

Groundwater monitoring for mapping aquifers in Belize as a tool for climate change

Assessment of water resources of the New
River - Belize

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Project manager	Azucena Rodriguez Yebra
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1 Introduction

1.1 Project summary

In Belize, 56% of the population lives in rural areas where groundwater is a vital source for fresh water and represents almost 95 per cent of the fresh water supply in these rural areas.

Groundwater is also used as a source of drinking water in the cities of the Corozal, Orange Walk, Cayo and Toledo Districts and in some rural areas of Toledo and Cayo. However, the existing aquifers and their annual recharge rate have not been quantified.

Increase in demand for fresh water resulting from increasing population, greater economic activity and agricultural expansion are threatening the quality and availability of fresh water. Each year during low rainy seasons exists the possibility of droughts due to low recharge of aquifers.

Transboundary aspects and distribution of population are other factors that affect the water sector. For example, central and northern regions (Orange Walk and Corozal) have much larger populations and higher agriculture zones for water intensive crops, but less water resources.

Transboundary aspects and distribution of population are other factors that affect the water sector. For example, central and northern regions (Orange Walk and Corozal) have much larger populations and higher agriculture zones for water intensive crops, but less water resources. Although there is a need for groundwater information across the country, the priority area will focus on the New River watershed.

The Nationally Determined Contribution (2022) indicated water resource assessment (especially groundwater) as part of the main actions to be implemented to build resilience.

The results of the prioritization of adaptation technology factsheets for the Water Sector documented in the Technology Needs Assessment (TNA) for adaptation (National Climate Change Office et al., 2017) include:

- Drought Monitoring System for Northern Belize with Specific Focus on Groundwater Resources;
- Water Efficient Fixtures and Appliances;
- An Integrated Management Strategy for Water Safety for Eight Rural Water Supply Systems in Belize.

The National Hydrological Service (NHS) is leading a process for building an inventory of existing data on groundwater. The objective is to identify and homogenize information that is currently available but spread among different agencies and institutions, and their various departments.

Requests have been made from the executive level of the Ministry of Natural Resources, Petroleum, and Mining (responsible for the NHS) to other ministries for sharing of relevant groundwater data. However, this is still a work in progress. Additionally, the Ministry of Rural Transformation has indicated that they do not geo-reference their wells.

Following the foreseen adaptation actions in the NDC and the TNA for Adaptation for the water sector, the National Climate Change Office of the Ministry of Sustainable Development, Climate Change, and Disaster Risk Management, and the National Hydrological Service (NHS) of the Ministry of Natural Resources, Petroleum, and Mining started conversations to develop a proposal for a Groundwater Monitoring Network.

1.2 About this report

The purpose of this report is to assess the water resources of the New River watershed in Belize with a focus on groundwater resources. This includes a review of previous work and an assessment of key risks to water resources,

such as saline intrusion in vulnerable coastal aquifers. The development of a water balance for the area has also been completed and described in detail in Section 4.

2 Water Resources of the New River Watershed

2.1 Geology and soils

The geology of Belize consists of extensive limestone formations (UNDP, 2014). Structurally, northern Belize is part of the Yucatan Platform and southern Belize an extension of the geology of eastern Guatemala (Esselman and Boles, 2001). The Corozal Basin in the Northern region consists of calcareous sediments with high permeabilities (United Nations, 2022). A complex of Tertiary limestones and marls that are not highly weathered (Hartshorn et al., 1984), quaternary alluvial deposits, and swamps underlain by the flat lying carbonate deposits of Cenozoic age are found in the New River watershed (Polk et al., 2013). A brief description of the main lithologies found can be found in Table 1 and a geological map is presented in Figure 2.1.

Table 2.1: Description of the lithologies found in the geological time periods found in the New River watershed. Data from the Ministry of Economic Development (2023)

Geological Period	Lithological Description
Pleistocene to recent	Composed of alluvium, river terraces, sand bars, modern reef and calcareous sand and mud. This formation has experienced Holocene karstification.
Miocene to Pleistocene	Orange Walk Group: consists of marls, coral, coquinal (corals, gastropods, oysters, pelecypods, fish scales, echinoid spines and chara seeds) limestones and gyspm (sand and clay).
Paleocene to Eocene	Limestone with > 1 m chert nodules and lagoonal limestone and dolomite, marl, gypsum, chert nodules and bentonitic clay.
Undifferentiated Cretaceous	Hill Bank Formation: dolomite – anhydrite.

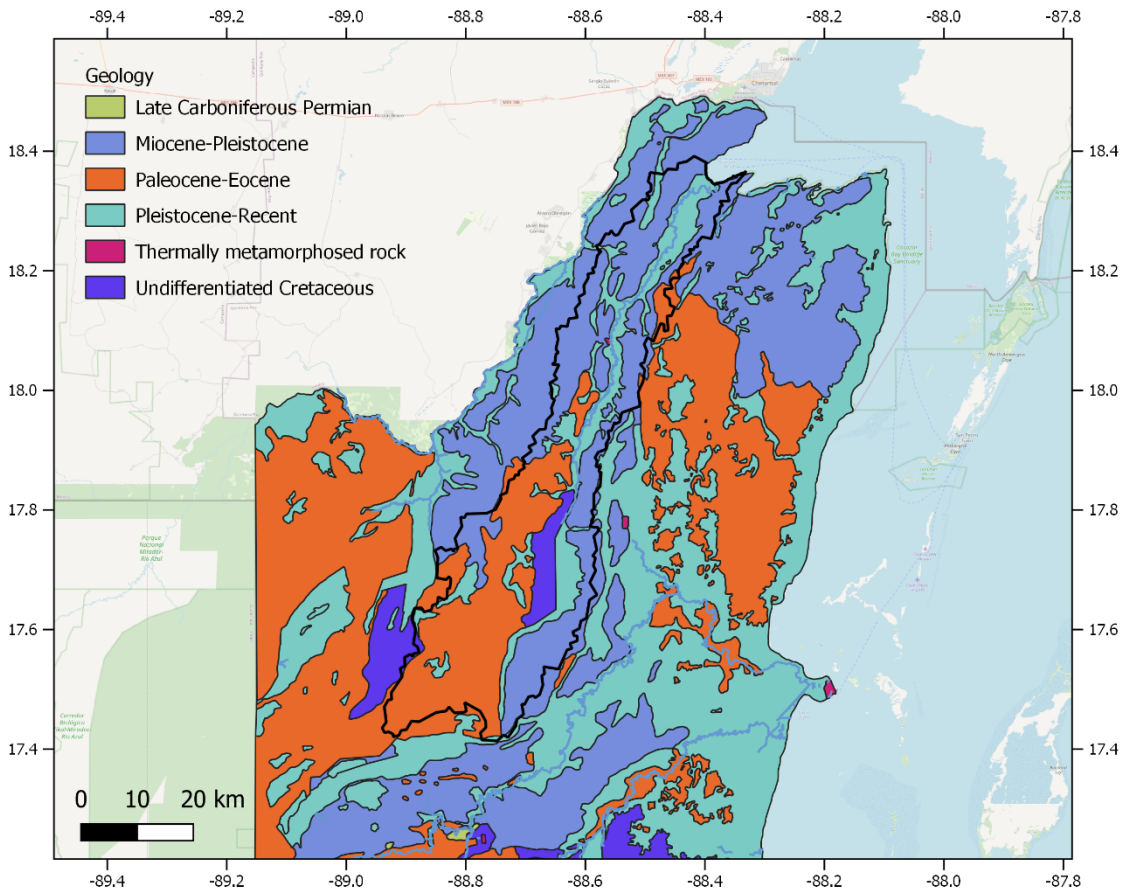


Figure 2.1: Map showing the age of the geological formations found within the New River watershed (outlined in black). Data from the Ministry of Economic Development (2023)

The Coastal Plain and Belize Shelf developed in the Quaternary period. Though the Yucatan Platform has been stable, the opening of the Yucatan trough allowed the eastern edge of the platform to slump along faults that trend north-northeast (Figure 2.2). Slumping of limestone is well displayed in Booth's River escarpment and the Rio Bravo escarpment a few miles farther west. East of Booth's River, slumping is represented by the narrow, deep (15 m), New River lagoon and to a lesser degree by the much shallower lagoon at Crooked Tree. Further evidence of slumping exists in the alignment of New River and Progresso and Shipstern lagoons (Hartshorn, 1984).

North of the Maya Mountains, the Belize River flows generally northeast in a tortuous course from San Ignacio to about 19 km south-southeast of Crooked Tree, then south and southeast to enter the sea near Belize City. Dixon (1956) postulates that the Belize River formerly flowed north, possibly into the New River. The Belize River carries the largest volume of water, draining about 27% of the country (Hartshorn, 1984).

North of the Belize River all rivers drain northeast following faults in the limestone bedrock Booth's River and New River undoubtedly receive most of their recharge from the underlying Cretaceous limestones. East of Crooked Tree and north-eastward to Sarteneja, drainage systems are poorly developed and most drainage is internal (subsurface). This vast area is mostly lower than 15 m above msl, hence freshwater and brackish water lagoons abound (Hartshorn, 1984).

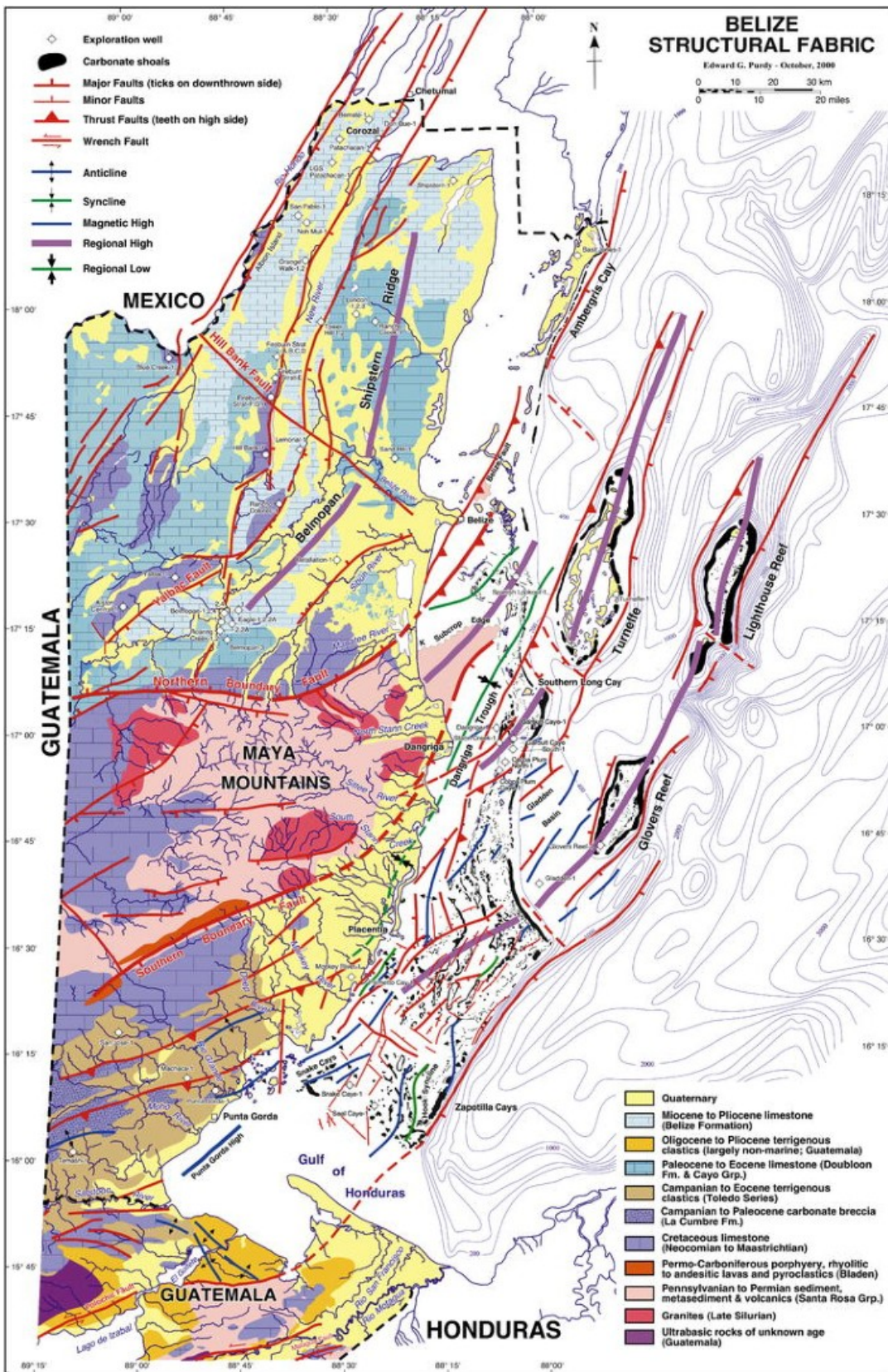


Figure 2.2: Map of Belize structural geology (Purdy et al., 2003)

Soil classifications in Belize by Baillie et al., (1993) provide an overview of land resource assessments from 1986 to 1990. Generally, the soils of Belize can be grouped into the nine categories listed in Table 2.1. And the revised classification from the USDA Soil Taxonomy provides the following map of soils in the New River Watershed area (Figure 2.3), and description is given in the table below (Table 2.2).

Table 2.2: Generalized division describes the main soils in physiographic groups(Baillie et al., 1993)

Category	Soil type/group
1	Soils of the Maya Mountains: a) Soils of the Mountain Pine Plateau; b) Soils of the rugged land systems.
2	Clays of the limestone uplands and foothills.
3	Grey and brown soils of the Toledo Beds.
4	Pine ridge soils of the coastal plain.
5	Dark limestone soils of the Northern Coastal Plain.
6	Reddish limestone clays of the Northern Coastal Plain.
7	Swamp soils.
8	Young soils on river alluvium.
9	Young coastal soils.

Table 2.3: USDA Soil Taxonomy Orders found on the New River Watershed in Belize (Selva Maya consortium, 2004)

Order	Description
Gleysols	Gleysols are formed under waterlogged conditions produced by rising groundwater. In the tropics and subtropics they are cultivated for rice or, after drainage, for field crops and trees.
Leptosols	Leptosols are soils with a very shallow profile depth (indicating little influence of soil-forming processes), and they often contain large amounts of gravel. They typically remain under natural vegetation, being especially susceptible to erosion, desiccation, or waterlogging, depending on climate and topography.

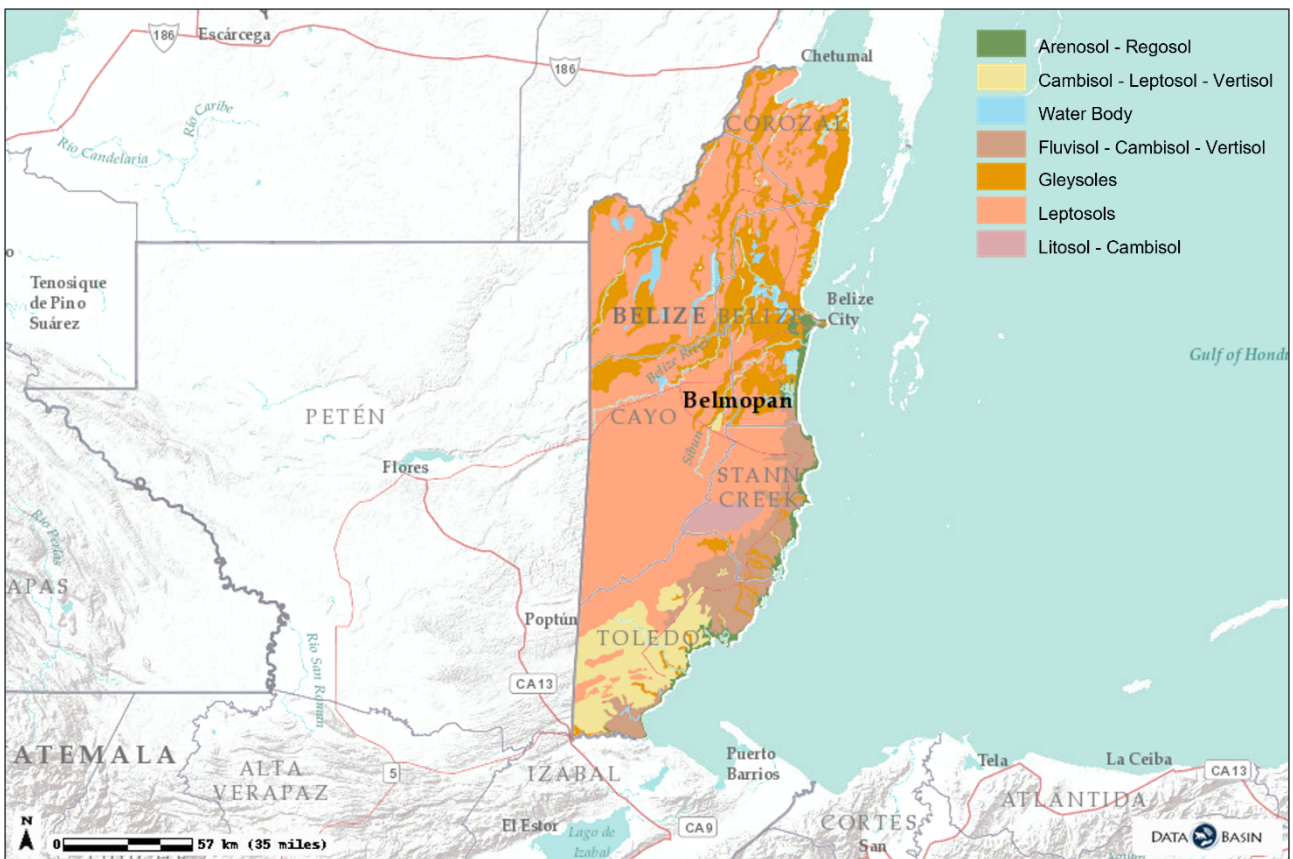


Figure 2.3: Soils map of New River Watershed (Selva Maya consortium, 2004)

2.2 Hydrogeology

Northern Belize is characterised by low lying topography and lower precipitation compared to the rest of the country. The highest elevation in the New River watershed is around 150 masl. The New River Watershed is one of the sixteen major watersheds of Belize. It has an area of 1,864 km² and it is formed mainly by limestone rock. The greatest concentration of wetlands is in Northern Belize, and one of the major freshwater and brackish wetlands of the area is the New River Lagoon (Esselman and Boles, 2001).

Belize has been divided into seven hydrogeological provinces with broadly similar hydrogeological characteristics (Hartshorn et al., 1984). The New River Watershed is located in the northern groundwater province of Belize, named Coastal Plains (Figure 2.5) which is within the Corozal and Orange Walk administrative districts. The province is described in Hartshorn et al. (1984) as follows: Numerous village and private wells in this province tap into chalks and marls of Eocene age or younger. It would appear that hydrogeological characteristics vary considerably in these shallow aquifers, which makes the success of well drilling unpredictable. Beneath these Eocene deposits are older limestone formations. These are referred to in Hartshorn as the Lacandon and Campur formations, while the more recent geology map uses different names. These formations outcrop in the Campur province to the south of the coastal plains where they provide reliable yields. These are presently not exploited, with the exception of a well at the Caribbean International Brewery at Carmelita in the Orange Walk district which is around 238 m deep with artesian flow at 92 imperial gallons per minute from fractured dolomite at 236 m (based on drilling log provided by the NHS). These deeper aquifers are likely to provide a more resilient source of groundwater, although very little exploration has been carried out to determine the depths of these formations beneath the province and to quantify their hydrogeological characteristics.

Based on a well survey completed by the NHS most wells are of open construction and are less than 10 m deep, reaching the water table between 1 and 10 m below the surface. Drilled boreholes are typically less than 30 m deep and reach the water table at similar depths as the open wells (Figure 2.4), the location of these wells is shown in Figure 2.6.

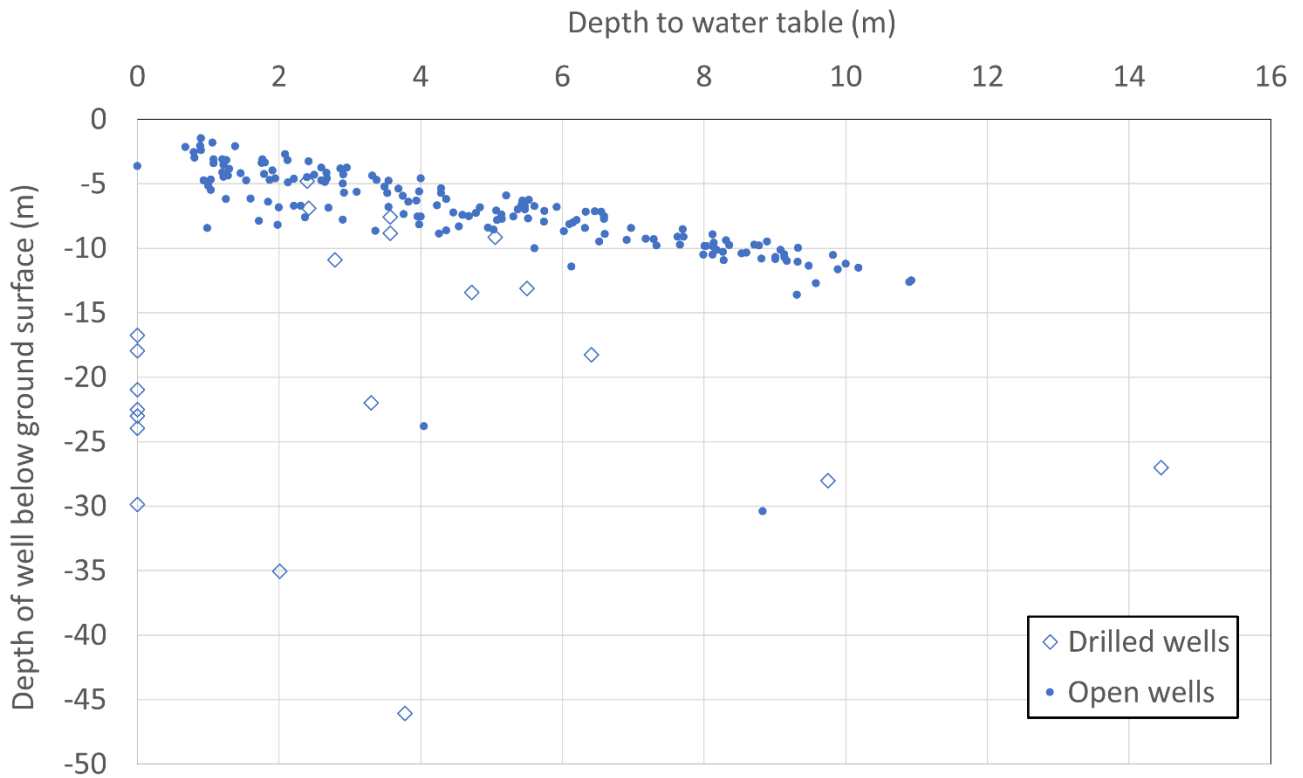


Figure 2.4: Depth of well (open and drilled) vs depth to water table from NHS well survey

Based on interviews with a Belizean drilling company, the hydrogeological characteristics are highly heterogeneous. Most domestic wells are drilled less than 20 m deep, although for larger wells for farms equipment is used to drill up to 200 m. Due to the lack of detailed geological and hydrogeological mapping information and the variability of the strata it is hard to predict the likely required well depth to reach suitable yields of fresh water, and therefore wells are drilled at a preferred location and then drilling abandoned and moved nearby to try again. Generally, if more than 300m from the coast, freshwater can be found, although saline groundwater can also be found interbedded with fresh water bearing strata.

As part of the aquifer mapping on the New River watershed, the data available has been analysed and shown in a series of figures described in Appendix A.

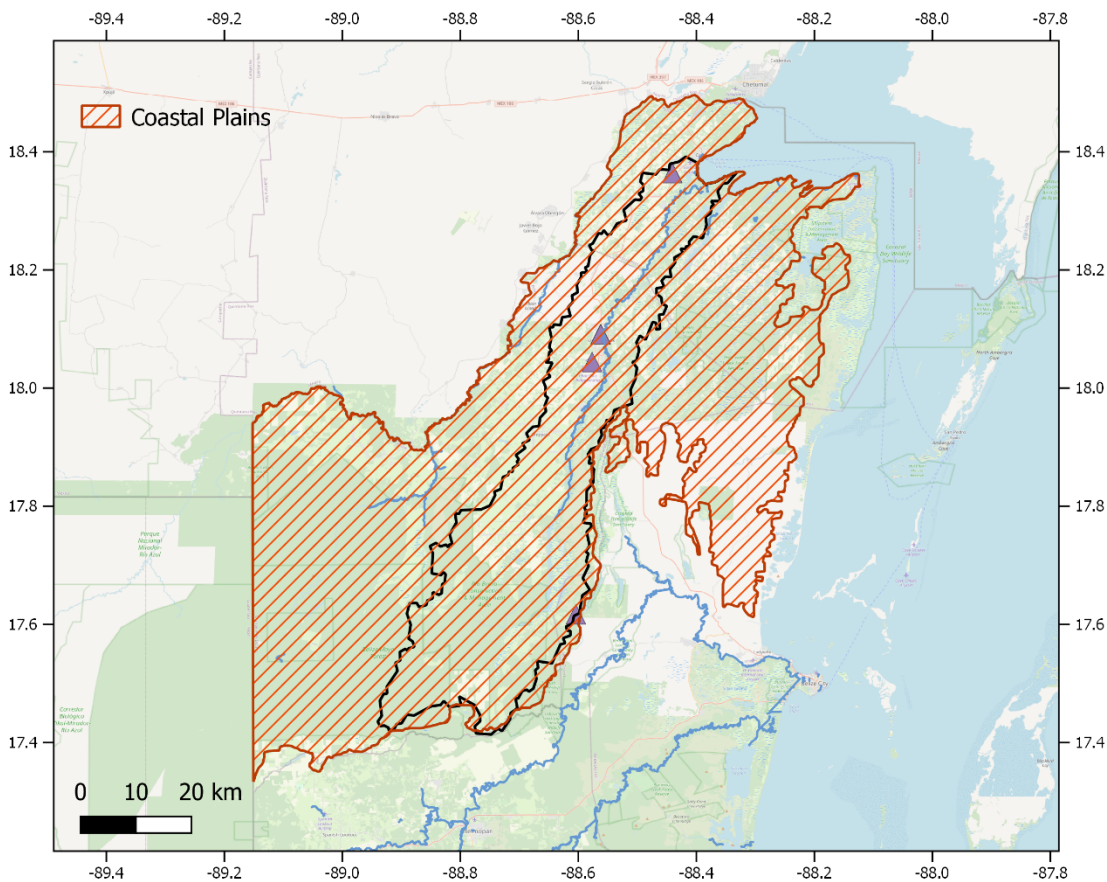


Figure 2.5: Coastal Plains groundwater province (provided by National Hydrological Service)

2.3 Groundwater exploitation

Groundwater is exploited in the New River watershed for domestic, municipal, industrial, and agricultural water supplies as follows:

- Belize Water Services (BWS) have three groundwater wells located in the New River Watershed, one located in Corozal and two located in around Orange Walk town. These wells are shown in the figure below (Figure 2.6) as pink triangles. Based on BWS production figures provided in February 2023 these abstracted 2.02 million cubic metres per year (MCM/yr), with Orange Walk being 1.03 MCM/yr (746,000 gallons per day) and Corozal being 0.99 MCM/yr (718,000 gallons per day);
- Rural communities (those not supplied by BWS) operate wells either privately or through the rudimentary water systems (RWS) which are operated by village water boards. It is understood that the Department of Rural Transformation holds data on the location of these systems, their number of connections and approximate production rates which if made available could be used to estimate the approximate groundwater abstraction from these systems. The NHS conducted a survey of 391 wells (see Figure 2.6), both open and boreholes, predominantly for domestic and RWS and a small number of agricultural wells. These provide well depth and depth to water table but do not provide estimates of production rates. Groundwater abstraction data for non-BWS systems is not available. However, if it is assumed that the population of the New River watershed is 50,000 (based on WorldPop data for 2020) and that BWS serves 25,000 through the 5,700 connections in the Orange Walk area, the remaining 25,000 persons, with a demand of 50 US gallons per day would consume 1.72 MCM/yr.

This estimate is subject to considerable uncertainties, and requires actual production data from non-BWS water supply systems to verify, but does provide an order of magnitude estimate;

- Industries such as the Belize Sugar Industries, Breweries, quarries and water bottling plants abstract groundwater in the catchment based on annual licenses provided by the National Hydrological Service. Based on actual abstraction volumes over the period 2019 to 2022 inclusive, these abstracted 0.5 MCM/yr from groundwater sources. It should be noted that not all industrial users apply for license to abstract, or provide actual abstraction figures, therefore this is likely to be a substantial underestimation of the true figure;
- Small scale farmers, and larger commercial farmers own and operate private wells for irrigation. Nationally, about 10 percent of the agriculture land under production at any given time is irrigated and the remainder is rainfed (Caribbean Community Climate Change Centre, 2015). Sugar cane is predominantly rain-fed, but there is concern that irrigation may be required in future to sustain production in the warmer, drier conditions projected with climate change. Data on agricultural water consumption is not collected at present, however, the Ministry of Agriculture have recently developed the Belize Agriculture Information Management System (BAIMS). This contains information on the water source of each farm surveyed. BAIMS data provided by the Ministry of Agriculture for northern Belize is mapped in Figure 2.7 showing the location of farms by water source. A total of 8594 farm data points were provided, of which 1723 have a well as their water source, 711 have a well and another water source, 4841 farms use rainfall only as a water source, and the remaining 1319 use other sources of water (i.e. not wells, or rainfall alone). The figure shows concentrations of farm wells in the Libertad/Concepcion to Corozal areas, and again in the area around Shipyard south towards Indian Creek. The areas around Little Belize and Neuland also contain large numbers of farms using wells. It is recommended that the BAIMS data is supplemented with information on actual patterns of farm water abstraction.

The following section provides some more detail on BWS groundwater production. BWS has three groundwater wells located in the New River Watershed, one located in Corozal, two located in and around Orange Walk town and one in Lemonal, Belize District. These wells are shown in the figure below (Figure 2.6) as purple triangles.

Data on water production for wells located in the New River Watershed was obtained from BWS and values from 2016 to 2020 are shown in the next figures as well as monthly means for all wells (Figure 2.8 and Figure 2.9).

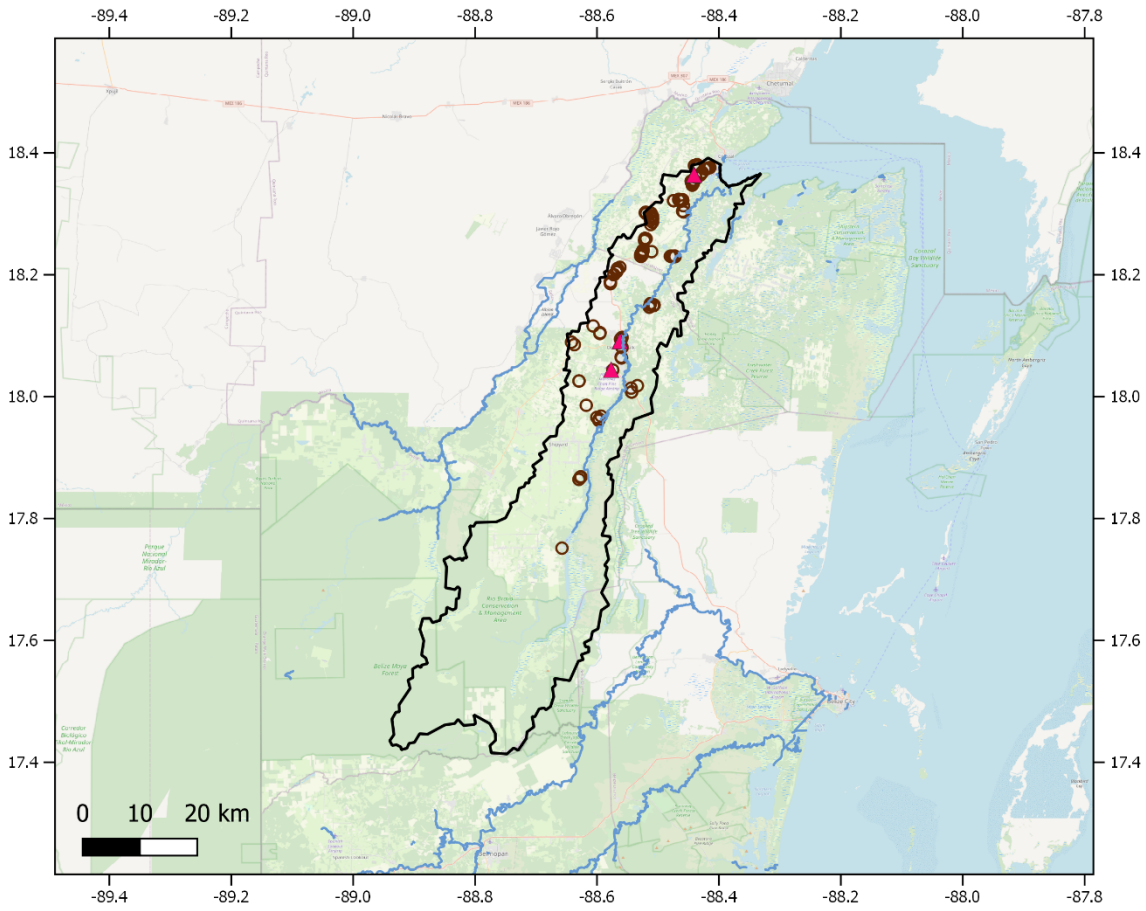


Figure 2.6: Wells located within the New River Watershed. Belize Water Services sources (pink triangle) and surveyed by the NHS (brown circle)

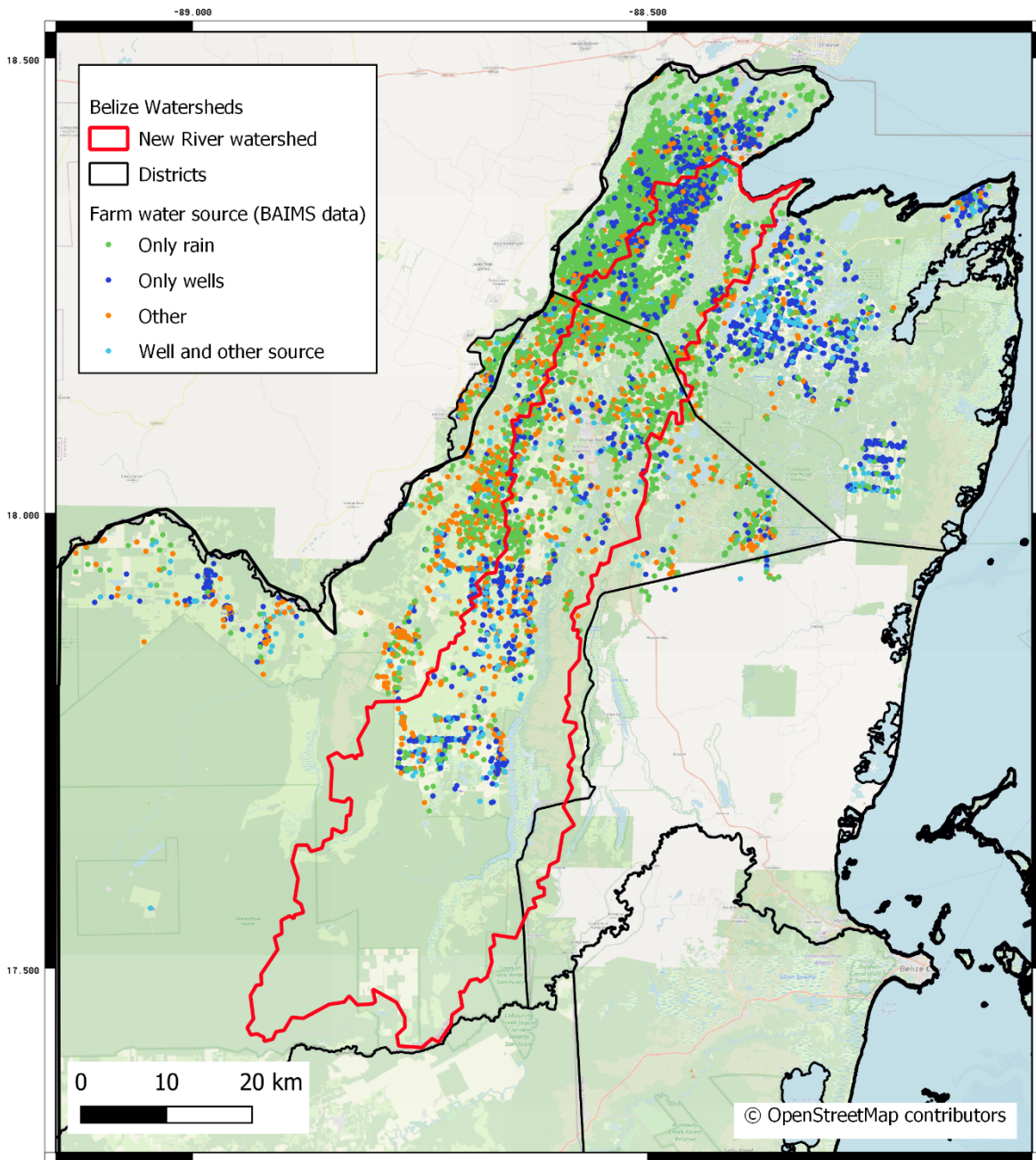


Figure 2.7: Location of farms in northern Belize disaggregated by farm water source

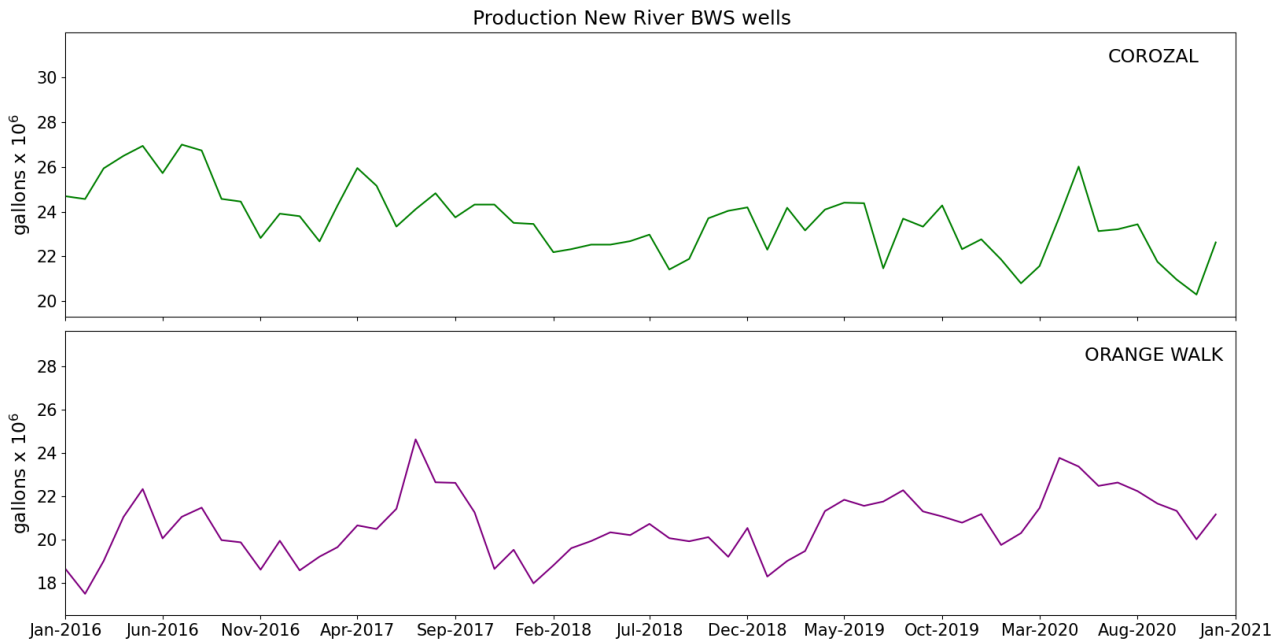


Figure 2.8: Monthly production data for BWS wells in the New River watershed

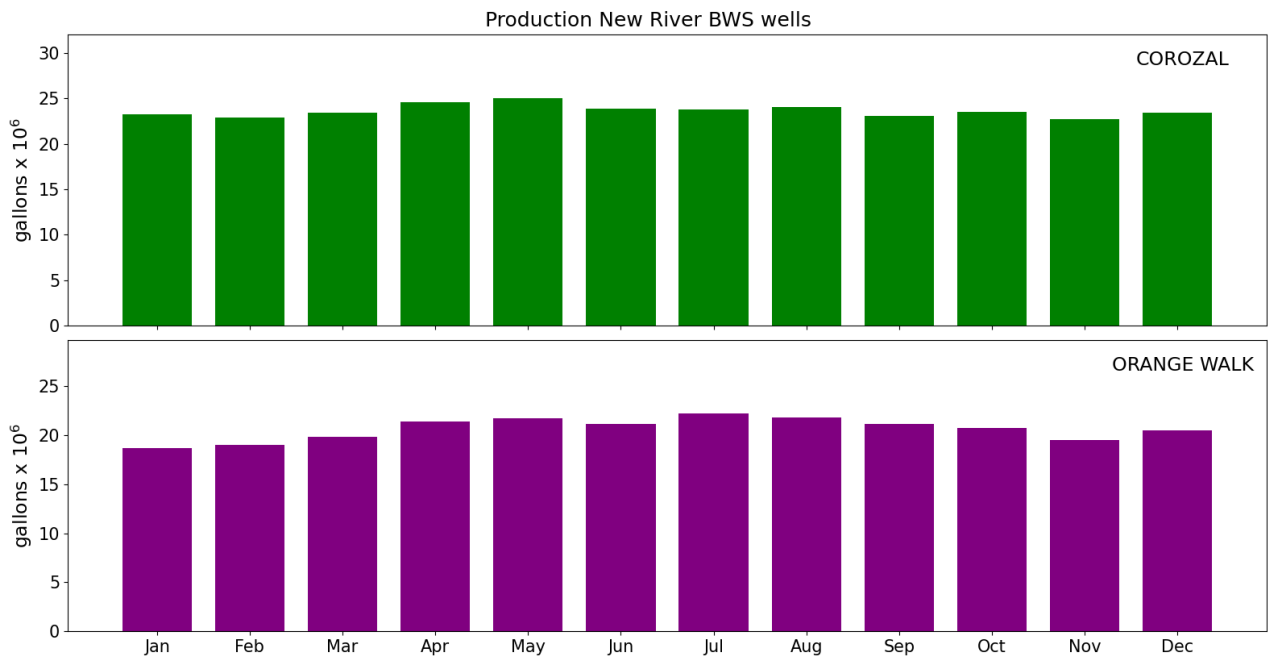


Figure 2.9: Mean monthly values of production for the BWS wells in the New River watershed

2.4 River flow

The NHS records daily stage values for the New River at the Tower Hill bridge. Records extend from 1992 to present day, with some periods of missing data Figure 2.10. This has been converted into flow using a rating curve provided by the NHS. Annual average flow is shown in Figure 2.11 and is on average 530 MCM/year (million cubic metres per year), with missing periods infilled using monthly average values.

Figure 2.12 shows the monthly flow statistics for the gauge, showing the dry season conditions from January to May with a median flow of around 10 m³/s with a small range of uncertainty. In the wet season between June and November this increases towards 25 m³/s with much greater variability as a result of peaks in flow associated with rainfall events.

The topographic catchment area upstream of the gauge is 1,400 km², and based on an annual average rainfall at the Tower Hill rainfall gauge of 1,400 mm/year the total rainfall volume in the catchment is 1960 MCM/year. The annual average river flow is 530 MCM/year, and therefore approximately 27% of catchment rainfall is being converted into river flow. It should be noted that this is an approximate calculation and assumes that both rainfall and river flow data are accurate and representative of the catchment conditions and that no groundwater flow crosses the topographic catchment boundary, which, given the flat and karstic nature of the geology, may not be the case.

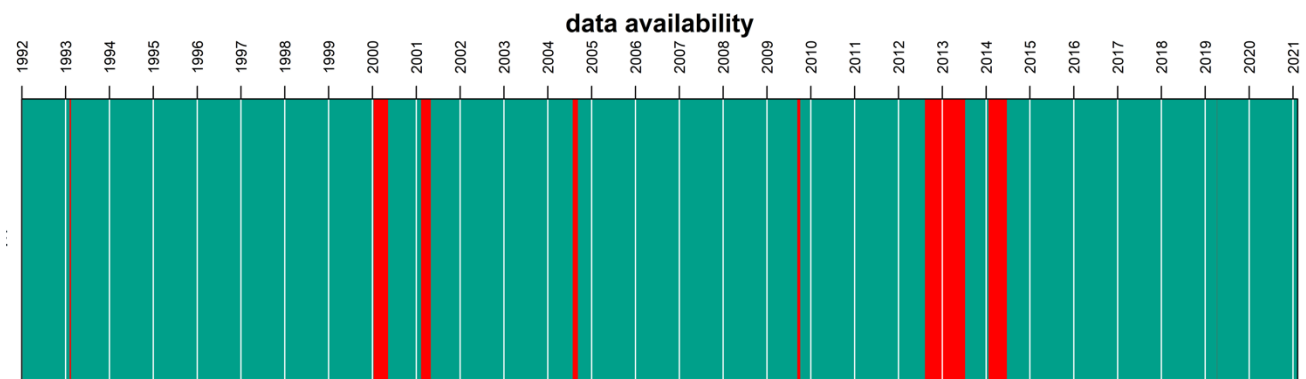


Figure 2.10: Tower Hill stage data showing periods of missing data in red

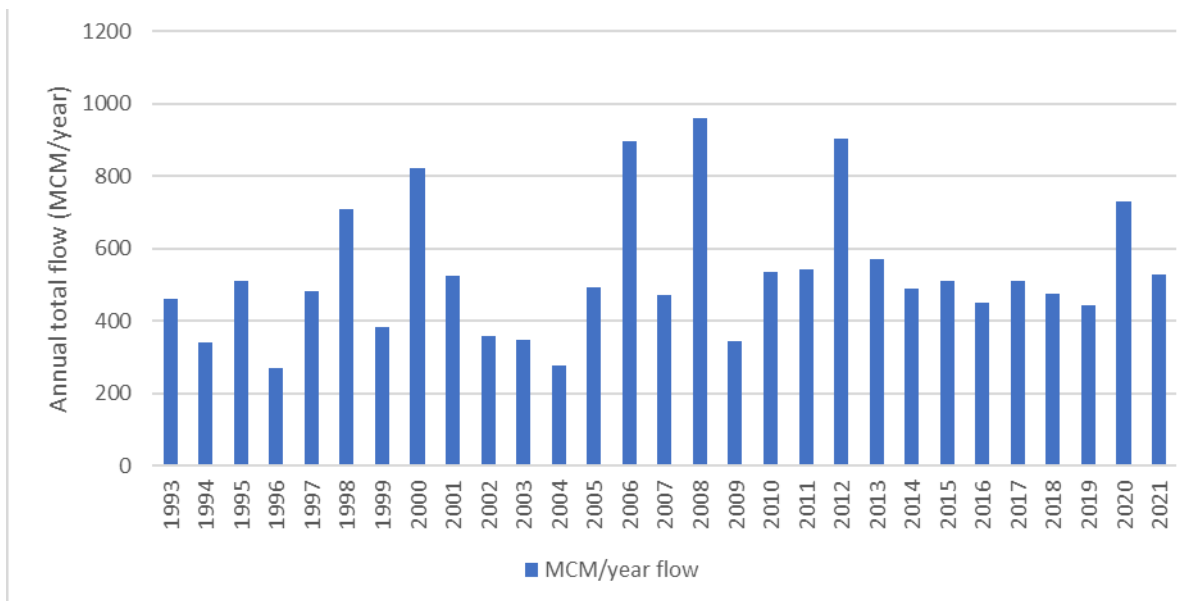


Figure 2.11: Annual total flow volumes for the New River at Tower Hill

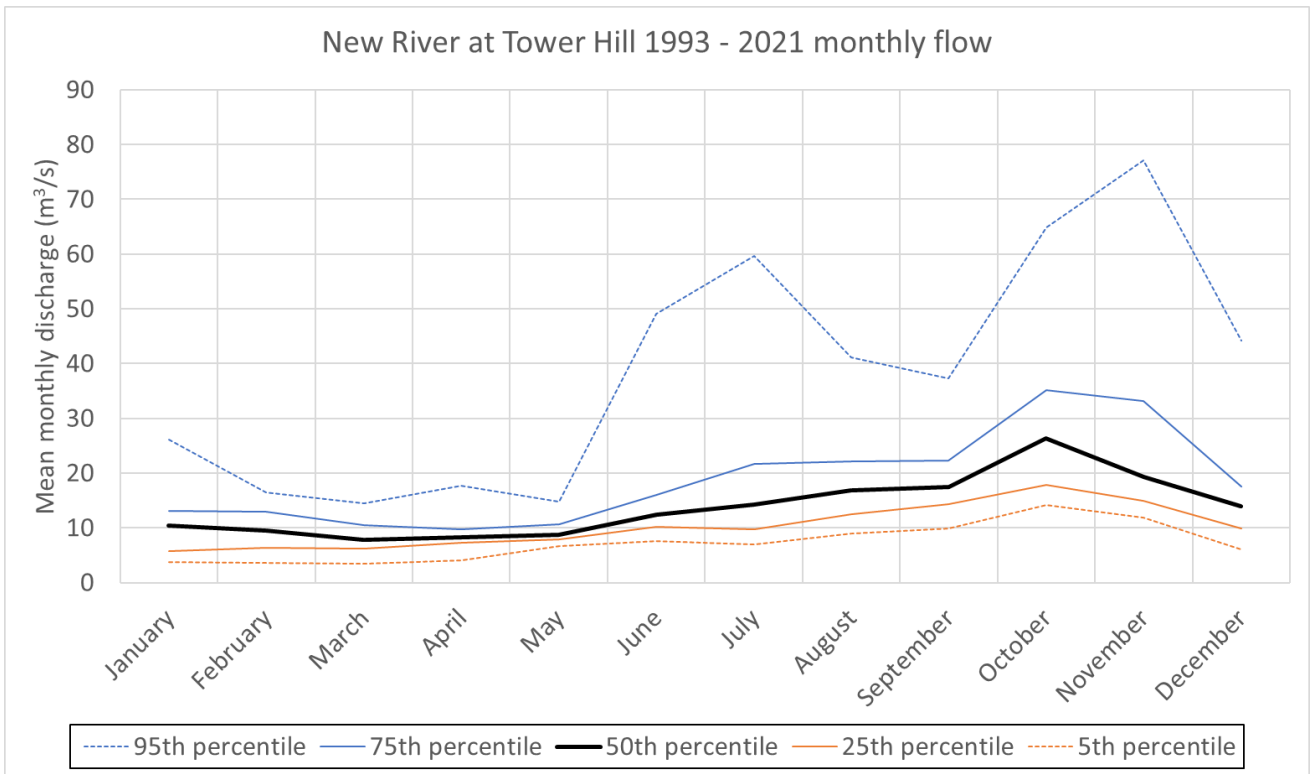


Figure 2.12: Monthly flow statistics for the New River at Tower Hill over the period 1993 to 2021

3 Assessment of key risks to water resources

Based on consultations with the Stakeholder Working Group (SWG) during the in-country visit in November 2022 and reflected in the Inception Meeting Report (Output 2.3), the following was found to be the key risks to water resources in the New River watershed:

1. Saltwater Intrusion, in both river systems (Belize River, New River) and in coastal aquifers;
2. Climate change resulting in reduced levels of rainfall in future and potentially requiring more groundwater abstraction for irrigation;
3. Increased population pressures on water resources;
4. Persistent Organic Pollutants (POPs) in the New River;
5. Faecal coliform, nitrate and other pollutants occurring as a result of agricultural activities and the presence of point source pollution such as soakaways;
6. Trace pharmaceuticals in groundwater; and,
7. Loss of forest cover and conversion to farmland with attendant changes in water demand for agriculture and agricultural runoff/infiltration of agrochemicals to aquifers.

The SWG also identified the following areas of quality and quantity risks which require monitoring along the New River during a focused discussion (hotspots):

1. Wells that are no longer viable due to limited supply or salination, being used as garbage dumps, pit latrines and soakaways;
2. Libertad, Caledonia, and wells in Consejo that are next to pit latrines;
3. Distilleries (Caribbean International Brewery, Cuello's Distillery);

4. Poultry producers (Blue Creek);
5. Shrimp industry (Libertad);
6. Mechanics and butchery shops;
7. Tortilla factories; and,
8. Bottled water companies (Zeta Water, Trial Farm, Yo Creek, there are at least 5 in Corozal).

4 Water balance calculation

4.1 Overview

Water availability and sustainable water management benefit from a good understanding of the hydrologic cycle and water balance. A water balance evaluation provides an accounting of the rates of water movement and the change in water storage in the atmosphere, land surface and subsurface. It can also be beneficial in evaluating availability and sustainability of water supplies, underpinning effective water-resource and environmental planning and management (Healy et al., 2007).

The simplest form of water balance equation can be expressed as follows:

$$P = Q + E \pm \Delta S \quad (4.1)$$

Where P is precipitation; Q is surface runoff; E is evapotranspiration and ΔS is change in storage.

Although simple in concept, water balance calculations are usually complicated by the lack of direct measurements of its components, as is particularly the case for evapotranspiration data. Often a water balance is calculated by numerical or hydrological models, and particularly useful is the use of numerical models to estimate groundwater recharge. However, a water balance can also be a simplified hydrological calculation to account for all the inputs, and outputs of the area of interest.

Several examples of such calculations exist in the literature from Palmer (1965), which will be used here for Belize, to Freeze and Cherry (1979), based on precipitation, runoff, evapotranspiration and changes in storage for surface water and groundwater. For groundwater-dominated catchments, water balance calculations such as the one proposed by Freeze & Cherry (1979), can be complex due to differences in groundwater and surface water boundaries and the uncertainties in inflows into and out of the systems.

To obtain a simplified water balance calculation at a point in the New River watershed, ground data and averages of Earth Observation (EO) -based data, where certain assumptions were made. The EO-based data include evapotranspiration and surface runoff. For this report we have also not considered groundwater abstraction. Due to the complexity of recharge processes and limited observations, estimating groundwater recharge without a numerical model is one of the main difficulties for a water balance calculation. For the purposes of this assessment, a simple regression equation developed by Gemitzi et al. (2017) relating precipitation and evapotranspiration was used. Both calculations of groundwater recharge and water balance were compared to the scarce data available to provide an overview of whether this approach is valid. For this initial calculation of a water balance, abstractions were not considered.

4.2 Methodology

4.2.1 Mathematical approach

The water balance equation used in Belize is based on Palmer (1965), as part of the methodology used in Falalakis & Gemitzi (2020), describing the flow of water into and out of a system (Equation (4.2)):

$$P + L = ET + SR + I \tag{4.2}$$

Where, P is precipitation, L is moisture loss from the soil in the form of capillary rise or transport through vegetation, ET is evapotranspiration, SR is surface runoff and I is the infiltration to the vadose zone (soil water) and to groundwater, which results in changes in subsurface storage; and L is moisture loss from the soil in the form of capillary rise or transport through vegetation. This I parameter can be approximated as groundwater recharge. All parameters are measured with units of volume per unit of time (e.g. m^3/time) or units of length (vertical depth of water) per unit of time (e.g. $\text{mm}/\text{day}/\text{time}$).

Based on the water balance proposed before, the system could be conceptualised according to Figure 4.1, where evapotranspiration is defined as the aggregation of evaporation and transpiration; and infiltration recharges the aquifers (represented as groundwater recharge).

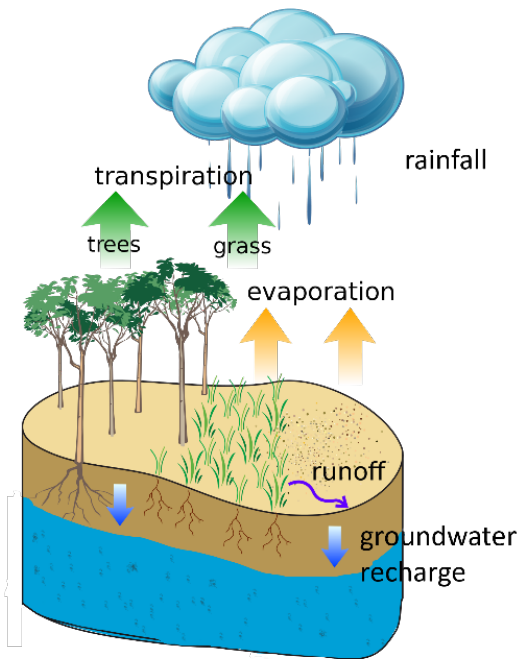


Figure 4.1: Conceptual diagram of water balance based on Palmer (1965) - modified from Toews (2007)

4.3 Data description

4.3.1 Precipitation

Spatial and temporal variations of precipitation are difficult to represent adequately due, mainly, to availability and quality of observed data. The quality of observed data, obtained from rainfall gauging stations, can be limited by the location and errors in measurements, and lack of temporal resolution. EO data, obtained from gridded precipitation products, can provide an alternative to observed data; however, estimates of precipitation from satellite data, can be limited by temporal sampling and algorithm errors (Centella-Artola et al., 2020). For the particular case of the New

River watershed, two rainfall gauging stations provide precipitation data (Belize MET Services) from Libertad and Tower Hill (Figure 4.2), and these datasets could be completed with EO data if needed for spatial calculations. Figure 4.3 shows timeseries of rainfall in both gauging stations.

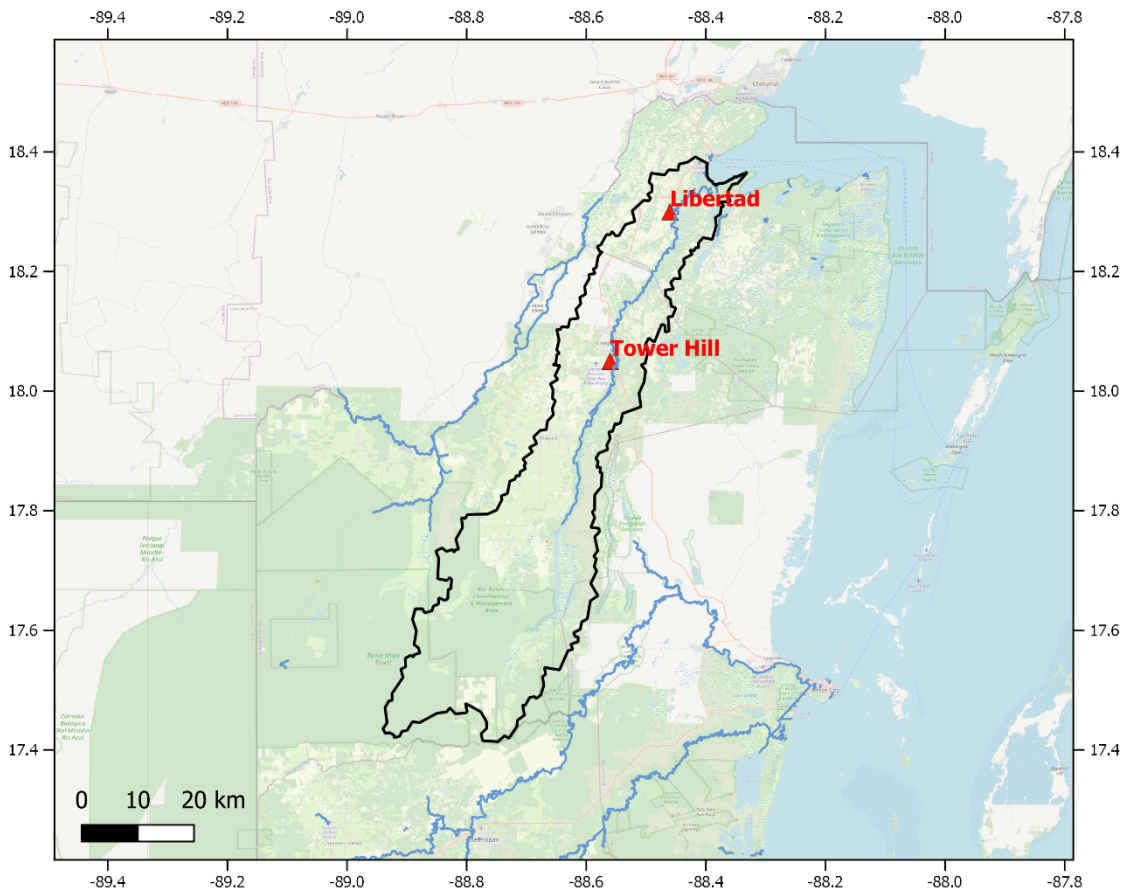


Figure 4.2: Rainfall gauging station location

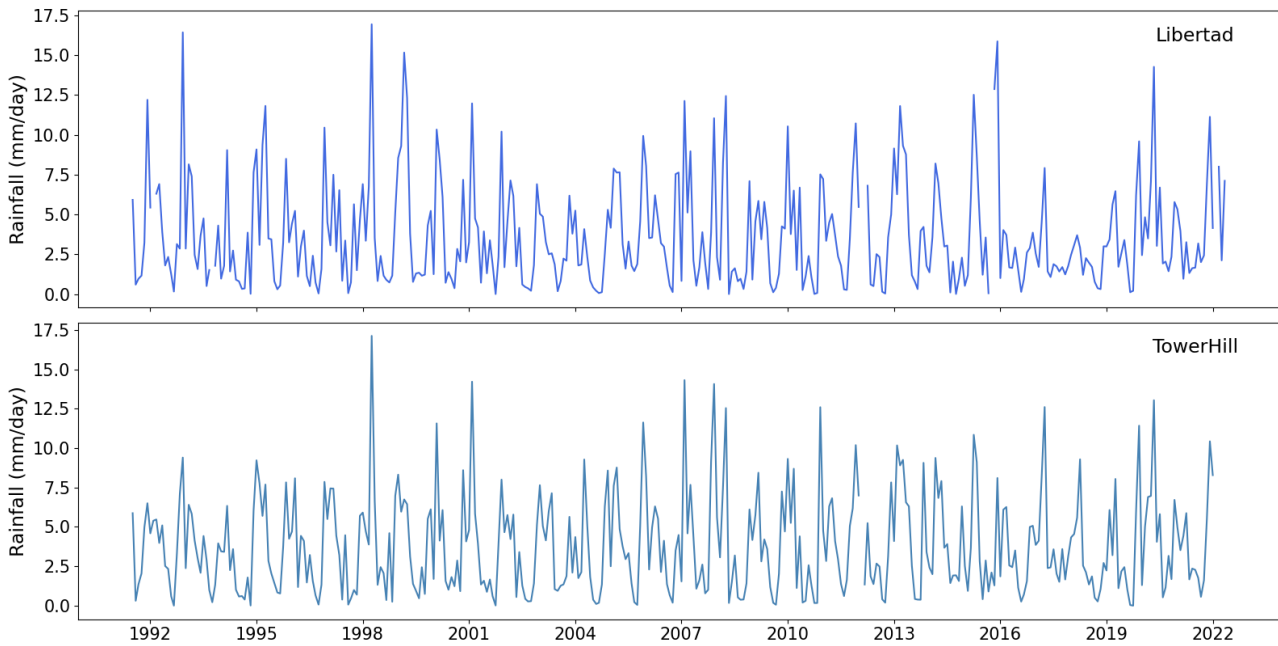


Figure 4.3: Rainfall from gauging stations located in the New River watershed (Belize MET services). Averaged monthly values in mm/day

4.3.2 Evapotranspiration

Due to the difficulty in measuring evaporation and transpiration directly, there is a lack of reliable data, and accurately estimating evapotranspiration (ET) can be complex. This is no different for Belize, but remote sensing can be used to estimate values of ET globally. For the water balance calculation, MODIS ET gridded data sets at 500 m spatial resolution were used (Running et al., 2017). These are 8-day composites of ET, Latent Heat Flux (LE), Potential ET (PET) and Potential LE (PLE) along with a quality control layer. The initial algorithm for computation of MODIS ET (Mu et al., 2007) used the Penman–Monteith ET formula (Monteith, 1965) and MODIS land cover, albedo, Leaf Area Index (LAI), Fraction of Photosynthetically Active Radiation (FPAR) and Enhanced Vegetation together with daily meteorological reanalysis data from NASA’s Global Modeling and Assimilation Office. Timeseries of ET for Belize (and in particular for the New River Watershed at the grid cell where Tower Hill rainfall gauging station is located) is shown in Figure 4.4. ET values are very consistent for the 20-year period analysed.

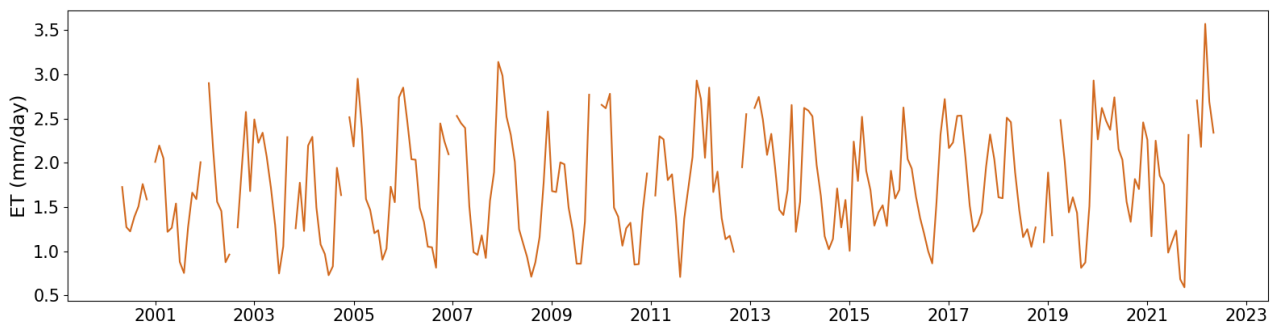


Figure 4.4: MODIS evapotranspiration timeseries for grid cell located at Tower Hill coordinates (New River), for the period 2001-2022. Averaged monthly values in mm/day

4.3.3 Surface runoff

Surface runoff for the water balance was obtained from ERA5, the 5th generation reanalysis project from the European Centre for Medium-Range Weather Forecasts (ECWMF). Reanalysis products combine model data and observations, using a technique called data assimilation, based on the method used by numerical weather prediction centres, where every few hours (12 hours at ECMWF) a previous forecast is combined with newly available observations to produce a new best estimate of the state of the atmosphere, called analysis, from which an updated, improved forecast is issued. Surface runoff is defined as the water that drains away over the surface. Runoff is a measure of the soil water availability, and can be used as an indicator of drought or flood (Hersbach et al., 2019). Timeseries of surface runoff for Tower Hill location in the New River watershed are shown in Figure 4.5.

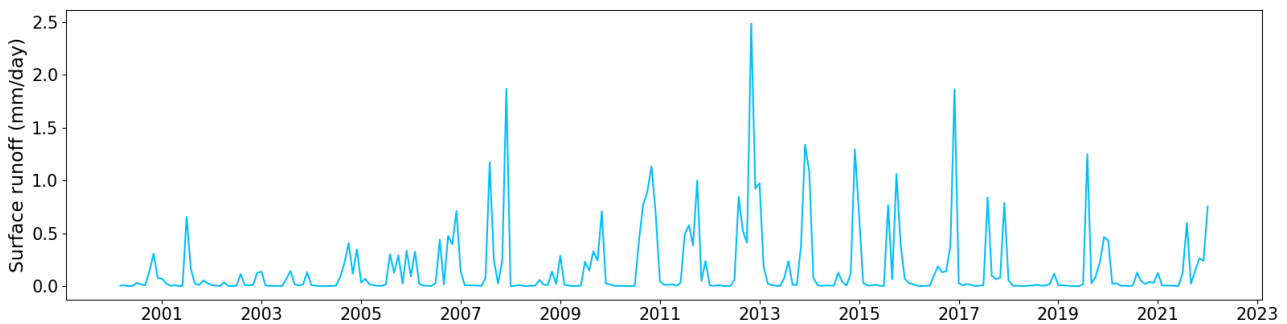


Figure 4.5: ERA5 surface runoff timeseries for grid cell located at Tower Hill coordinates (New River), for the period 2001-2022. Averaged monthly values in mm/day

4.3.4 Estimation of groundwater recharge

Groundwater recharge (GR) is computed using the regression equation developed by Gemitzi et al. (2017). As one of the main components of the water balance that is difficult to quantify due to the complexity of recharge processes and limited observations, GR for Tower Hill is estimated by a simple regression equation developed by Gemitzi et al. (2017), shown below (Equation (4.3)). The water quantity that infiltrates the surface to the subsurface can be used as an approximation of the infiltration (*I*) parameter in the water balance equation (Equation (4.2)).

$$GR = 0.5174 * (P - ET_{MODIS}) + 0.2154 \tag{4.3}$$

Where *GR* is groundwater recharge; *P* is precipitation; and *ET* is evapotranspiration.

For Tower Hill, whenever monthly *ET* exceeded monthly precipitation, negative groundwater recharge values were set to zero. Timeseries of GR for Tower Hill is shown in Figure 4.6.

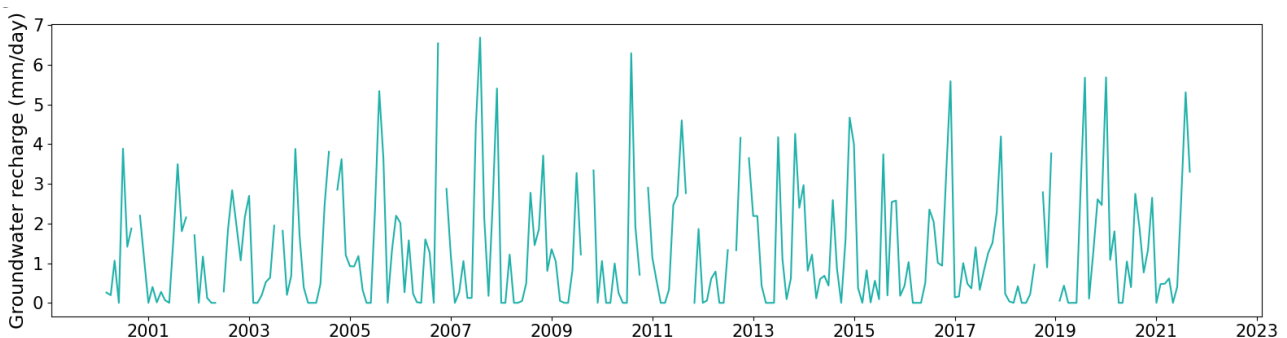


Figure 4.6: Estimated groundwater recharge timeseries for Tower Hill. Averaged monthly values in mm/day

4.4 Results and discussion

Based on all datasets of precipitation, evapotranspiration, and surface runoff, with estimated groundwater recharge, the water balance equation can be solved for moisture losses. A common outcome observed in Tower Hill is that rainfall is the largest component of the water balance when compared against the other parameters, which is easily observed when the sum per year is calculated. Results of the sum annual water balance for Tower Hill and for the period of available data (2001-2022) are shown in Figure 4.7.

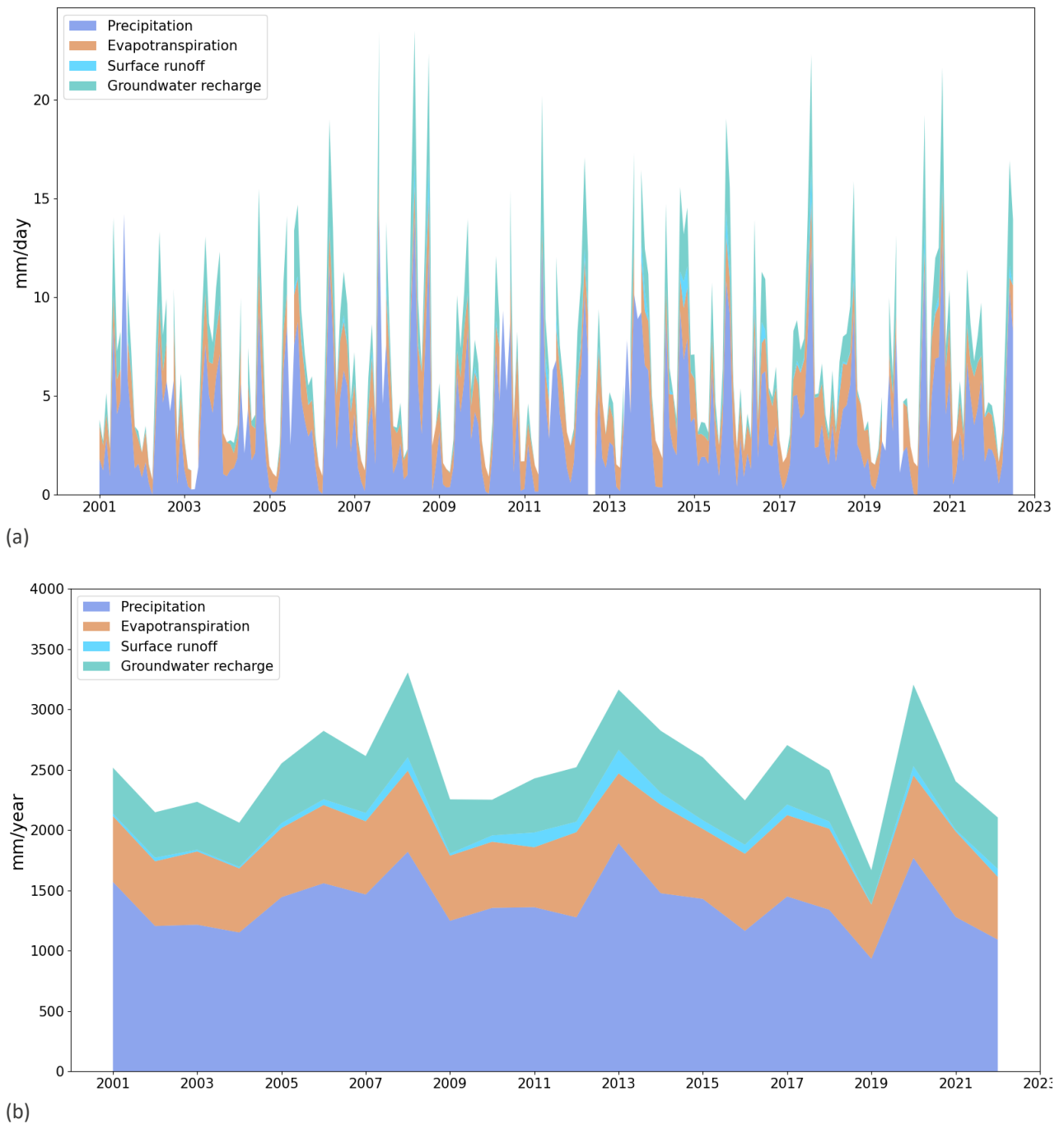
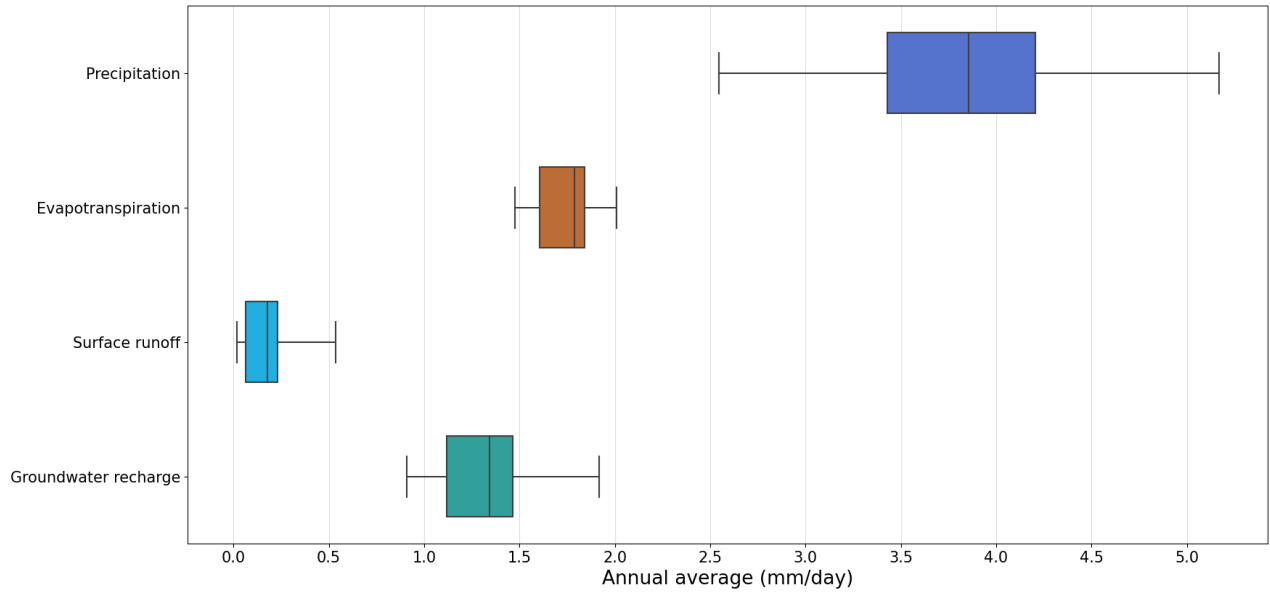


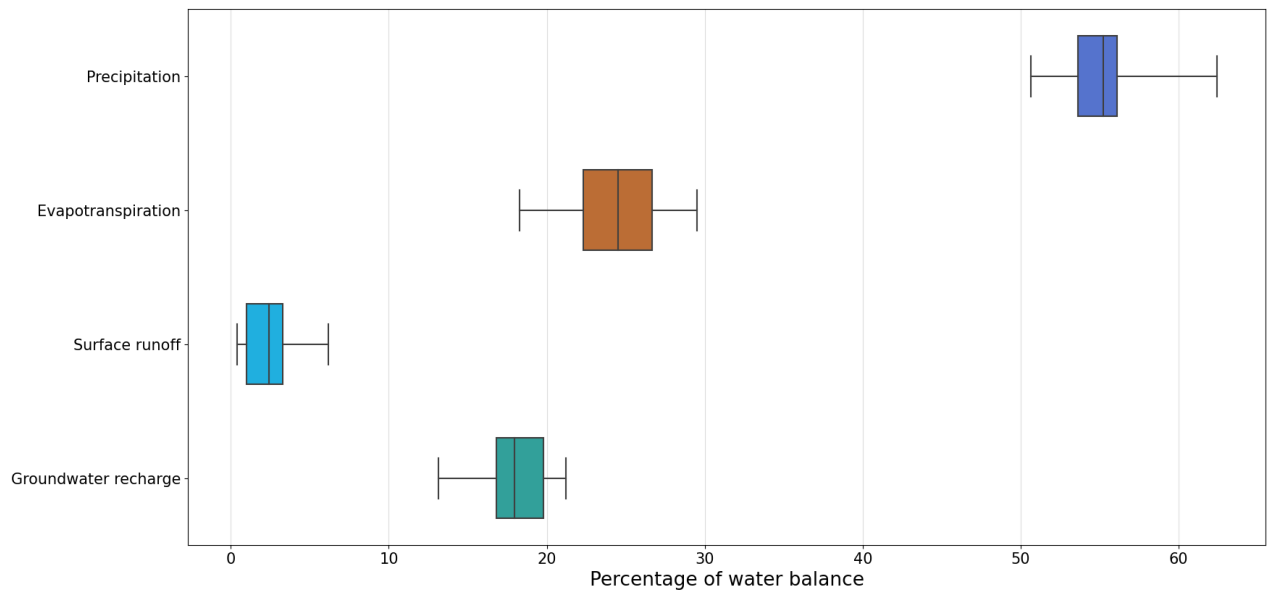
Figure 4.7: Stack areas for monthly values of the water balance in Tower Hill (a). Yearly sum of water balance values (b)

Based on long term averages of annual values in Tower Hill, the annual average rainfall is 1387 mm/year; annual average ET is 602 mm/year (43.4% of rainfall); annual average groundwater recharge is 454.6 mm/year (32.8% of rainfall); and annual average surface runoff is 62.7 mm/year (4.5% of rainfall).

Results of the mean annual water balance were calculated, as well as the percentages of each component to the water balance. These calculations are shown in box plots (Figure 4.8a). The boxes in these figures represent the middle 50% of all the datapoints. The bottom and top of the boxes represent the 25% and 75% percentiles respectively, and lines the median or middle quartile of the data. The whiskers extend to all data available representing the lowest and highest points in each dataset. Table 4.1 show the respective mean annual water balance values for Tower Hill. These results confirm the previous statement that rainfall accounts for the majority of the water balance, and precipitation is the most varied parameter, with values that range from approximately 2.6 to 5.5 mm/day. Surface runoff is the parameter with lowest and more constant values, with values that range from 0.1 to 0.6 mm/day. Estimated values of groundwater recharge present values in the range of 0.8 to 1.8 mm/day. Similar pattern is observed for the percentage of water balance for each component (Figure 4.8b). For the period 2001-2022, precipitation on average accounts for 53%, and is the largest component of the water balance, followed by ET with 24% on average. The smallest component is surface runoff with 1.2% on average.



(a)



(b)

Figure 4.8: Annual average water balance components in Tower Hill (2001–2022). Box lower and upper limits represent the lower and upper quartiles and black line the median value of the data set. Upper and lower whiskers extend to the smallest and highest values of the data

Table 4.1: Annual averages statistical values in mm per day

Tower Hill Parameters	Min	25% percentile	Annual average 50% percentile	75% percentile	Max
Precipitation	2.55	3.43	3.86	4.21	5.17

Tower Hill Parameters	Annual average				
	Min	25% percentile	50% percentile	75% percentile	Max
Surface runoff	0.02	0.06	0.18	0.23	0.54
ET	1.47	1.61	1.79	1.84	2.01
Groundwater recharge	0.91	1.12	1.34	1.47	1.92

Table 4.2: Annual percentage statistical values in percentage of the total water balance

Tower Hill Parameters	Annual percentage				
	Min	25% percentile	50% percentile	75% percentile	Max
Precipitation	48.69	51.14	52.32	53.37	58.91
Surface runoff	0.34	0.93	2.36	3.12	5.71
ET	19.63	22.06	23.88	26.21	28.44
Groundwater recharge	13.68	17.28	17.79	19.51	21.33

Conversion of groundwater recharge rate to volume

To convert the annual average groundwater recharge rate (units of mm/day) to volume of water (million cubic metres per day (MCM/day), the New River watershed area is multiplied by the annual average groundwater recharge rate (50th percentile). This gives the total volume of groundwater recharge. This can be done approximating the calculation that has been done for Tower Hill, and applied as an average for the whole watershed (see Tower Hill location in Figure 4.2).

New River watershed area = 1864 km².

New River volume of groundwater recharge = 1864 km² x 1.34 mm/d = 2.5 MCM/day, or 912 MCM/year.

4.5 Summary

For the current water balance calculation in Belize, the methodology proposed by Falalakis & Gemitzi (2020). Falalakis et al. (2020) was used as it included a basic calculation of groundwater recharge that most other water balance calculation methods do not. This calculation (Gemitzi et al., 2017) allows for groundwater recharge, based on an empirical relationship between precipitation and evapotranspiration, to be estimated and consequently used in the water balance equation. Observed rainfall data, MODIS ET, and ERA5 surface runoff data were processed and incorporated in the process. This approach was applied to Tower Hill in the New River watershed for the period of data available (MODIS ET was available since 2001), covering a 21-year period: 2001-2022. Monthly water balance parameters were computed (groundwater recharge and moisture loss). Several assumptions were made in this approach as the lack of data at this stage of the project does not allow for a more detailed calculation (i.e. at catchment scale). Based on long term averages of annual values in Tower Hill, the annual average rainfall is 1387 mm/year; annual average ET is 602 mm/year (43.4% of rainfall); annual average groundwater recharge is 454.6 mm/year (32.8% of rainfall); and annual average surface runoff is 62.7 mm/year (4.5% of rainfall).

In a warming climate, higher temperatures are expected to increase evaporative demand, but how much this will induce moisture deficits and evaporative stress, as opposed to increased evapotranspiration, is partially dependent on climate (Maxwell & Kollet, 2008). Plant water availability is controlled by local precipitation and soil moisture, but soil moisture and streamflow may also be supported by shallow groundwater (Fan, 2015). Under climate change, increased evapotranspiration may shift the fraction of precipitation that runs off as surface water or infiltrates to the subsurface as recharge. Long-term shifts in recharge patterns can change groundwater levels (Portmann et al., 2013), with potentially negative consequences for availability of freshwater on the country.

5 Concluding remarks

This report highlighted the geology, soils, watersheds, and hydrogeology of the New River watershed and gave an overall impression of the freshwater resources currently available for the country. The New River watershed is characterised by low lying topography and shallow unconfined aquifers consisting of heterogenous carbonate deposits. These are mainly exploited for domestic and agricultural purposes, with some industrial abstraction. Almost all wells tap into shallow aquifers with depths to the water table between 1 and 10m below the ground surface. Notably one well at the Caribbean International Brewery reached fractured dolomite and produced artesian flow, further deep drilling may reveal high yielding aquifers in the older carbonate deposits dipping north beneath the New River catchment. However, the depth to these deposits is not well understood.

Recharge has been estimated at around 30% of the approximately 1400mm annual average rainfall, based on analysis of data for the Tower Hill station which is approximately in the centre of the New River watershed, although this estimate is subject to some uncertainty. Long term river flow data indicate a long term average flow rate of around 530MCM/year, 27% of rainfall is discharged as river flow (a combination of groundwater derived baseflow and surface runoff).

Groundwater abstraction by BWS is around 2 MCM/year (around 1 MCM/yr each for Orange Walk and Corozal respectively), around 1.7 MCM/yr for non-BWS systems within the New River watershed. Industrial abstraction data indicates around 0.5 MCM/yr is abstracted, although this is likely a substantial underestimate as not all industrial users obtain licences or report abstractions. Mandatory licencing and reporting of industrial and commercial water consumption is recommended for significant users in order to more effectively manage water resources. While it is possible to estimate groundwater abstraction for domestic purposes and to a limited extent industrial purposes, water abstraction for agriculture is largely unknown, although some limited data on the location of agricultural wells exists, no data on their actual pumping volumes is available. An investigation of agricultural water consumption is recommended to provide such data.

In terms of groundwater monitoring, this report provides an overview of the hydrogeology of the New River watershed on which to begin the process of a monitoring system design. The increasing population, intensification of agricultural development and drier and warmer climate in future underscores the need for monitoring of both groundwater quantity and quality moving forward. Together with the assessment of drought risks (Output 3.1), the path forward to design an effective groundwater monitoring system is clearer. Output 4 will begin the development of the monitoring system.

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Appendices

A Geology and Hydrogeology - New River

Table A.1: Geology & Hydrogeology

Figure	Description	Source
Figure A.1	Surface Geology	Geology mapping provided by the Geology and Petroleum Department.
Figure A.2	Surface Geology and BAIMS wells location	Geology mapping provided by the Geology and Petroleum Department. BAIMS data provided by the Ministry of Agriculture, Food Security and Enterprise.
Figure A.3	GWPC well survey - type of well	Well location data provided by the National Hydrological Service.
Figure A.4	GWPC well survey - depth of well	Well location data provided by the National Hydrological Service.
Figure A.5	GWPC well survey - depth of water table	Well location data provided by the National Hydrological Service.
Figure A.6	MOH WQ Conductivity	Water quality data provided by the Ministry of Health and Wellness. Locations inferred by HR Wallingford based on settlement names.
Figure A.7	MOH WQ Nitrate as N	Water quality data provided by the Ministry of Health and Wellness. Locations inferred by HR Wallingford based on settlement names.
Figure A.8	Flow direction	Flow direction inferred by HR Wallingford. Digital Elevation Model from the World Bank data catalog and licenced under Creative Commons Attribution 4.0 https://datacatalog.worldbank.org/search/dataset/0039936 .

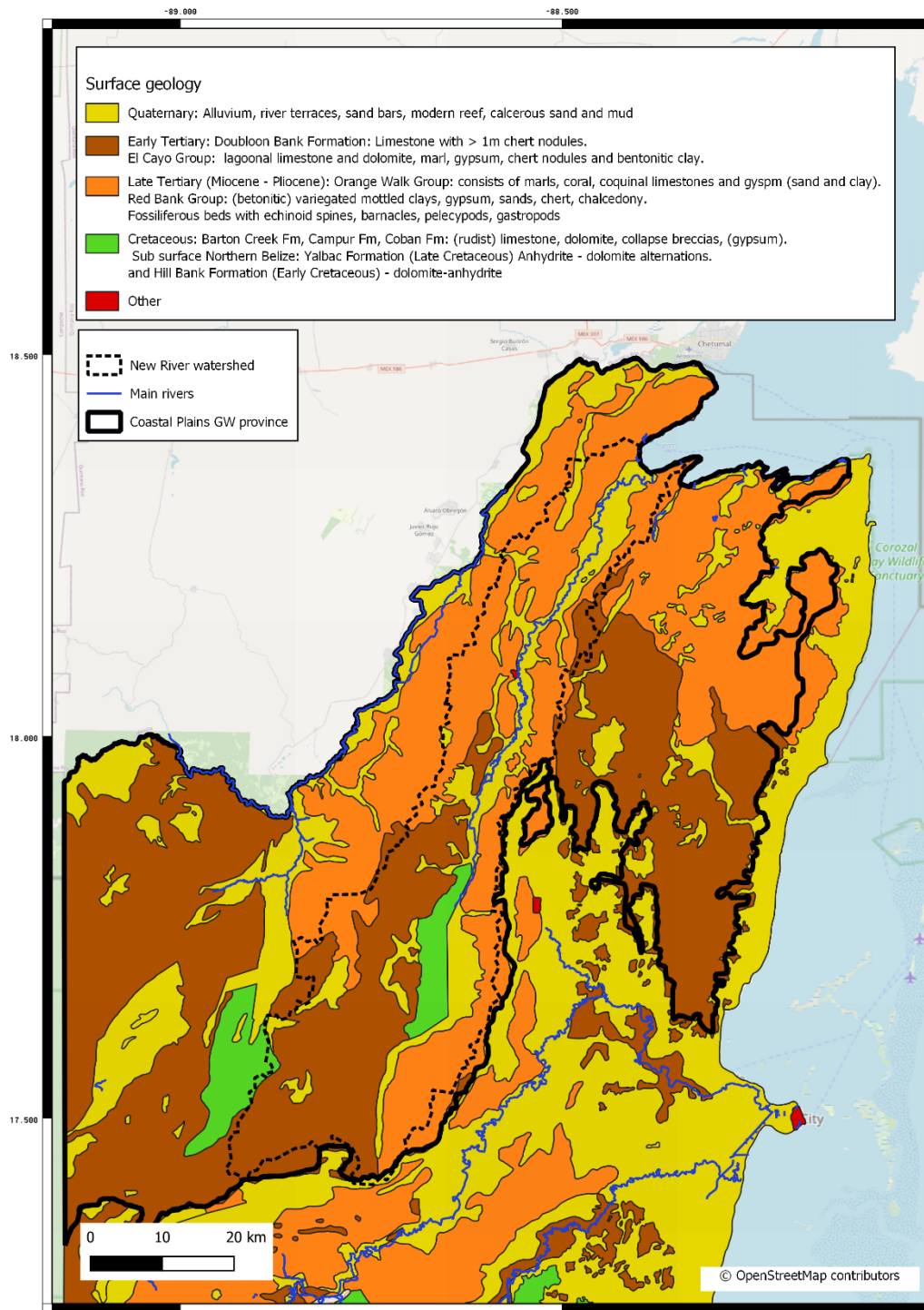


Figure A.1: Surface geology at the New River watershed

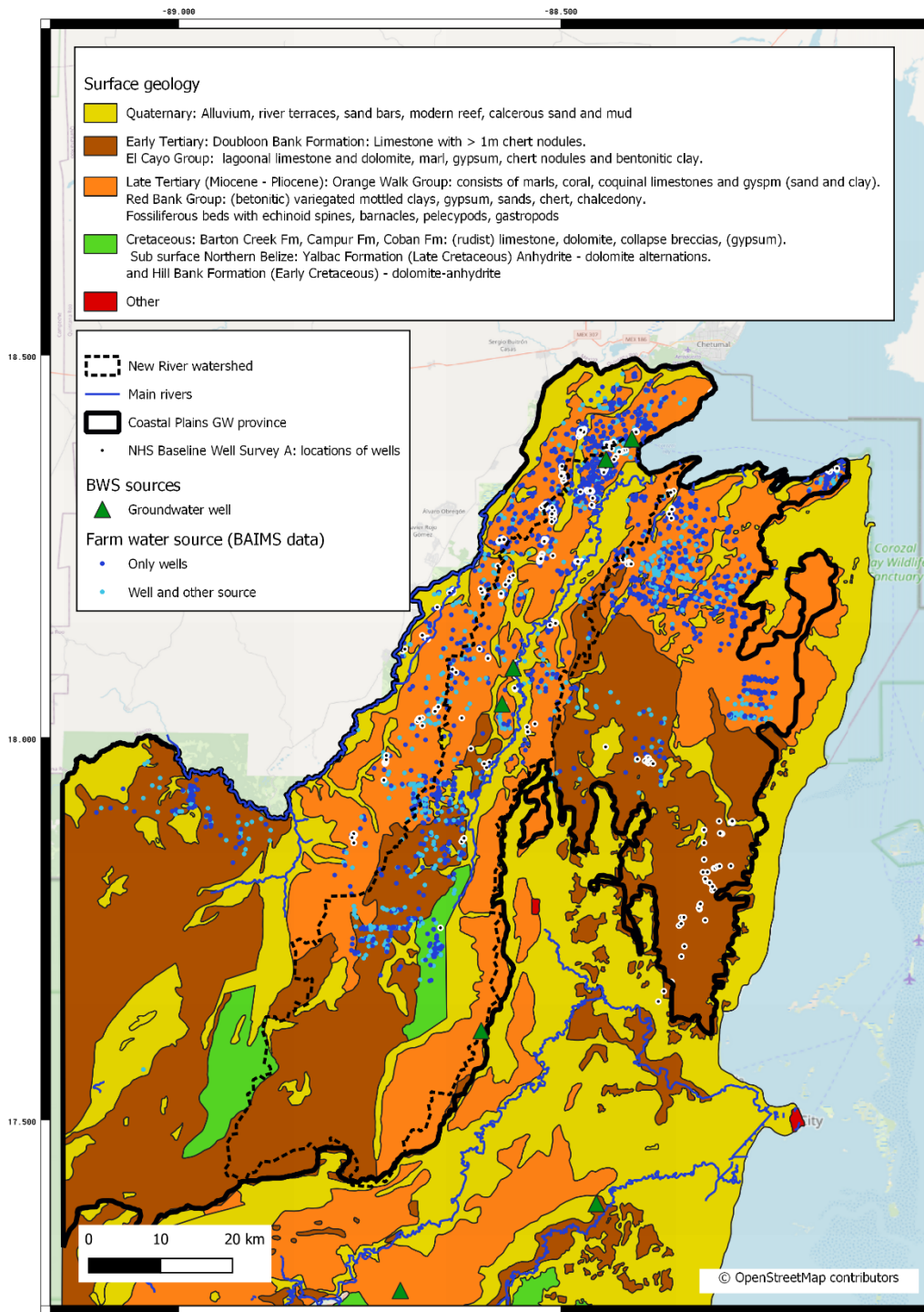


Figure A.2: Surface geology at the New River watershed and wells

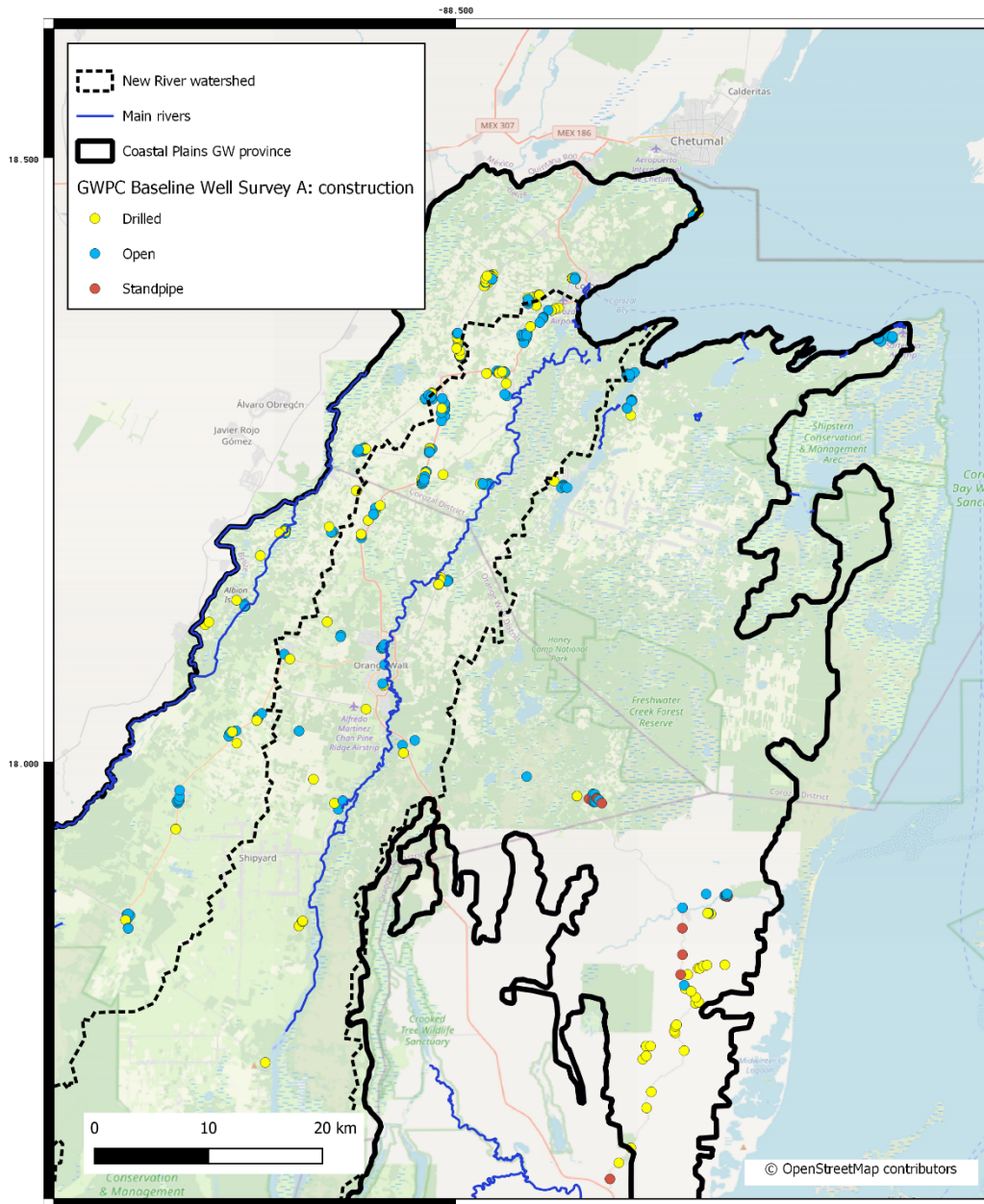


Figure A.3: NHS wells construction

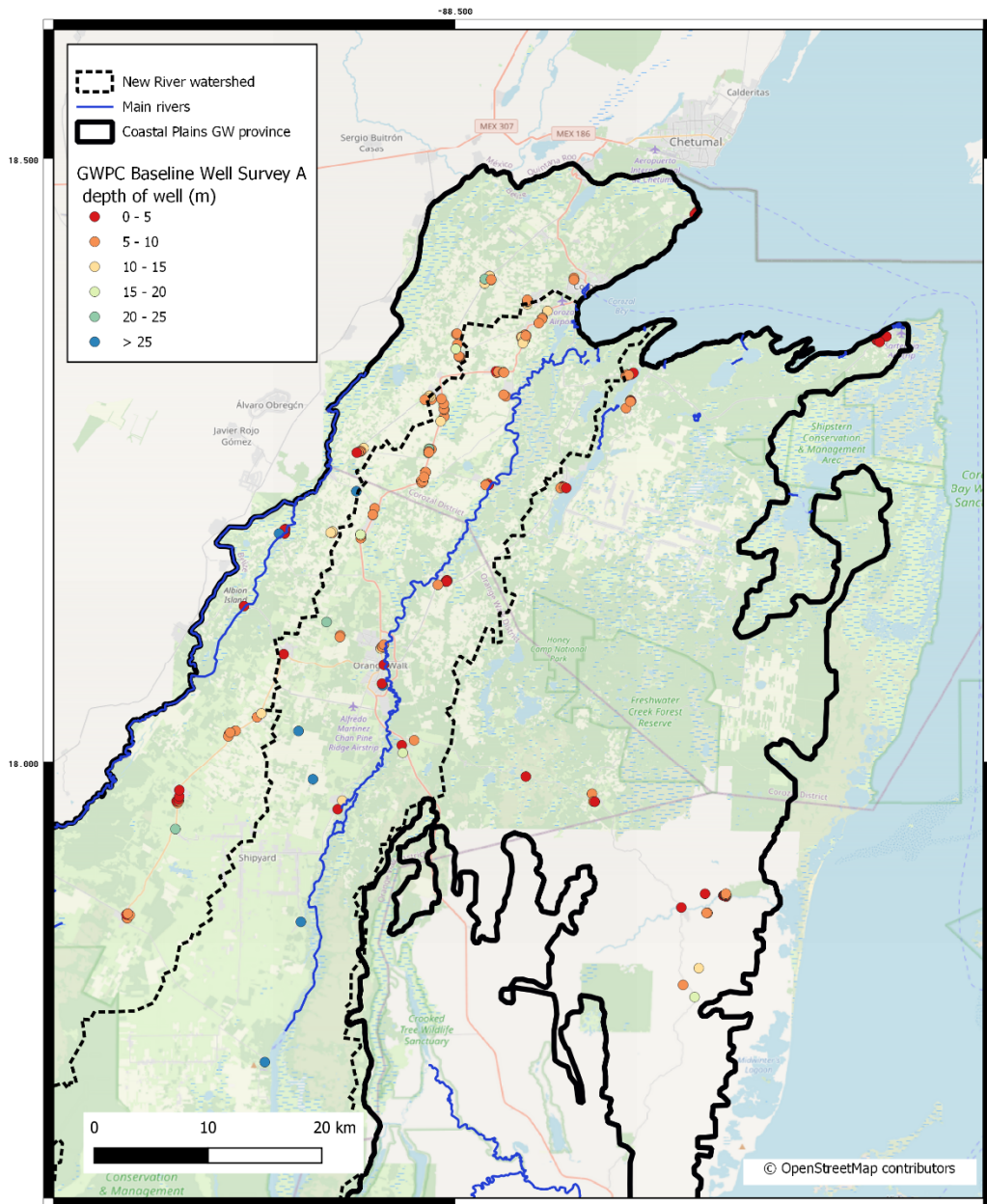


Figure A.4: NHS wells depth of well

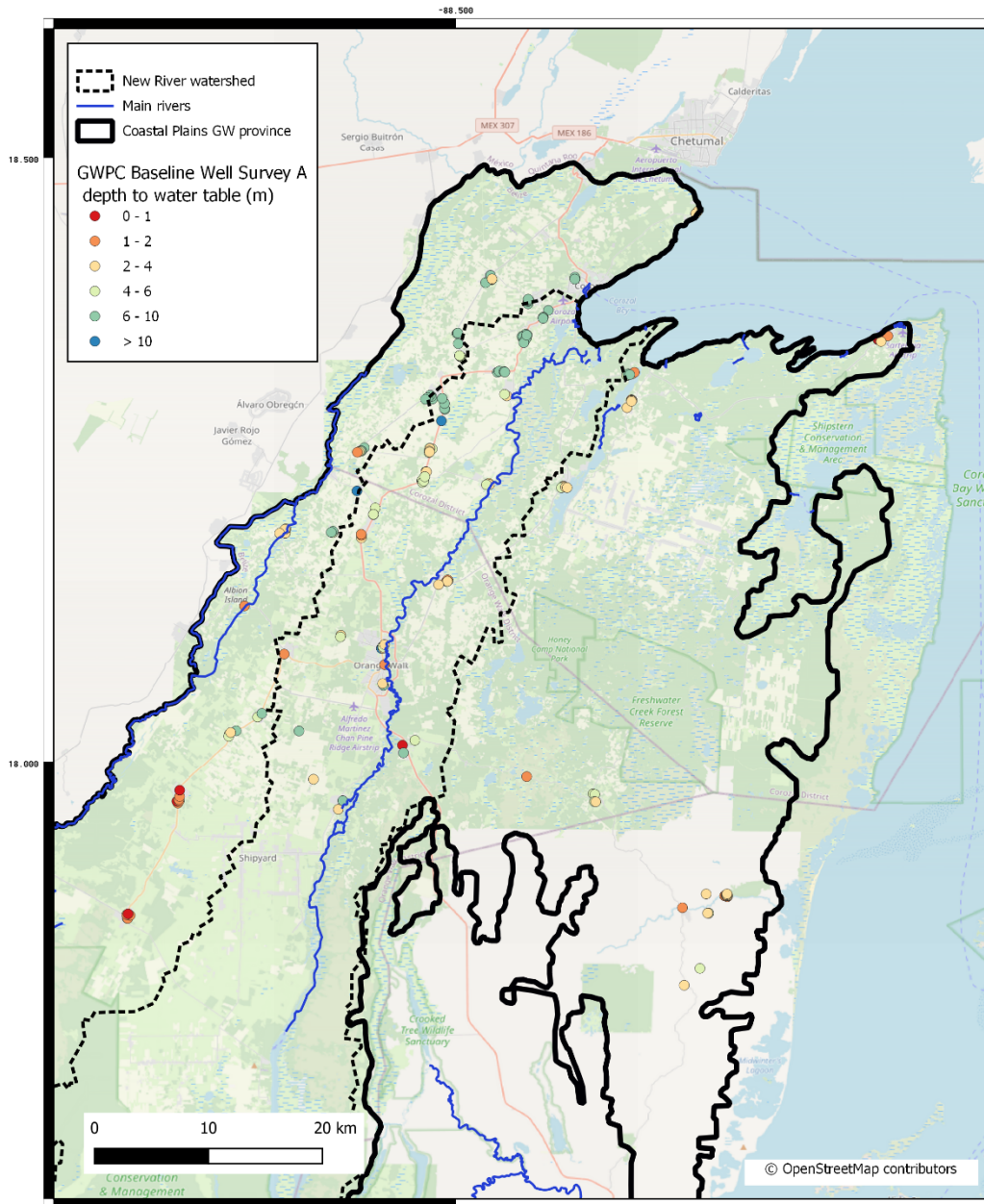


Figure A.5: NHS wells depth of water table

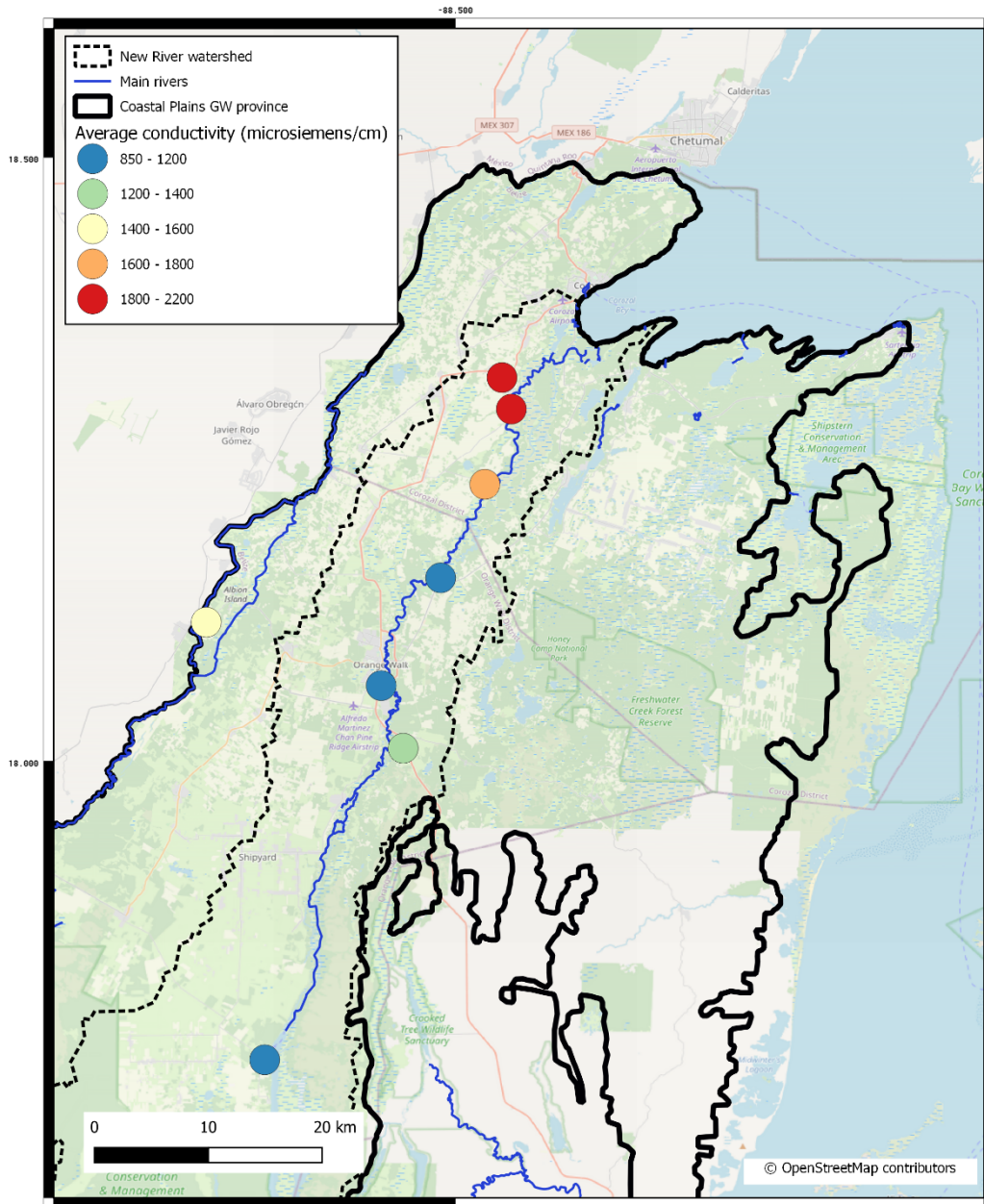


Figure A.6: MOH WQ Conductivity

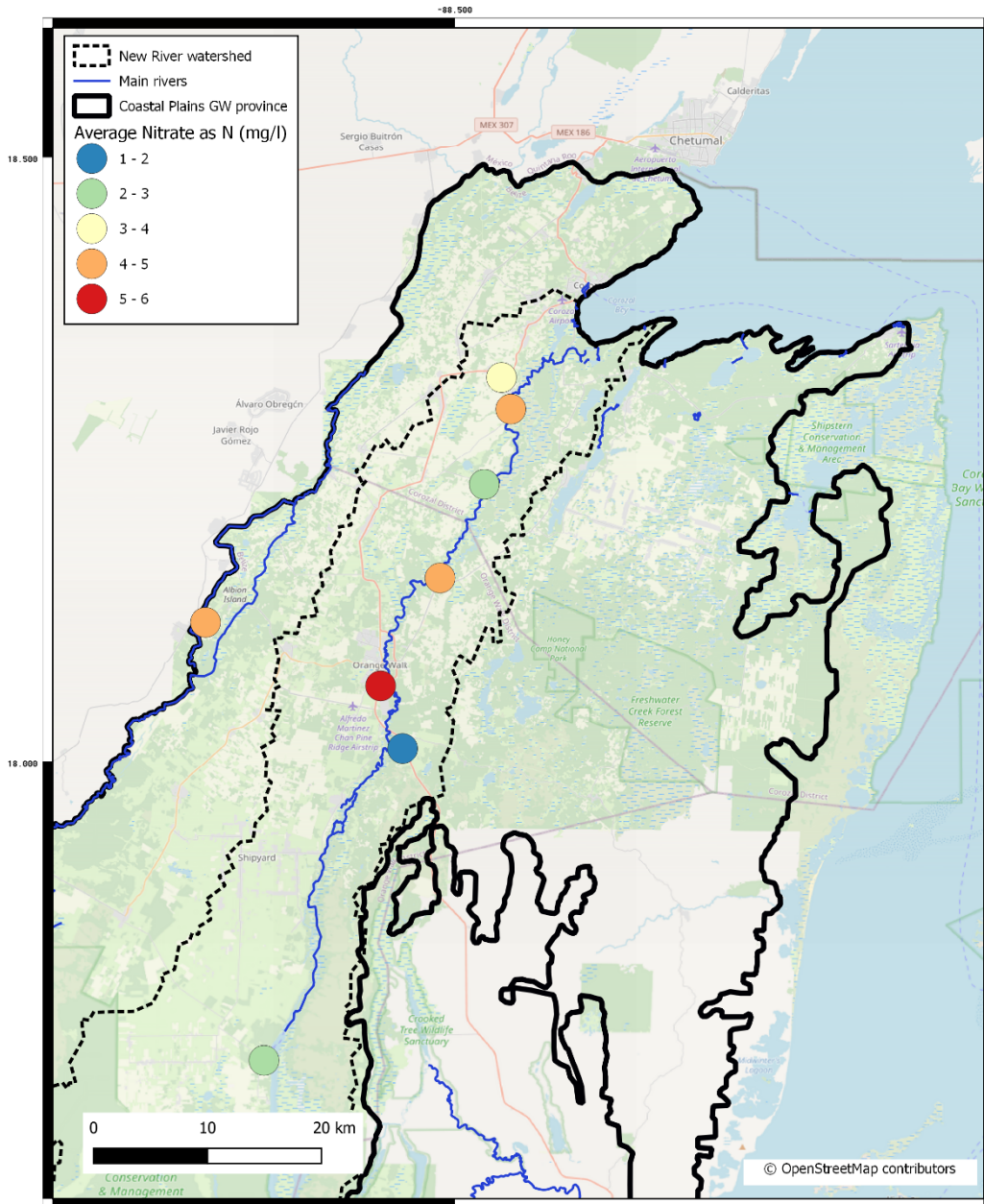


Figure A.7: MOH WQ Nitrate as N

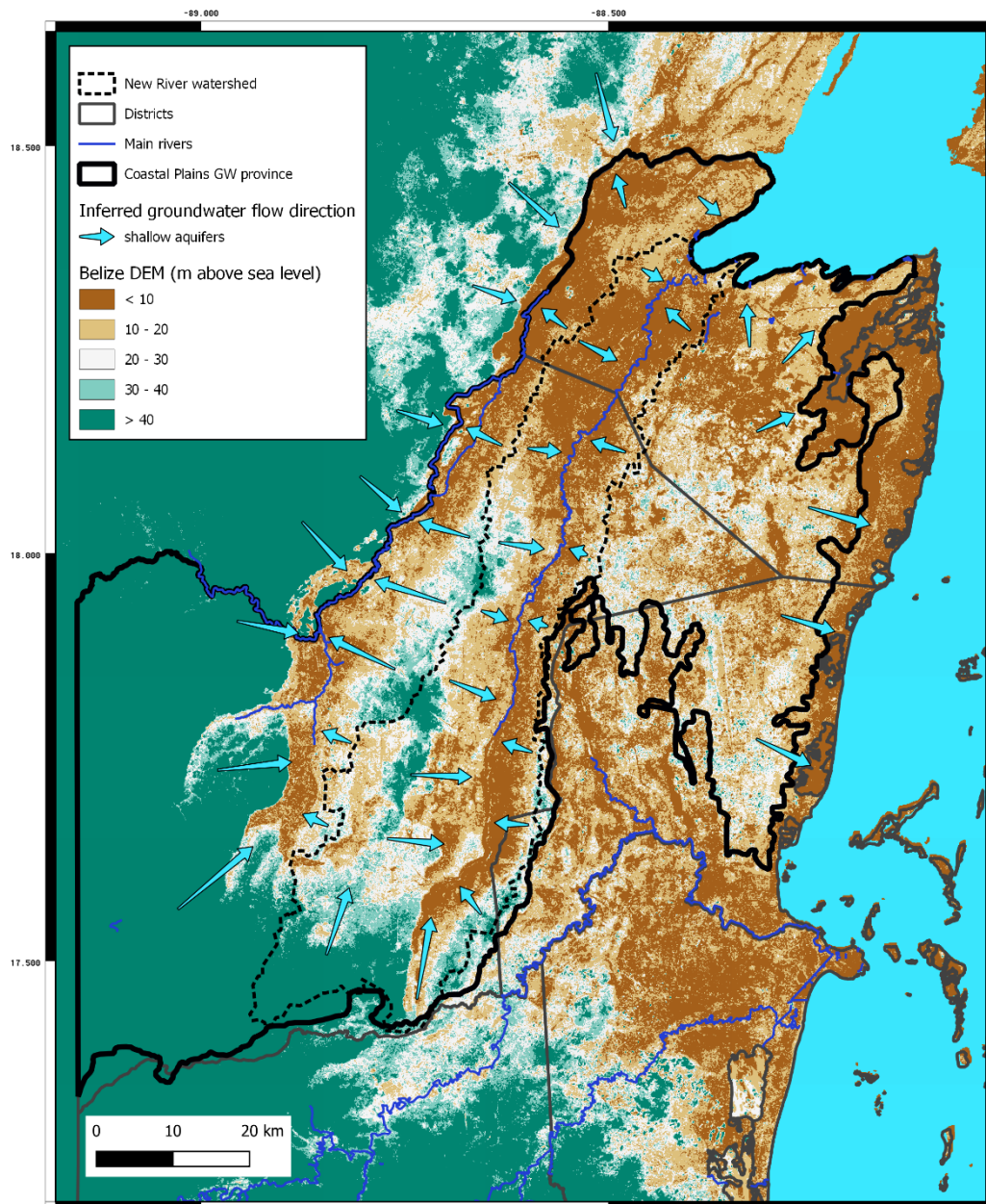


Figure A.8: Flow direction

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HR Wallingford
Howbery Park
Wallingford
Oxfordshire OX10 8BA
United Kingdom

+44 (0)1491 835381

info@hrwallingford.com

www.hrwallingford.com



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