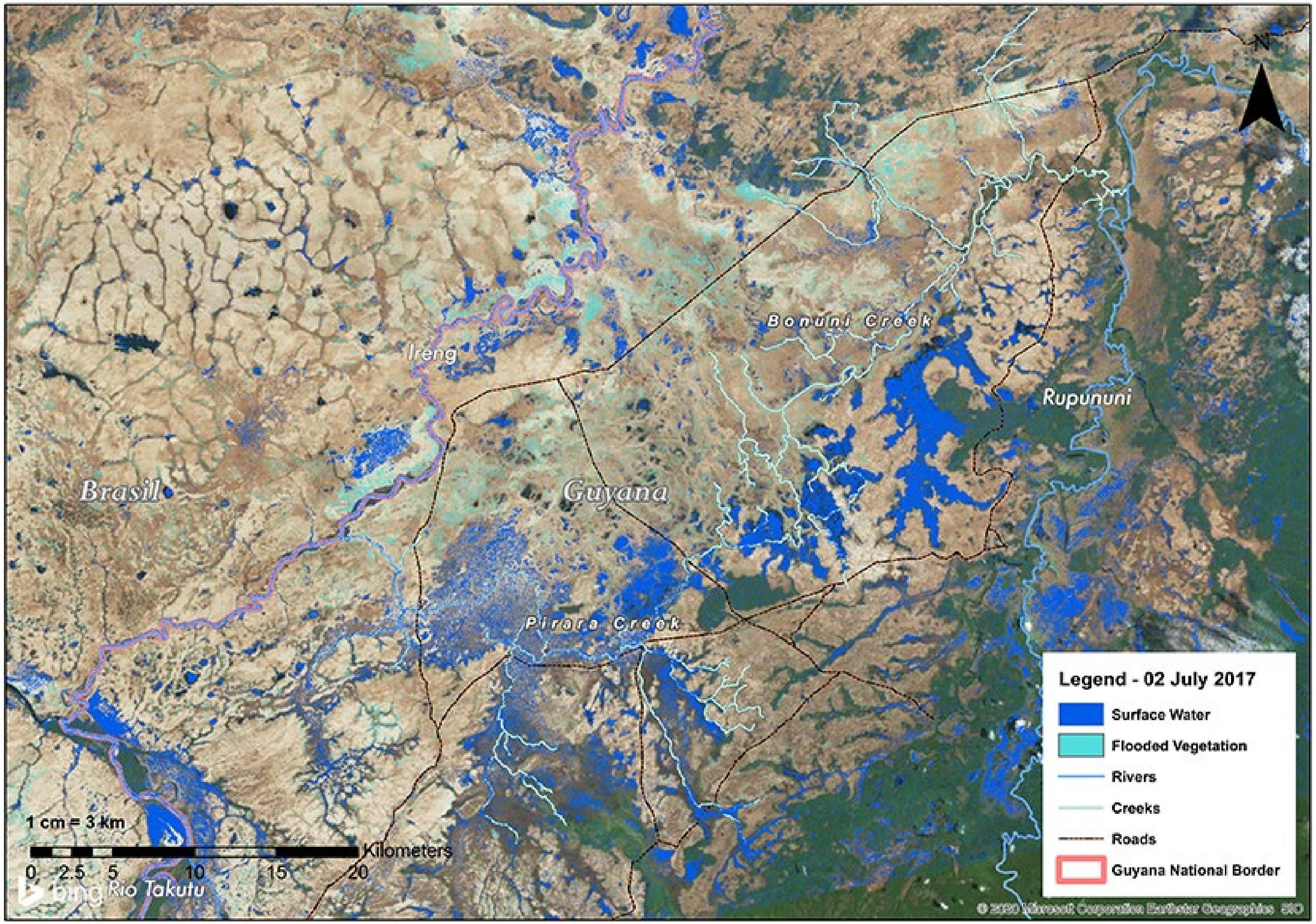
Ireng
Bonuni Creek
Rupununi
Brasil
Guyana
Pirara Creek
Rio Takutu
1 cm = 3 km
0 2.5 5 10 15 20 Kilometers
Legend - 07th December 2019
Surface Water
Flooded Vegetation
Rivers
Creeks
Roads
Guyana National Border

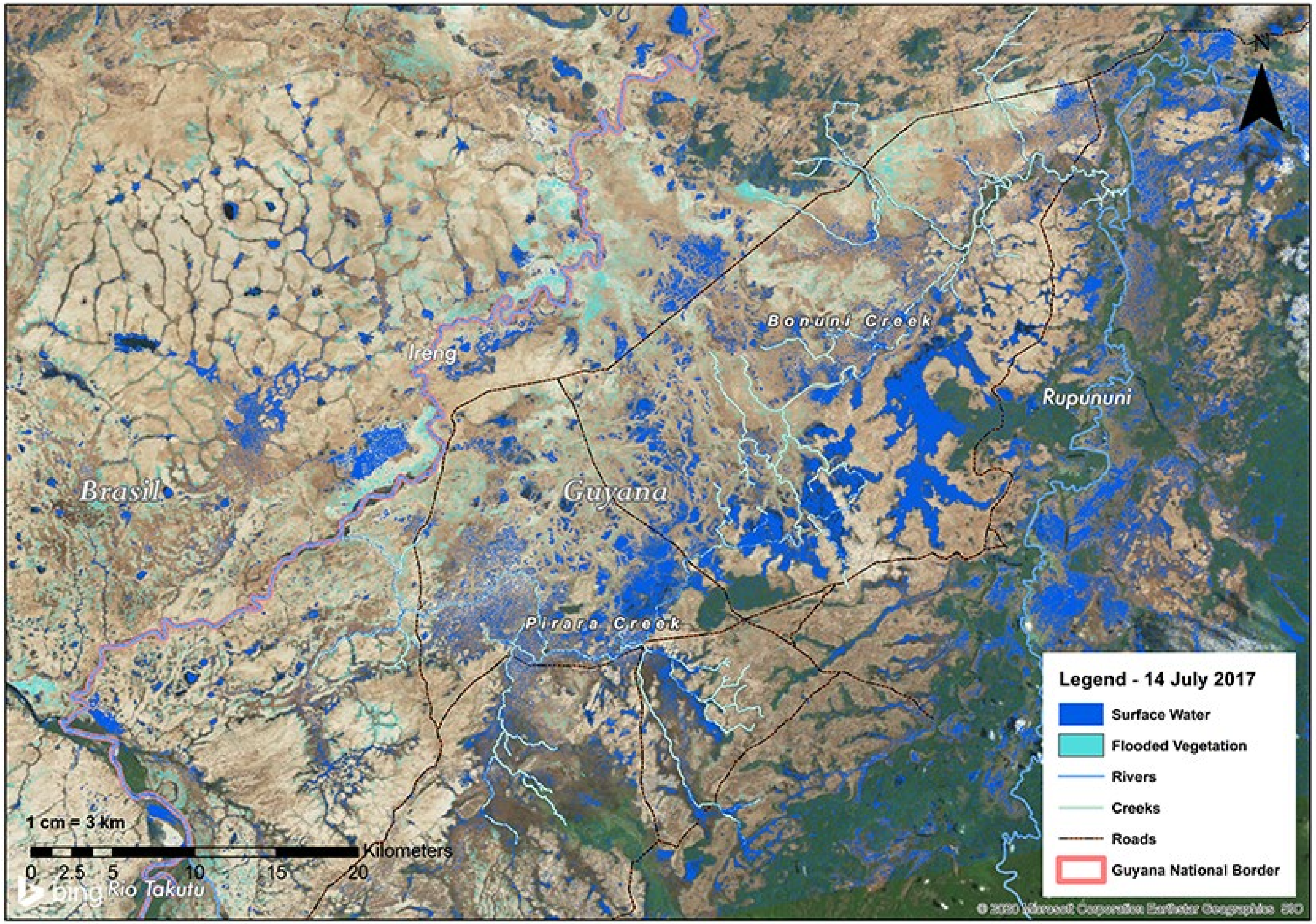
APPENDIX IX. 2018 flood dynamics of the North Rupununi Wetlands



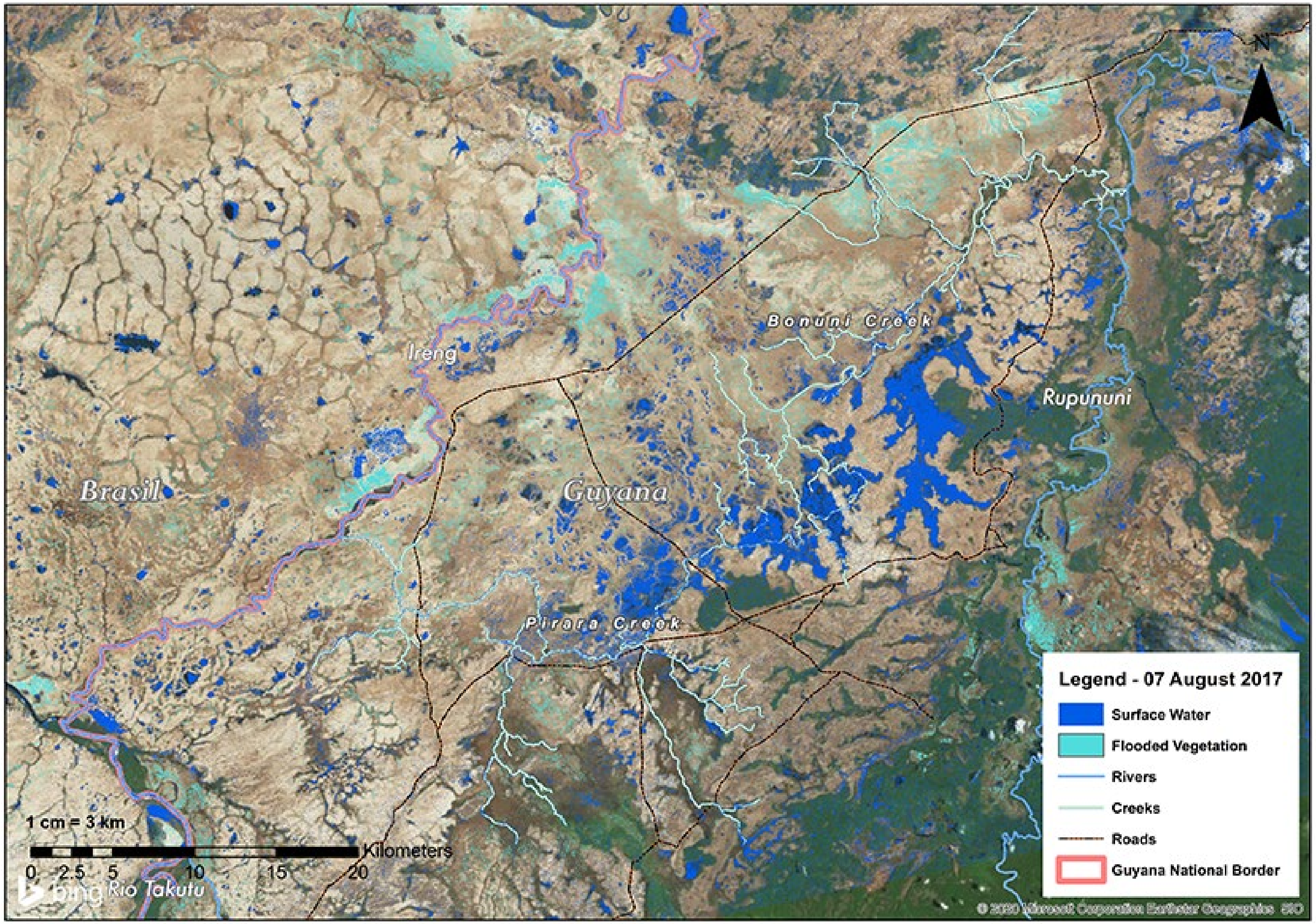
APPENDIX X. 2017 flood dynamics of the North Rupununi Wetlands




Ireng
Bonuni Creek
Rupununi
Brasil
Guyana
Pirara Creek
Rio Takutu
N
1 cm = 3 km
Kilometers
0 2.5 5 10 15 20
Legend - 02 July 2017
Surface Water
Flooded Vegetation
Rivers
Creeks
Roads
Guyana National Border



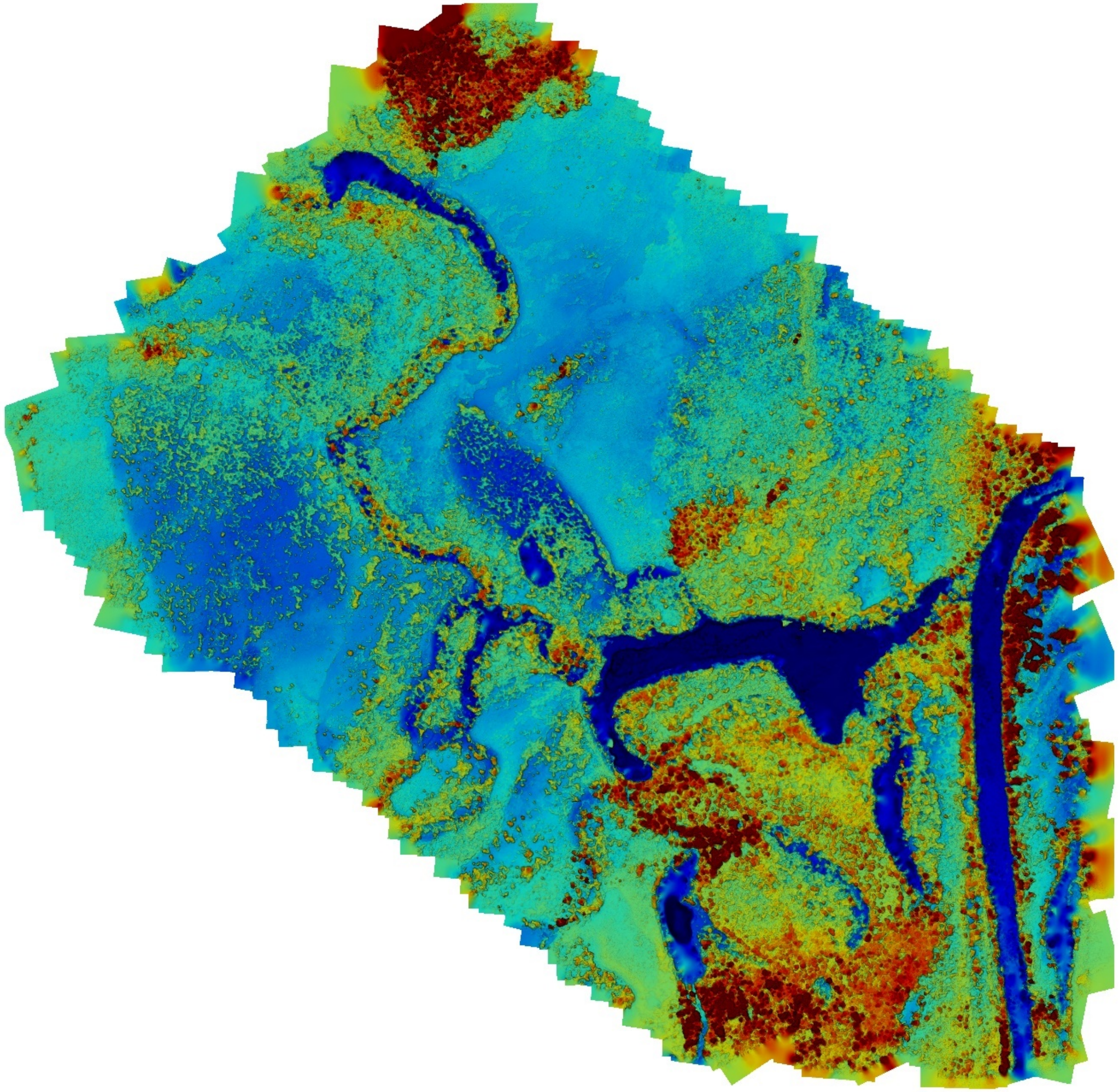
Ireng
Bonuni Creek
Rupununi
Brasil
Guyana
Pirara Creek
Rio Takutu
N
1 cm = 3 km
0 2.5 5 10 15 20
Kilometers
Legend - 14 July 2017
Surface Water
Flooded Vegetation
Rivers
Creeks
Roads
Guyana National Border


N
Ireng
Bonuni Creek
Rupununi
Brasil
Guyana
Pirara Creek
Rio Takutu
1 cm = 3 km
0 2.5 5 10 15 20
Kilometers
Legend - 07 August 2017
Surface Water
Flooded Vegetation
Rivers
Creeks
Roads
Guyana National Border

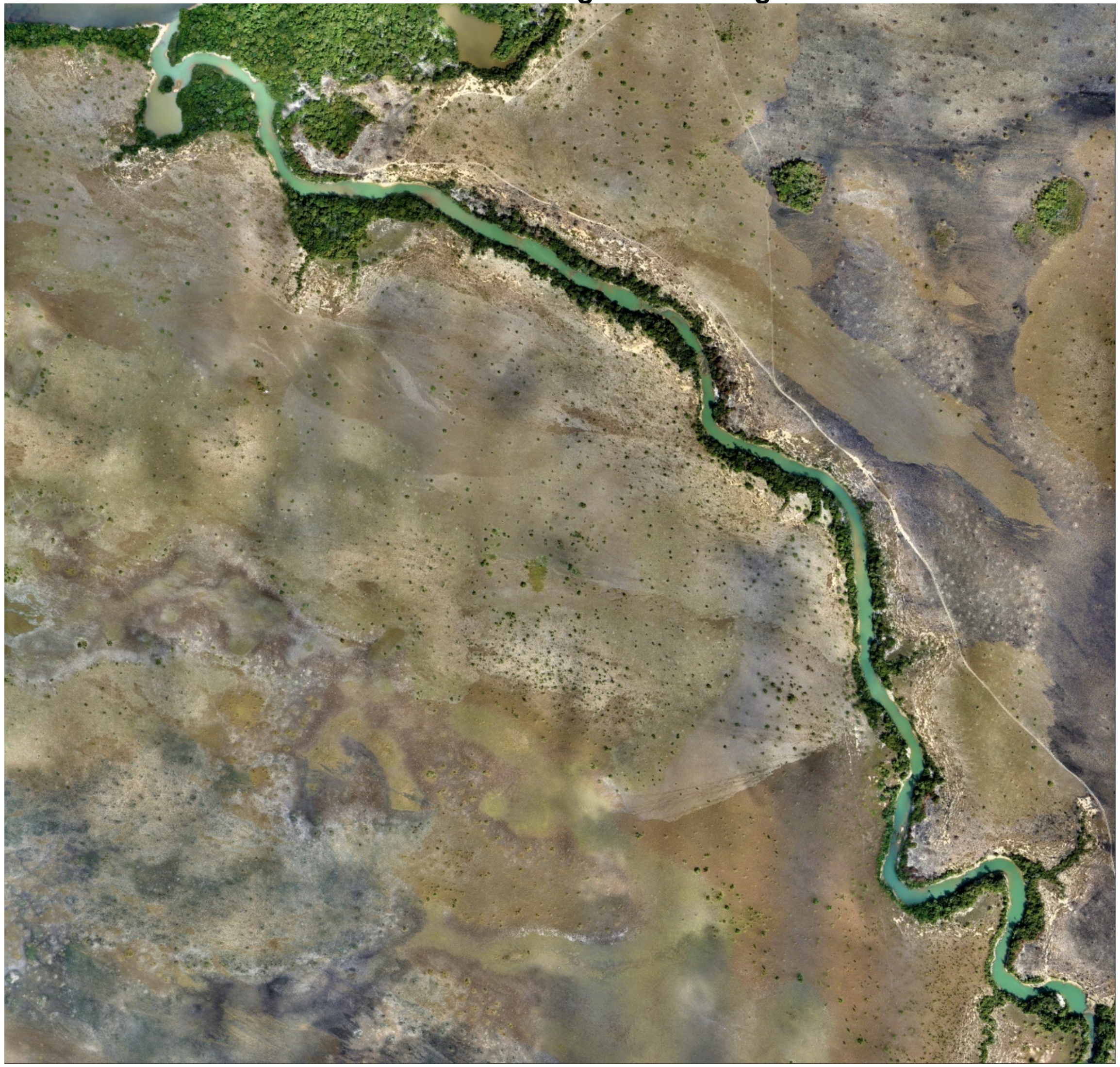
APPENDIX XI. Example drone survey images and digital elevation models

Confluence of Bonuni Creek and Rupununi River - image

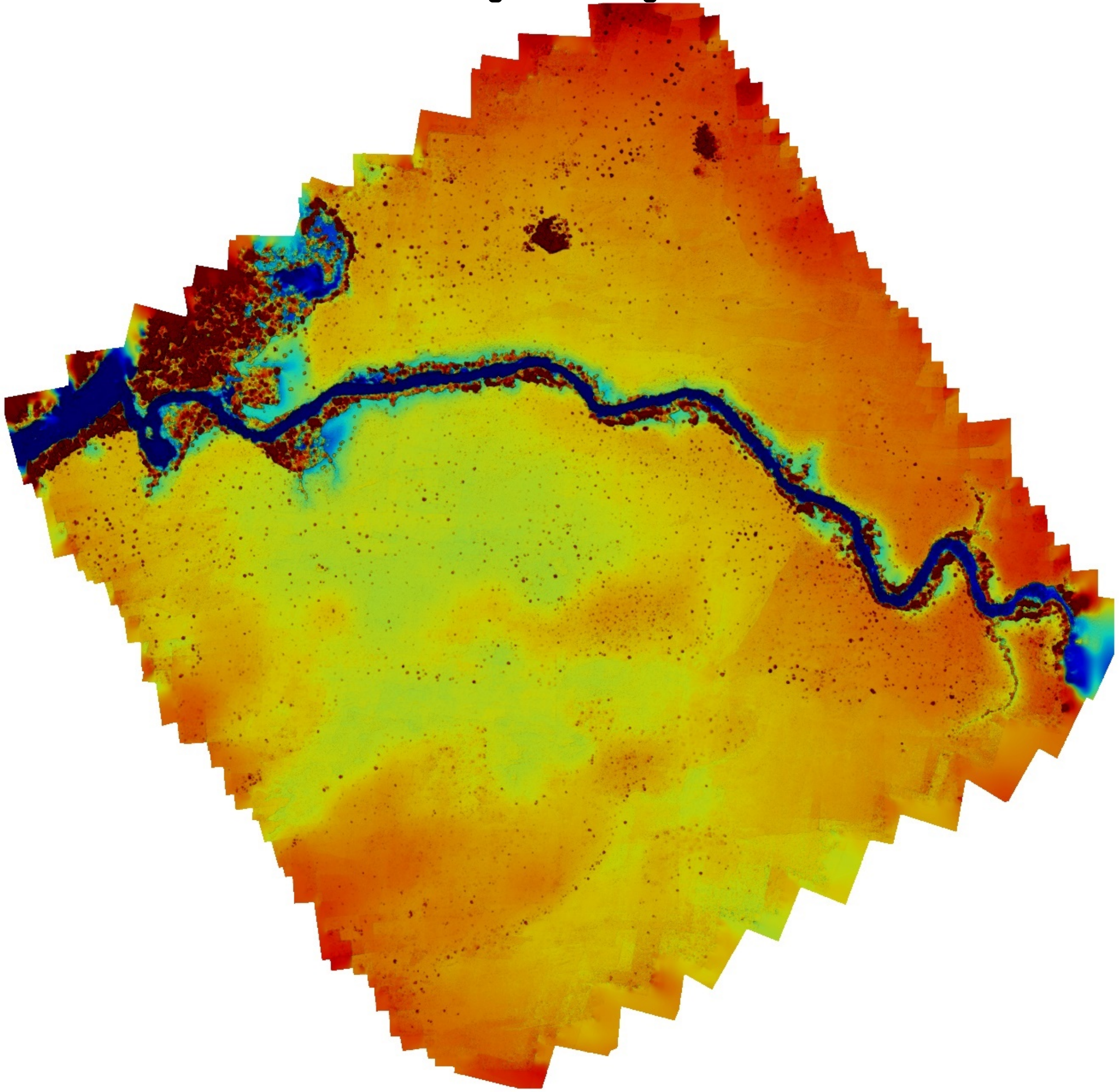
Confluence of Bonuni Creek and Rupununi River – digital elevation model



Confluence of Pirara Creek and Ireng River – image

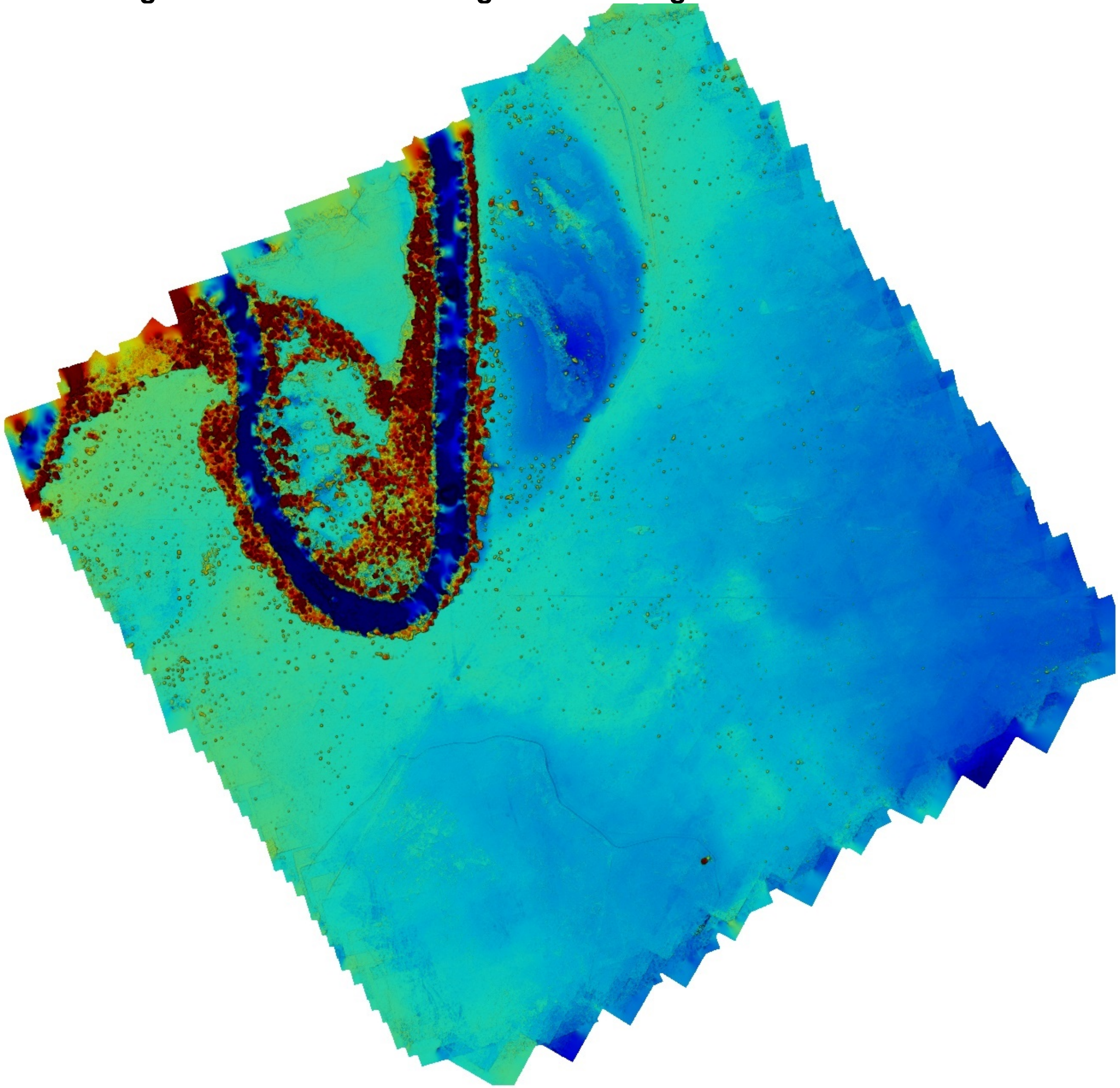


Confluence of Pirara Creek and Ireng River – digital elevation model

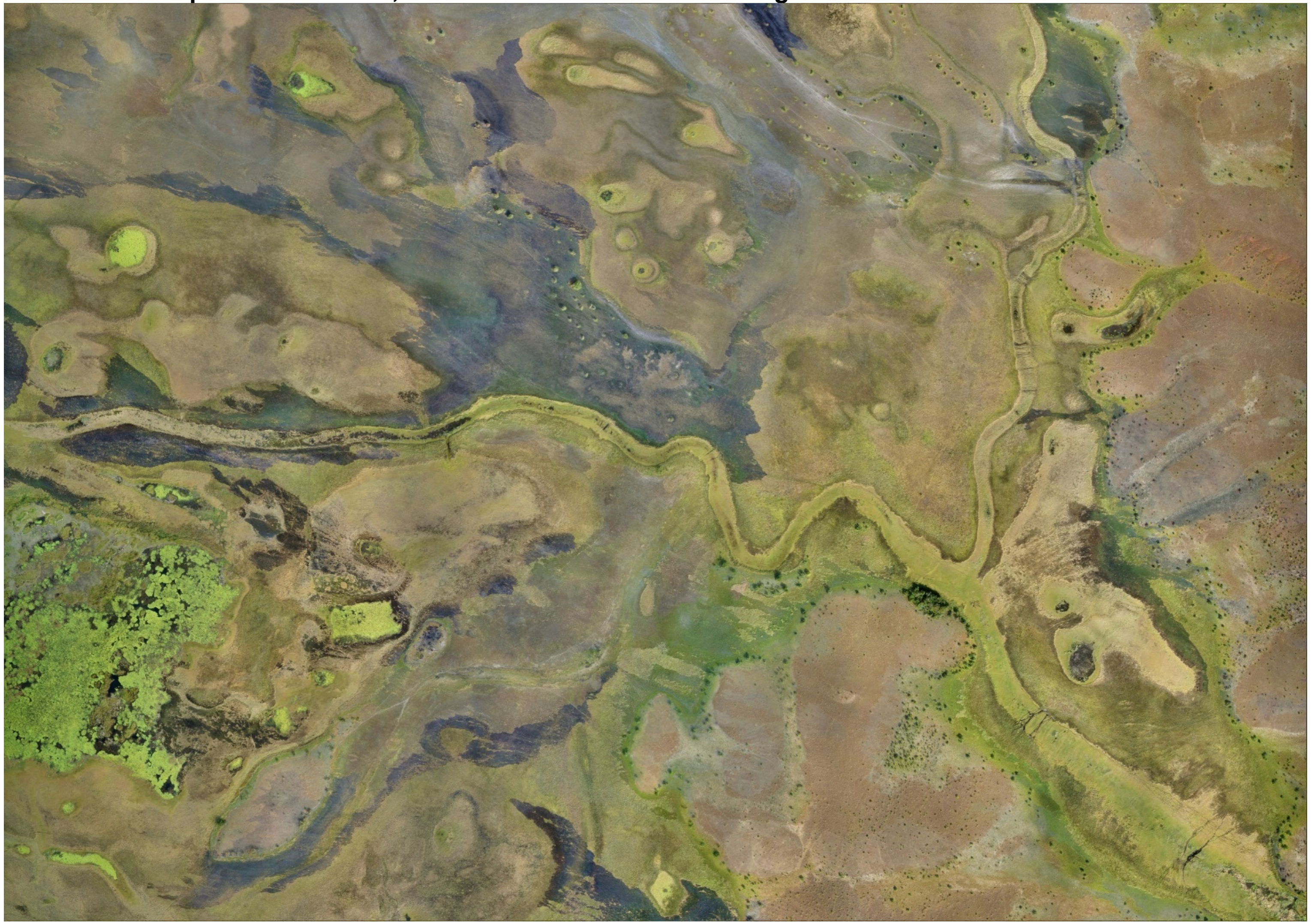


Ireng River overbank flooding location – image

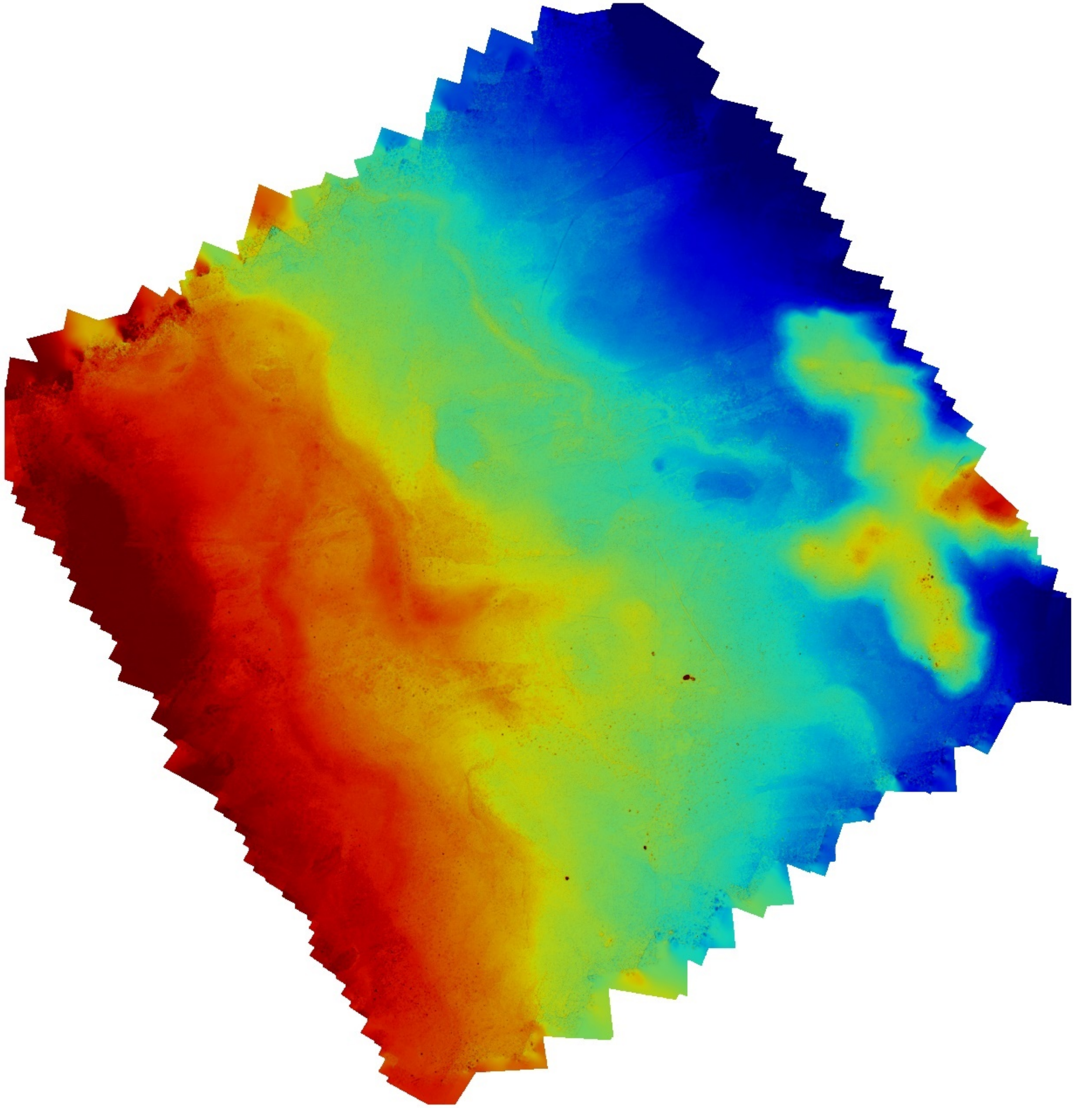
Ireng River overbank flooding location – digital elevation model



North Rupununi Wetlands, Pirara Creek Headwaters – image



North Rupununi Wetlands, Pirara Creek Headwaters – digital elevation model



3 Mile Bush – digital elevation model