Assessment of Groundwater Resources in the Southern Coastal Water Province of Belize Referred to as Savannah Groundwater Province

Final Report

Volume A

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List of Basic Abbreviations

BAL - Belize Aquaculture Limited
BAN - Banana Farm
BAS – Basic data
CCCCC – Caribbean Community Climate Change Centre
GIS – Geographic Information System
GOB – Government of Belize
GW – Groundwater
GWG – Groundwater and Geology
HCH – Hydrochemistry
ID – Identity number of documentation point
NEMO - National Emergency Management Organization
NIWRA – National Integrated Water Rersources Authority Project
PUC – Public Utilities Commission
SW – Surface water
TNCE – Tunich-Nah Conusltants & Engineering
UNDP – United Nations Development Programme
UNEP – United Nations Environment Programme
UNFCCC – United Nations Framework Convention on Climate Change
USGS – U.S. Geological Survey
WHO – World Health Organisation
WMD – Water Management Database
WQL – Water Quality Limit

Unit Conversion Table

1 in	0.0254 m
1 ft	0.3048 m
1 mi	1.61 km (1609.344 m)
1 m	39.73 in
1 m	3.281 ft
1 km	0.6214 mi
1 ac	0.004 km^2
1 km^2	247.105 ac
1 gal	3.785 L
1 L	0.264 gal
1 gpm	0.06 L/s
1 L/s	15.85 gpm

in-inch, ft-foot/feet, mi – mile, m – meter, km – kilometer, km2 – square kilometer, ac – acre, gal – gallon, L – liter, gpm – gallons per minute, L/s – litres per second

1. Introduction

The Final Report is presented in accordance with the Contract No. GCCA/PS/2013/04 between UNDP (client) and GEOMEDIA Ltd. (contractor) signed on 4th November 2013 concerning the Project **Enhancing Belize's Resilience to Adapt to the Effects of Climate Change – Assessment of Belize's groundwater resources in the southern coastal water province referred to as the Savannah Groundwater Province**.

The Project has been managed by UNDP jointly with the Strategic National Technical Committee of the project, being represented by:

Organization	**Name**
United Nations Development Programme	Ms. Diane Wade
United Nations Development Programme	Mr. Colin Gillett
Ministry of Natural Resources and Agriculture, Policy Coordination and Planning Unit	Dr. Paul Flowers
Ministry of Natural Resources and Agriculture, Policy Coordination and Planning Unit	Mr. Nelson Link
Ministry of Natural Resources and Agriculture, Hydrology Unit	Ms. Rhona Lopez
Ministry of Natural Resources and Agriculture, Policy and Planning Unit	Ms. Tennielle Williams
Ministry of Labour, Local Government and Rural Development, Department of Rural Development	Mr. Hilbert Lopez
Ministry of Health	Mr. Anthony Flowers
Ministry of Health	Mr. Mark Bernard
National Meteorological Service, Hydrology Unit	Mr. Dennis Gonguez
Public Utilities Commission	Mr. Rudolph Williams
Caribbean Community Climate Change Centre	Dr. Kenrick Leslie
National Climate Change Office	Mr. Colin Mattis

The Project has been followed and supported by a number of national and local stakeholders, representatives of whom are listed in the Annex 1. Various parts of the Project were suitable as basis for know-how transfer and capacity building, in the interaction among the project team and the stakeholders. The opportunities included especially the field work and drilling as well as data collection and review in the developed Water Management Database.

The know-how transfer and capacity building shall continue after the Project completion in the following areas:

- groundwater monitoring;
- data management and assessment;
- simulation modeling of groundwater development scenarios.

The Final Report provides substantive results acquired within the project including introduction of applied methodology, overview of relevant data collected from various governmental bodies and agencies, description of field work activities as well as the interpretation of the groundwater regime in the Savannah Groundwater Province based on existing and newly collected data compilation.

The Report introduces the methodology applied for groundwater assessment study in the Savannah Groundwater Province in southern Belize. The methodological part describes the sequence of activities carried out during the project duration and emphasizes the acquisition of existing data being a crucial part of the Project, the field work with the aim to complete the data set to the maximal extent possible, drilling activities and modeling of current groundwater regime and proposed development scenarios.

The Final Report provides a set of recommendations related to mitigation measures of groundwater vulnerability, further operation of monitoring well, Water Management Database database and groundwater model. Implementation of the report's recommendations shall deepen the understanding of character and regime of groundwater systems and their relationships to current land use management practices, surface water systems, and ecological and public health.

Acknowledgement

GEOMEDIA Ltd. wishes to thank and express appreciations to all project partners and interested parties who have willingly provided valuable data and information in their respective fields.

GEOMEDIA Ltd. also thanks all involved government agencies as well as private parties for their forthcoming and support during the execution of the Project.

2. Project Background

Belize is a country rich in surface water sources including streams and rivers as well as many groundwater aquifers found in calcareous rock. The main source of freshwater in rural areas is predominantly groundwater, where approximately 95% of freshwater is extracted from groundwater supplies. Freshwater supplies are sufficient for the current population, though there is an increased stress on these supplies due to population growth, increases in economic and agricultural activities, as well as an increase in droughts (BEST, 2009; CARIBSAVE, 2012).

Like many other low-lying coastal nations, Belize is vulnerable to the effects of climate change. Its geographical location leaves the country exposed to the risk of rising sea levels and increasing frequency and intensity of tropical storms. The anticipated effects of sea-level rise, flooding, stronger storms and hurricanes as well as the salinization of groundwater supplies threaten the coastal communities of Belize. Salt water intrusion is regarded as the displacement of fresh surface water or groundwater by the advance of saltwater due to its greater density. It usually occurs in coastal or estuarine areas (e.g. either from reduced runoff and associated groundwater recharge or from excessive water withdrawals from aquifers) or increasing marine influence (Bates et al 2008; UNFCCC, 2009).

It is obvious that water supply management shall be evaluated for normal as well as for emergency conditions as mentioned here above. National Emergency Management Organization developed National Plan-Relief and Supplies Management outlining necessary measures to be taken for acquiring and distributing relief supplies before and after an extreme event.

Groundwater is particularly important for domestic supply accounting for 95% use (Ballestero et al., 2007). However the lack of information regarding groundwater leads to a difficulty in the management of future water resources under climate change and increases the vulnerability of communities.

In Belize, the distribution of all wells that have been drilled or dug out by hand is unknown. There is a lack of coordination between the BWS and the local village water boards, of which there approximately 90 and thus no concrete number exists. Where there is no access to piped water service, or no local provider, then the water is accessed using hand pumps (CARIBSAVE, 2012). The lack of information regarding groundwater leads to a difficulty in the management of future water resources under climate change and increases the vulnerability of communities.

The focused groundwater and surface-water systems are hydrologically interconnected and function together to provide water for public, industrial, agricultural, and recreational use. Knowledge of these complex systems gained through scientific research is paramount to the protection and sustainability of this irreplaceable resource.

This groundwater assessment Project was put in place in order to focus on the southeastern region, referred to as Savannah Groundwater Province, with highest amount of freshwater availability in Belize (Fig. 1).

3. Project Objectives

The objective of the consultancy is to support the Government of Belize, Ministry of Natural Resources and Agriculture in completing an assessment of Belize's groundwater resources in the Savannah Groundwater Province in the face of increasing demand for water resources in growing urban, touristic and agricultural areas requiring access to safe, adequate and reliable water supplies.

Specific objectives of the consultancy include the following:

- Overall snapshot of groundwater conditions as they were known before this Project
- Provision of an aggregated overview of the current groundwater potential, estimates of the ground water potential in the delineated region
- Extension of set of existing hydrological, hydrogeological and geological data
- Groundwater and surface water sampling
- To the extent possible, determine the extent of ground water resources degradation based on past and current land use practices
- Provision of the hydrogeological characteristics of the province
- Re-assessment of the Savannah Groundwater Province boundaries
- Integrated groundwater assessment study which is to serve as the basis for regional groundwater development master plan
- To the extent possible, identification complex relationships and interactions of various components of geo-hydrological environment by means of GIS database
- Investigation of processes of sea water intrusion
- Develop a conceptual site model of hydrogeological conditions
- Construct a groundwater flow model to show current characteristics of groundwater flow
- Model simulation of proposed scenarios of development in groundwater management reflecting growing population centers and large expansion in tourism, aquaculture and agriculture

The project deals with qualitative and quantitative assessment of groundwater resources, delineation of regional and local structure features and dynamics of groundwater. One of project aims is to improve understanding of the impacts of climate change on groundwater resources and local demand.

Fig. 1 District map of Belize with delineated Savannah Groundwater Province (detailed view provides Annex2, Map 1)

4. Methodology

Groundwater assessment is a systematic study of geology, hydrogeology, geochemistry and contamination at the investigated area.

In order to achieve a reliable groundwater assessment, several general steps need to be addressed (Fig. 2):

- Comprehensive data collection;
- Data management & processing;
- Evaluation & analysis using conceptual, analytical and numerical modeling techniques;

These steps together with continuous monitoring of the hydrogeological structure are considered to be essential for the final goal to advise water policy.

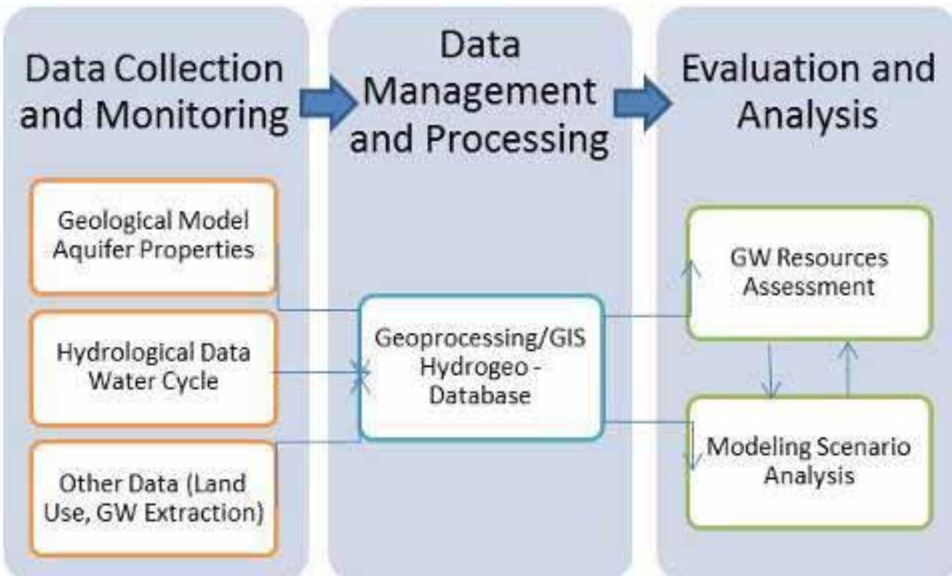

Fig. 2 Work flow resulting in a Groundwater Resources Assessment and recommendations for groundwater management.

Based on prior agreement with the Client (UNDP), the units used in the Final Report as well as other project parts use the metric system. The units generally used for parameters of measurement, volume and flow rate are expressed in meters or kilometers (m or km), litres (L) and litres per second (L/s). Units such miles, feet, inches, gallons were converted using the unit conversion table, provided at the beginning of the Report.

4.1. Acquisition of Existing Data

The initial step of each groundwater resource assessment study includes always a comprehensive desktop study addressing archive data sets, reports and maps from previous studies as well as national and international publications.

In the first step, data are collected from existing publicly available national reports as well as from international sources. The collected data relevant for comprehensive assessment of the groundwater potential are covering the areas of topography, land use, meteorology, hydrology, geology and hydrogeology.

No comprehensive water-quality monitoring program exists in Belize. A number of agencies monitor water quality and quantity for their own purposes and no comprehensive set of information is currently available.

In order to obtain a comprehensive data set for the Savannah Groundwater Province including multiple environmental sectors, the support in assisting GEOMEDIA Ltd. with data acquisition during the groundwater assessment Project was requested from GOB bodies, private companies and agencies in Belize (see the list in

Annex 1). GEOMEDIA Ltd. supported by UNDP organized several meetings in order to meet departmental representatives and experts for the Savannah Groundwater Province area and discuss the data availability, as listed in Tab. 1.

Tab. 1 List of provided data on geology, hydrogeology, hydrology and geochemistry.

Data Source	Provided Data
National Meteorological Service, Hydrology Unit	• Continuous record of precipitation • Continuous record of temperatures • Information on evaporation and transpiration • Data on stage levels in Monkey and Sittee Rivers, discharges / flow rates
Public Health Bureau, Ministry of Health	• Chemical analysis of groundwater including date of sampling, well identification • Chemical analysis of surface water including date of sampling, identification of sampling sites
Geology and Petroleum Department, Ministry of Energy, Science & Technology and Public Utilities	• Well log profiles including complete record of measurements (resistivity, temperature, lithology etc.) for petroleum wells Monkey River – 1 / Susan -1 MR (S-1) • Documentation report for wells Monkey River-1 and Susan -1 • Well logs of San-Juan wells • Belize spatial data for GIS processing
Department of the Environment, Ministry of Forestry, Fisheries and Sustainable Development	• Environmental Impact Assessment Studies relevant for the Savannah Groundwater Province
Department of Rural Development, Ministry of Labour, Local Government and Rural Development	• Water well logs of Stan Creek and Toledo districts
Public Utilities Commission	• Daily precipitation, temperatures • Available chemical analyses • Report: Aquifer and pumping tests for Ara Macao wells near Riversdale, Stann Creek District • Report: The Savannah Groundwater Province Threats and Challenges
Belize Water Service Ltd.	• Available chemical analyses for 2 wells • Well yield information
Ministry of Agriculture and Fisheries	• Irrigation Policy and Strategy for Belize • Agricultural Production Statistics for 2012
Banana farms	• Chemical analyses of irrigation water from 19 banana farms
Belize Aquaculture Ltd.	• Chemical analyses for 5 wells (time series)

A set of thematic map layouts was prepared in GIS in order to display natural conditions of the investigated area as well as to display the spatial distribution of geo-referenced acquired or measured data (Annex 2).

The collected data were retained for subsequent checking and review. Chemistry data were evaluated using statistical methods in Annex 3.

4.1.1. Hydrogeological and Geological Data

A large number of records were collected in the frame of the Groundwater Assessment Project concerning water chemistry data, water well log reports, groundwater yield (Tab. 2).

These datasets include water well logs containing also information about well depth, diameter, water static level, shallow geology etc. The missing coordinated of the documented sites were replaced by estimates corresponding to nearby villages (Annex 2, Map 10). Further hydrochemical data were collected for groundwater and surface water, whereby groundwater data prevail. All chemical values were compared to drinking water standard limits.

Tab. 2 List of processed hydrogeological data in the Savannah Groundwater Province, Belize.

Data Source	Data description	Total number of records
GEOMEDIA Ltd.	Field chemical analyses	113
	Field hydrogeological measurements	84
	Laboratory analysis (Bowen&Bowen Ltd.)	13
	Well log data, pump test, geological profile, laboratory chemical analysis (HGE-1)	1
Ministry of Labour, Local Government and Rural Development, Department of Rural Development	Water well log reports, Stan Creek District	38
	Water well log reports, Toledo District	17
Public Utilities Commission	Chemical well data, Stan Creek District	4
	Hydrogeological characteristics (yield, GW level)	3
	Basic Information about 4 wells and chemical data for 1 well, Ara Macao Resort (Report TNCE, 2006)	4
Ministry of Health	Groundwater and surface water chemical data, Stan Creek District	92
	Groundwater and surface water chemical data, Toledo District	10
Belize Aquaculture Ltd.	Chemical data for 5 wells (time series)	76
	Chemical data for one surface water sample (time series)	11
Belize Water Service Ltd.	Chemical data for 1 wells (Dangriga Village) – raw and treated water	2
Public Health Bureau (The Ministry of Health)	Chemical data for 3 wells, Stan Creek District	3
Banana farms	Chemical data for banana farms	108

Pumping test data were collected in a limited extent. Beside several pumping tests carried out by the Rural Development, aquifer and pump tests leading to Transmissivity and Storativity calculation were conducted in the frame of the Project „Future Solutions for Today's Water Challenges" related to proposed Ara Macao residential and commercial project (TNCE, 2006). The investigated site, Ara Macao, lies approximately half mile from Riversdale Village at the top of the Placencia Peninsula, approximately in the middle of the Savannah Groundwater Province.

Sources and type of evaluated data are illustrated in a set of maps in Annex 2. It is necessary to note that coordinates of investigated sites were not often included in the acquired information. Missing coordinates were allocated according to field localization coordinates (during field work). The least exact assignment of coordinates was based on map reading of the nearest populated area.

The comprehensive database of all chemical data includes also a list of banana farms (BAN). During the GEOMEDIA field work banana farms no. 4, 5, 6, 7, 8, 12, 14, 16, 20, 21 & 22, 25, 26 and 27 were investigated and documented.

4.1.2. Hydrological and Meteorological Data

The dataset on hydrological and meteorological information was compiled using data from National Meteorological Service. Meteorological data set (Tab. 3) includes information on maximal and minimal daily temperatures, daily precipitation and some of them contain daily evaporation values. Continuous records of meteorological parameters enabled calculation of annual average values. Meteorological data from 4 meteorological stations are relevant for the Savannah Groundwater Province, particularly: Savannah (Forest Station), Stann Creek (Maya King), Stann Creek (Melinda Forest) and Punta Gorda (Agri Station) – beyond the Savannah Province limits.

Tab. 3 Hydrological and meteorological data.

Data Source	Data description
National Meteorological Service, Hydrology Unit	Flow rate, Sittee River – Kendal Bridge (1995 – 2009)
	Flow rate, Monkey River - Swasey bridge (1993 - 2010)
	Flow rate, Monkey River - Bladen bridge (1993 - 2010)
	Flow rate, Rio Grande, Big Falls – Toledo (1982 – 2012)
National Meteorological Service, Climatology Section	Meteorological Data – Forest Station (1966 – 2013)
	Meteorological Data – Maya King (1994 – 2009)
	Meteorological Data – Melinda Forest (1973 – 2010)
	Meteorological Data – Punta Gorda (1966 – 2009) (beyond limits of investigated area)
Public Utilities Commission	Yield values for the Savannah Groundwater Province

4.1.3. Geophysical Data

Geophysical well-logs from 4 deep oil & gas exploration boreholes (San Juan 1, 2, 3, Monkey River) in the overall length of over 3 100 m were acquired and subsequently analyzed.

Tab. 4 Geophysical data.

Data Source	Well	Well depth	Data description
Princess Petroleum Ltd.	San Juan No.1	689 m	Well log curves
	San Juan No.2	394 m	Well log curves
	San Juan No.3	1 042 m	Well log curves
Geology and Petroleum Department, Ministry of Energy, Science & Technology and Public Utilities	Monkey River	1 070 m	Well log curves Geological interpretation

4.2. Field Work

In Belize, the distribution of all wells that have been drilled or dug out by hand is unknown (CARIBSAVE, 2012).. The aim of the field work is to verify and enrich the information collected from the existing archive documentation. In particular, the site visit was used to confirm locations of wells mentioned in various reports, acquire GPS co-ordinates of investigated sites, confirm local land use, surface water body features, obvious sources of potential groundwater contamination (industrial land use, landfills, etc.) and water sampling.

The field work was conducted in two stages:

1. Mapping, measuring, sampling, etc.
2. Drilling (see the drill well documentation in Annex 4)

Overview of sites visited and documented during the first stage of the field work is included in the Field notes in Annex 8. The Field notes provides detailed description of each documented site including GPS coordinates, information on sampling, analyses, groundwater level and description of the site. In the same time, the field data were categorized in comprehensive Water Management Database (Annex 9).

Detailed description and methodology of the field work is given in section 6.1 of the Report.

4.3. GIS Processing

Follow-up activities are dedicated to the assessment of the collected data and information and to preparation of a conceptual model for the Savannah Groundwater Province. For handling groundwater data, the GIS-technology is well suited as it enables concurrent handling of locational and attribute data. GIS also offers technological avenues for integrating the variety of data sets in both qualitative and quantitative terms.

Applied projection for GIS data processing as well as map layouts in Annex 2 is World Geodetic System 1984 WGS 84/UTM zone 16N.

Data processing by means of GIS and data assessment activities follow three directions:

- Analysis of natural conditions throughout the whole Savannah Groundwater Province area including the evaluation of climate data (rainfall, evapotranspiration, temperature), hydrologic data (flow rate), data on land use (land cover) and their interactions. This analysis is necessary for quantifying the natural water cycle in the investigated area.

- Analysis of groundwater dynamics, regional hydrogeological structure, geology and physical properties of rock formations. This analysis and synthesis includes definition of regional geology structures, occurrence of aquifers and aquitards, their geometry, evaluation of pumping tests, estimation of hydraulic conductivity of hydrogeological formations, their spatial distribution and interpretation of groundwater levels throughout the Savannah Groundwater Province.

- Analysis of groundwater and surface water chemistry including existing collected chemical data and field data measured during the project. The analysis and chemical data processing should reflect the spatial distribution of sampled sites or if available the time series enabling the interpretation of local hydrochemical stability. Results of this analysis facilitate the identification of separate zones characterized by different hydrogeological conditions and regime.

4.4. Groundwater Modeling

Previous data assessment facilitated the creation of a conception model of the investigated area based on number of assumptions which were further validated during mathematical modeling. The applied software was the industry standard FEFLOW simulation package.

The objective of the mathematical model is to simulate groundwater circulation in the upper sedimentary formation (flow velocity and direction) of the Savannah Groundwater Province and impacts of water abstraction. Groundwater model shall help to define options for water supply ensured from the upper part of aquifer and quantity of total and exploitable groundwater reserves.
Groundwater modeling shall be further applied to simulate proposed scenarios of development in groundwater management in the Savannah Groundwater Province, such as growing population centers and large expansion in tourism, aquaculture and agriculture in order to properly asses the availability and sustainability of encountered groundwater resources for public demands. Furthermore, it shall support the proposals for design the groundwater monitoring system.

4.5. Groundwater Assessment

4.5.1. Quantitative Groundwater Assessment

Meteorological data (precipitation, evaporation, etc.) and hydrological data (river flow rate) data were used for evaluation of basic components of water runoff in watersheds. These runoff components and meteorological data are fundamental parameters for water balance assessment within watershed. Parameters of water balance (mainly base flow) create essential input parameters for groundwater resources assessment. There are numerous approaches and methods for evaluation of water balance within area of interest. Application of specific methods depends on data availability as well as on quantity and quality data. Basic evaluation of base flow from watershed can be easily done by hydrological estimation of water balance and hydrograph analysis.

Method of hydrological water balance estimation in watershed is based on estimation of individual variables of hydrological equation. These variables are represented primarily by precipitation, evapotranspiration, base flow, direct flow. There are other parameters in water balance such as changes in water storage or groundwater communication among watersheds. These parameters are mostly negligible in comparison with primary parameters and have not to be considered especially in long-term evaluation.

There are also numerous approaches for hydrograph separation. Method of hydrograph separation by Kille was selected for time series of rivers flow rate analysis. Method is based on frequency analysis of minimum monthly flows in 30 day period over evaluated time and is suitable for evaluation of regional data with long-term average values. Advantage of this method is fast and easy evaluation, easy availability of basic data, necessity of no additional data, minimizing of subjective intervention..

4.5.2. Qualitative Groundwater Assessment

Understanding the hydrochemical characteristics of water is crucial for groundwater management. Groundwater chemistry depends on a number of factors, such as general geology, degree of chemical weathering of the various rock types, quality of recharge water and inputs from sources other than water-rock interaction. Such factors and their interactions result in a complex groundwater quality.

Surface water and groundwater sampling was subject of the field work conducted within the Project. Sample analyses were evaluated using common geochemical methods with the aim to assess the geochemical character of sampled waters. For this purpose two types of diagrams were used – Piper and Stiff diagram.

During the field work, 106 documentation sites were sampled for groundwater and surface water in total (74 sites for groundwater samples, 32 sites for surface water samples) were measured for principal geochemistry in field during the field work. Some of the sites were sampled and analyzed in the field conditions twice.

13 documentation points were furthermore selected for detailed groundwater analysis (marked as S1-S13, Annex 2, Map 9) in Bowen & Bowen, Ltd. laboratory.

New chemical analyses considerably enriched the set of existing chemical data in the area. Results of all chemical analyses are included in the comprehensive Water Management Database in Annex 9.

The key issue of the groundwater quality assessment is the assessment of groundwater vulnerability. Observation during the field work enabled the identification of several occurrences of inappropriate municipal waste disposal and waste water disposal representing the risk for groundwater quality. The Report provides description of the groundwater vulnerability and proposes adequate mitigation measures as well.

Detailed description of the water quality and vulnerability assessment is given in section 8.3 of the Report.

The classical use of water analysis in hydrology/hydrogeology is to show the regional distribution of the water compositions in a map. Such maps serve environmental authorities, water resource managers, drilling operators and other practitioners to identify aquifers with good quality groundwater, but they are also useful for a first assessment of the relation between the aquifer mineralogy and groundwater composition.

Bulk chemical composition of groundwater might be graphically displayed in several diagram types facilitating the identification of groundwater (surface water) type:

In this study, two types of diagrams were primarily used for interpretation of surface and groundwater quality of the Savannah Groundwater Province:

- *Piper diagram:*

  Piper diagram is generally displayed into two triangular plots giving the relative composition of cations and anions, expressed in percentage of total cation or anion meq/L. From the triangular diagrams the points are conducted to the diamond shape diagram parallel to the outer side of the diagram until they intersect (Fig. 3, Fig. 39).

- *Stiff diagram:*
  Stiff plot is used to compare ionic composition of water samples. Typically, the left side of the diagram shows cation concentrations in meq/L and the right side shows anion concentrations in meq/L (the units used at laboratory analyses were for this purpose converted from ppm to meq/L). The further a point is from the center of the graph, the larger the ionic concentration. The largest ionic concentration for anions and cations suggests the character of groundwater.

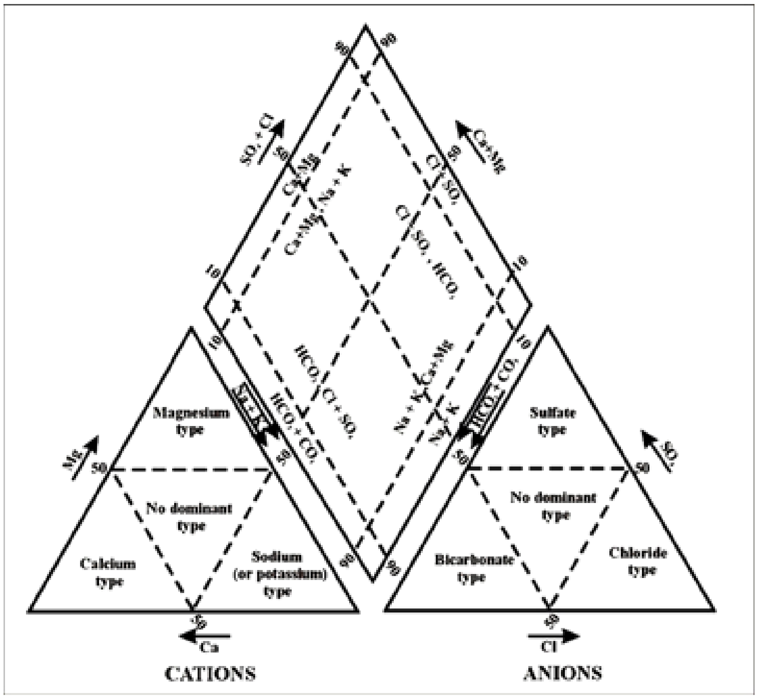

Fig. 3 Water type classification using the Piper trilinear diagram. Water types are designated according to the domain in which they occur on the diagram segments (Back, 1961; Hanshaw, 1965)

4.5.3. Drinking Water Standards

All chemical data were compared with generally applied drinking water standards (Tab. 5), such as: WHO's drinking water standards, United States Environmental Protection Agency and Canadian drinking water standards.

Tab. 5 Drinking water limits.

Physical	Unit	Standard	Status	Data source
Turbidity	ntu	5,00	Recommended	WHO's drinking water standards
pH	-	6,5-8	Recommended	WHO's drinking water standards
Conductivity	uS/cm	500,00	Recommended	WHO's drinking water standards
Calcium (Ca)	ppm	200,00	Maximum level	Guidelines for Canadian Drinking Water Quality
Copper (Cu)	ppm	1,30	Maximum level	United States Environmental Protection Agency
Aluminium (Al)	ppm	0,20	Recommended	WHO's drinking water standards
Iron (Fe)	ppm	0,30	Recommended	WHO's drinking water standards
Manganese (Mn)	ppm	0,05	Recommended	United States Environmental Protection Agency
Magnesium (Mg)	ppm	50,00	Recommended	Guidelines for Canadian Drinking Water Quality
Sodium (Na)	ppm	200,00	Recommended	WHO's drinking water standards
Fluoride (F)	ppm	1,50	Maximum level	WHO's drinking water standards

Physical	Unit	Standard	Status	Data source
Chloride (Cl)	ppm	250,00	Recommended	WHO's drinking water standards
Chlorine (Cl)	ppm	5,00	Recommended	WHO's drinking water standards
Ammonia (NH3)	ppm	0,30	Recommended	WHO's drinking water standards
Hardness (as CaCo3)	ppm	500,00	Recommended	Guidelines for Canadian Drinking Water Quality
Alkalinity (as CaCO3)	ppm	500,00	Recommended	United States Environmental Protection Agency
Nitrate (NO3-)	ppm	10,00	Maximum level	WHO's drinking water standards
Nitrite (No2-)	ppm	1,00	Maximum level	United States Environmental Protection Agency
Salinity	ppt	1,00	Recommended	United States Environmental Protection Agency
Sodium chloride (NaCl)	ppm	200,00	Recommended	WHO's drinking water standards
Sulphate (SO42-)	ppm	250,00	Recommended	United States Environmental Protection Agency
Total dissolved solids (TDS)	ppm	500,00	Recommended	United States Environmental Protection Agency

5. Natural Conditions

This section provides description of the physiographic features of the Savannah Groundwater Province such as land use, climate, geological and hydrogeological setting. Information presented in this section is based on published reports, available web pages and past investigations conducted in southern Belize. All information is properly cited and citations are listed in the reference list of this Report.

The Savannah Groundwater Province extends along coastal Belize from the extreme south-eastern Belize district to extreme north-eastern Toledo District in the length of about 80 km (Fig. 1). The eastern boundary is formed by the coastline. The investigated area of the Savannah Groundwater Province represents a regional hydrogeological structure including recharge area along the eastern slopes of the Maya mountains. This province extends along the eastern slopes of the Maya mountains to the coast.

5.1. Climate

Investigated area lies in the outer tropics or subtropical geographic area with mean monthly minima from 61° F (16° C) to 63° F (17° C) in winter and from 75° F (24° C) to 77° F (25° C) in summer and mean monthly maxima range from 82° F (28° C) in winter to 91°F (33°C) in summer.

Belize lies directly in the path of tropical storms and hurricanes and they are a consistent occurrence that bring heavy rainfall that challenge flood control management policies and infrastructure. Approximately 62% of the populated settlements in Belize lie within areas at high risk of flooding and many of these are located directly within flood plains that are inundated on an annual basis. The Belize National Emergency Management Organization (NEMO) handles the procedures that are needed during flooding events (http://www.wikipedia.com).

The on-shore breeze moderates the daily high temperature. The Belize coastal area is exposed to southeast trade-winds which attain greatest constancy in July. The northern coastal plain of Belize receives about thirty percent of the rainfall of southern Toledo district. Annual rainfall ranges from 1 347 mm at Libertad (Corozal district) to 4526 mm at Barranco (Toledo district). Seasonal effects are more significant in the central and northern regions. In the south-central region the dry season lasts from February till April. A minor, less-rainy period usually occurs in August.

Two meteorological disturbances can alter typical weather patterns – those are northers and cyclones. Northers are cold, wet, northeast air masses occasionally pushed far to the south from November to February by arctic air masses. Local effects are cooler-than-normal temperatures, heavy rains and choppy seas. More dangerous are cyclones - non-frontal, low-pressure, large-scale systems that develop over tropical waters with a definite, organized circulation. Depending on wind speed and sustainability, cyclones are classified as tropical depressions, storms or hurricanes; hurricanes are the most powerful cyclones with minimum sustained winds of 119 km/hour (Hartshon G., 1984).

5.1.1. Climate Change

The United Nations Framework Convention on Climate Change has identified that Belize is one of those countries most vulnerable to the adverse impacts of climate change due to: (i) its long, low - lying coastline; (ii) its over 1 060 small islands; (iii) its second - longest barrier reef in the world and 17.276 km^2 of forest cover, each of which support fragile ecosystems; and (iv) the fact that it is very prone to natural disasters, especially hurricanes. Belize is ranked 8th from 167 countries for climate risk (World Bank).

Given that approximately one half of Belize’s population are concentrated in coastal population centres, and that the country’s economy is highly dependent on commodity exports and tourism, the nation’s economic and social exposure becomes significantly increased when one considers the compounding effects of climate change. While tropical cyclones have historically inflicted the greatest damage, a major threat is recurrent flooding due to storm surge, heavy and /or persistent rainfall and the altering of natural drainage and sink systems. Recent hydrometeorological events have resulted in significant losses to the country’s productive sectors.

The vulnerability of concentrated populations in exposed areas is exacerbated by inadequacies in housing and support infrastructure, and environmental fragility, in part a result of its location, climate, and topography. The 2007 Vulnerability Assessment of the Belize Coastal Zone detailed a range of possible effects, based on the scenario developed by the National Meteorological Service.

According to the study, the major impacts predicted on biophysical resources —will be from sea level rise, increased sea surface temperatures, changes in weather patterns and increased storm activity. Corals are the most susceptible to increased sea surface temperature and frequent storm events. Corals will be lost due to bleaching, disease and physical damage. Mangroves and sea grass beds will be most susceptible to changes in weather patterns and storm events that will result in physical damage and changes in biological processes such as reproduction. Mangroves are expected to retreat sequentially to maintain their position within the ecosystem. Coastal areas, beaches and cayes will be most susceptible to increasing sea levels and increase in storm events. These areas would suffer from inundation, erosion and storm surges. The socioeconomic impacts will be from loss of habitat and coastal areas which in turn will directly affect the tourism and fisheries industries. (UNEP, 2011)

5.1.2. Climate Change Impact on Groundwater Resources

Climate change is very likely to have a significant impact on the water sector of Belize. Under current climate conditions, the water resources sector is already subject to a number of pressures, including tropical storms and hurricanes that lead to flooding problems and droughts that restrict the available water supply and that is extremely detrimental to agriculture.

Although the most noticeable impacts of climate change could be fluctuations in surface water levels and quality, the greatest concern of water managers and government is the potential decrease and quality of groundwater supplies, as it is the main available potable water supply source for human consumption and irrigation of agriculture produce worldwide. Because groundwater aquifers are recharged mainly by precipitation or through interaction with surface water bodies, the direct influence of climate change on precipitation and surface water ultimately affects groundwater systems. Rainfall is projected to decrease slightly and become more variable leading to intense rains and flooding on the one hand and droughts on the other. Warmer temperatures would also exacerbate drought conditions (McSweeney et al., 2009; IPCC, 2007).

It is important to consider the potential impacts of climate change on groundwater systems. As part of the hydrologic cycle, it can be anticipated that groundwater systems will be affected by changes in recharge (which encompasses changes in precipitation and evapotranspiration), potentially by changes in the nature of the interactions between the groundwater and surface water systems, and changes in use related to irrigation (Kumar, 2012).

When considering groundwater resources in coastal zones, coastal aquifers are important sources of freshwater. Sea level rise and storm surges, by-products of climate change, will also affect the water sector through saline intrusions into coastal aquifers and soils and flooding of coastal lowlands and towns, where the bulk of the population of Belize is located (Singh and El Fouladi, 2007).

However, saline intrusion can be a major problem in these zones. Saline intrusion refers to replacement of freshwater in coastal aquifers by saltwater. It leads to a reduction of available fresh groundwater resources. Changes in climatic variables can significantly alter groundwater recharge rates for major aquifer systems and affect the availability of fresh groundwater. Salinization of coastal aquifers is a function of the reduction of groundwater recharge and results in a reduction of fresh groundwater resources. Sea-level rise will cause saline intrusion into coastal aquifers, with the amount of intrusion depending on local groundwater gradients. Shallow coastal aquifers are at greatest risk. Groundwater in low-lying islands is very sensitive to change. A reduction in precipitation coupled with sea-level rise would not only cause a diminution of the harvestable volume of water; it also would reduce the size of the narrow freshwater lense. For many small island states, such as some Caribbean islands, seawater intrusion into freshwater aquifers has been observed as a result of overexploitation of aquifers.

However, based on field investigation of groundwater resources in the Savannah Groundwater Province including identification of major withdrawal sites it is assumed that current groundwater exploitation is very low compared to total volume of groundwater reserves and no aquifer overuse from quantitative point of view has been identified so far.

Any sea-level rise would worsen the situation. A link between rising sea level and changes in the water balance and quality is suggested by a general description of the hydraulics of groundwater discharge at the coast. Fresh groundwater rides up over denser, salt water in the aquifer on its way to the sea (Fig. 4), and groundwater discharge is focused into a narrow zone that overlaps with the intertidal zone.

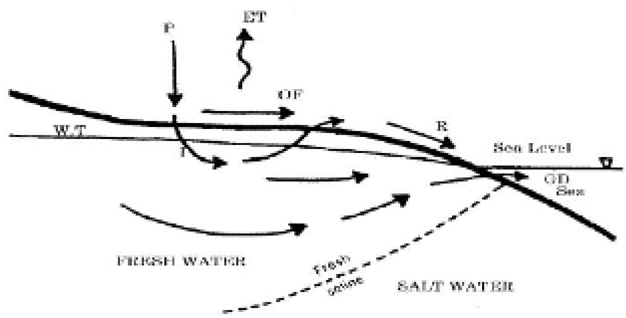

Fig. 4 Conceptual Model of the Water Balance in a Coastal Watershed (Kumar, 2012)

The width of the zone of groundwater discharge measured perpendicular to the coast, is directly proportional to the discharge rate. The shape of the water table and the depth to the freshwater/saline interface are controlled by the difference in density between freshwater and salt water, the rate of freshwater discharge and the hydraulic properties of the aquifer. The elevation of the water table is controlled by mean sea level through hydrostatic equilibrium at the shore.

5.2. Meteorology

Meteorological data from 1966 until 2013 were obtained from the Ministry of Natural Resources & Agriculture, Hydrology Unit. These data sets contain daily records of maximum temperature, minimum temperature, precipitation and some of them contain daily records of evaporation.

Meteorological observations have been recorded at four meteorological stations, i.e. Savannah Forest Station, Maya King Station, Melinda Forest Station and Punta Gorda (Agri Station, beyond of Savannah province limits); see Annex 2, Map 6. For short site description, see Tab. 6.

Tab. 6 Meteorological data acquired.

Name	Data Source	Description
Savannah Forest station	National Meteorological Service, Climatology Section	Meteorological Data measured between years 1966 - 2013
Maya King station	National Meteorological Service, Climatology Section	Meteorological Data measured between years 1994 - 2009
Melinda Forest station	National Meteorological Service, Climatology Section	Meteorological Data measured between years 1973 - 2010
Punta Gorda	National Meteorological Service, Climatology Section	Meteorological Data measured between years 1966 - 2009

5.2.1. Data evaluation

Daily precipitation, evaporation, maximum and minimum temperature data have been evaluated. Data series of the mentioned meteorological parameters are incomplete, some daily records or even data from whole months and years are missing. Only monthly series with at least 50% daily records for minimum and maximum average temperature and at least 75% daily records for monthly precipitation and evaporation were considered for statistical data evaluation.

The selected data were used to calculate monthly average values for minimum and maximum temperature and monthly sum of precipitation and evaporation. Annual average values of minimum and maximum temperature were assessed as average of all monthly values in year. The same approach was used for assessment of annual precipitation and evaporation. Total values of annual precipitation and evaporation were assessed as sum of all monthly values in year. These values of evaluated meteorological parameters are in detail described below.

Maximum daily temperature

For the Savannah Forest station, there are data series with daily records of maximum temperature for 360 months (May 1966 – January 2014). Daily temperatures vary from 17.8°C (recorded in January 1979) to 40.0°C (recorded in March 1973). According to the records evaluation the coldest month was January 1976 with average monthly temperature 25.81°C and the warmest April 1970 with temperature 36.2 °C. In point of long term average value the coldest months are January and December with average monthly values 28.57°C and 28.76°C, the warmest are May and June with average monthly values 33.25°C and 32.49°C. Annual maximum temperature varies from 30.3°C to 32.4°C with average value 31.1 °C.

For the Melinda Forest station, there are data series with daily records of maximum temperature for 387 months (January 1973 – August 2011). Daily temperatures vary from 18.9°C (recorded in January 1975) to 38.5°C (recorded in April 2010). According to the records evaluation the coldest month was January 1976 with average monthly temperature 25.31°C and the warmest April 1973 with temperature 34.1 °C. In point of long term average value the coldest months are January and December with average monthly values 28.26°C and 28.64°C, the warmest are May and August with average monthly values 31.95°C and 31.79°C. Annual maximum temperature varies from 28.9°C to 32.4°C with average value 30.4 °C.

For the Maya King station, there are data series with daily records of maximum temperature for 113 months (December 1992 – December 2009). Daily temperatures vary from 20.7°C (recorded in January 1996) to 38.8°C (recorded in April 1993 and 2005). According to the records evaluation the coldest month was January 1996 with average monthly temperature 25.93°C and the warmest September 2002 with temperature 34.05 °C. In point of long term average value the coldest months are January and December with average monthly values 29.06°C and 30.00°C, the warmest are May and June with average monthly values 32.47°C and 32.45°C. Annual maximum temperature varies from 30.8°C to 32.2°C with average value 31.5 °C.

Basic information about statistical evaluation of monthly average values for maximum temperature is summarized in Tab. 7 time behavior of average monthly temperature is pictured on chart (Fig. 5).

Tab. 7 Average monthly maximum temperature

Savannah Forest station												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Number of records	32	31	30	31	30	29	29	30	28	30	28	28
Minimum temperature	27.1	29.2	30.7	30.7	29.8	28.8	29.5	29.1	28.5	27.6	26.5	26.5
Maximum temperature	31.0	34.8	36.2	35.8	35.2	34.6	34.0	35.0	32.6	31.5	30.7	30.7
Average temperature	**29.4**	**31.2**	**32.5**	**33.3**	**32.5**	**31.9**	**32.1**	**32.1**	**31.1**	**29.7**	**28.8**	**28.8**
Melinda Forest station												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Number of records	33	34	34	33	34	33	33	31	30	30	31	30
Minimum temperature	25.3	25.4	27.9	28.7	30.5	29.6	29.2	30.1	29.0	28.3	27.7	26.5
Maximum temperature	32.3	30.9	32.2	34.1	33.5	33.2	32.7	33.2	33.8	33.0	32.1	31.6
Average temperature	**28.3**	**28.9**	**29.8**	**30.9**	**32.0**	**31.6**	**31.3**	**31.8**	**31.7**	**30.8**	**29.6**	**28.6**

Maya King station												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Number of records	10	10	9	8	9	8	8	9	9	10	10	12
Minimum temperature	25.9	28.8	30.3	31.3	31.6	31.2	31.5	31.6	31.3	30.4	30.2	28.6
Maximum temperature	31.3	32.0	33.4	32.9	33.7	33.5	32.6	32.9	34.1	32.7	31.2	31.7
Average temperature	**29.1**	**30.4**	**31.6**	**32.0**	**32.5**	**32.4**	**31.9**	**32.1**	**32.3**	**31.7**	**30.8**	**30.0**

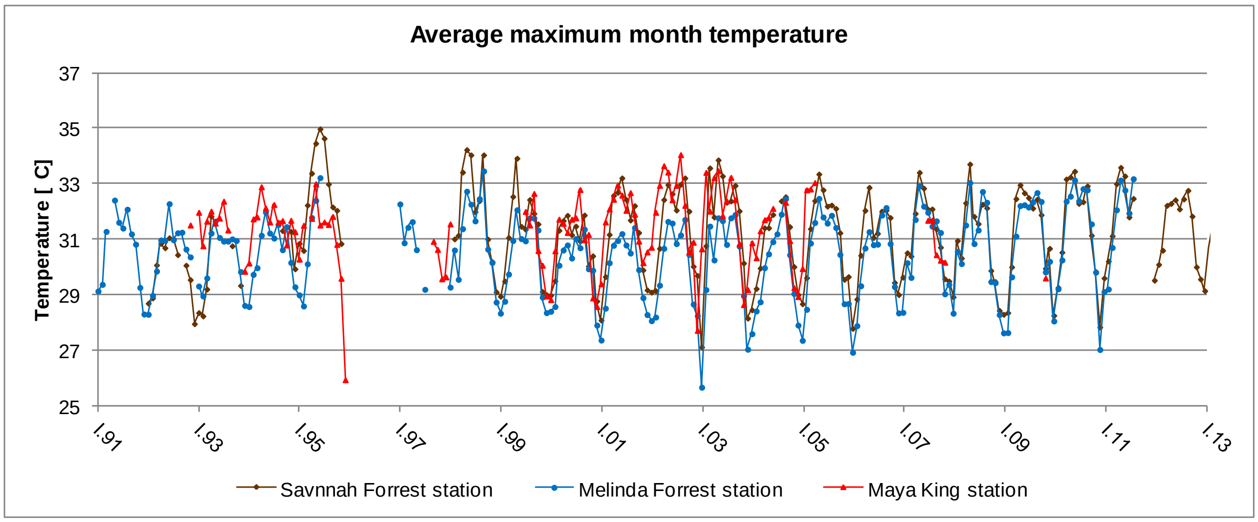

Fig. 5 Average monthly maximum temperature

Minimum daily temperature

For the Savannah Forest station, there are data series with daily records of minimum temperature for 373 months (January 1971 – December 2013). Daily temperatures vary from 10.0°C (recorded in February 1970) to 31.1°C (recorded in October 1973). According to the records evaluation the coldest month was January 1981 with average monthly temperature 16.13°C and the warmest June 1982 with temperature 27.58 °C. In point of long term average value the coldest months are January and December with average monthly temperature 20.19°C and 20.76°C, the warmest are June and July with average monthly temperature 24.56°C and 24.30°C. Annual minimum temperature varies from 22.0°C to 23.2°C with average value 22.7 °C.

For the Melinda Forest station, there are data series with daily records of maximal temperature for 435 months (January 1973 – August 2011). Daily temperatures vary from 10.6°C (recorded in February 1989) to 30.0°C (recorded in May 1973 and 1978). According to the records evaluation the coldest month was February 1976 with average monthly temperature 15.98°C and the warmest May 1975 with temperature 26.71 °C. In point of long term average value the coldest months are January and February with average monthly temperature 19.97°C and 20.21°C, the warmest are June and July with average monthly temperature 24.09°C and 23.89°C. Annual minimum temperature varies from 20.9°C to 24.4°C with average value 22.4 °C.

For the Maya King station, there are data series with daily records of maximal temperature for 188 months (December 1992 – February 2010). Daily temperatures vary from 12.3°C (recorded in January 1976) to 27.5°C (recorded in June 1998 and May 2002). According to the records evaluation the coldest month was January 2000 with average monthly temperature 17.86°C and the warmest July 2003 with temperature 24.11 °C. In point of long term average value the coldest months are January and February with average monthly values 20.07°C and 20.64°C, the warmest are June and May with average monthly values 24.11°C and 23.67°C. Annual minimum temperature varies from 20.8°C to 22.9°C with average value 22.4 °C.

Basic information about statistical evaluation of monthly average values for minimum temperature is summarized in Tab. 8, time behavior of average monthly minimum temperature is pictured on chart (Fig. 6).

Tab. 8 Average monthly minimum temperature

Savannah Forest station												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Number of records	32	32	31	31	31	31	30	31	32	30	31	30
Minimum temperature	16.1	17.6	17.8	20.3	21.5	22.9	23.6	22.1	20.6	20.8	19.7	17.2
Maximum temperature	22.1	24.7	24.9	26.5	25.5	27.6	25.8	25.7	26.1	26.1	24.4	24.0
Average temperature	**20.2**	**20.8**	**21.7**	**23.1**	**24.1**	**24.6**	**24.3**	**24.0**	**23.8**	**23.1**	**21.7**	**20.8**
Melinda Forest station												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Number of records	36	37	37	35	36	37	37	36	36	36	36	35
Minimum temperature	17.8	16.0	18.6	19.0	20.0	20.2	21.7	22.0	22.2	20.9	19.2	17.6
Maximum temperature	22.7	23.2	25.5	25.4	26.7	26.4	26.4	26.6	26.0	25.3	24.3	22.8
Average temperature	**20.0**	**20.2**	**21.2**	**22.3**	**23.5**	**24.1**	**23.9**	**23.8**	**23.6**	**23.0**	**21.5**	**20.5**
Maya King station												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Number of records	16	14	16	15	16	16	16	14	14	16	16	18
Minimum temperature	17.9	18.2	19.6	21.5	21.8	22.1	20.8	21.0	21.1	21.9	19.1	18.7
Maximum temperature	22.2	22.1	22.6	23.7	25.1	25.2	24.7	24.4	24.5	24.2	23.3	22.2
Average temperature	**20.1**	**20.6**	**21.2**	**22.6**	**23.7**	**24.1**	**23.6**	**23.7**	**23.7**	**23.1**	**21.7**	**20.8**

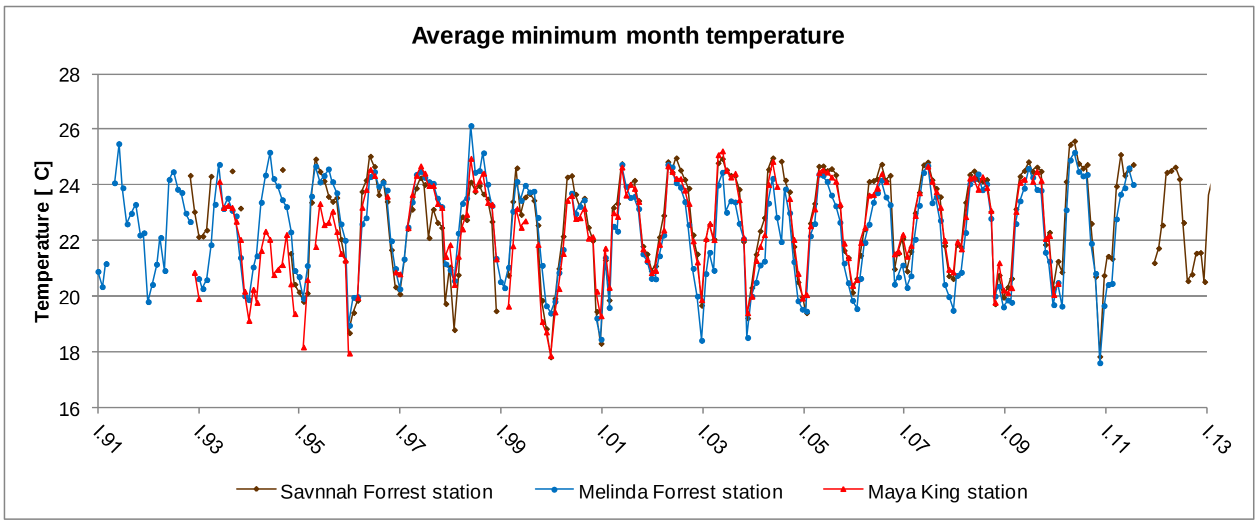

Fig. 6 Average monthly minimum temperature

Precipitation

For the Savannah Forest station, there are data series with daily records of precipitation for 401 months (January 1966 – August 2011). Daily precipitation varies from 0.0 mm/day to 255.5 mm/day (recorded in October 2008). According to the records evaluation the driest month was May 1995 with monthly precipitation 0.5 mm/month and the rainiest June 2006 with precipitation 755.7 mm/month. In point of long term average value the driest months are April and March with average monthly precipitation 49.29 mm/month and 54.99 mm/month, the rainiest are September and August with average monthly precipitation 358.1 mm/month and 352.6 mm/month. Total annual precipitation varies from 1715 mm/year to 3484 mm/year with average value 2419 mm/year.

For the Melinda Forest station, there are data series with daily records of precipitation for 452 months (January 1966 – August 2011). Daily precipitation varies from 0.0 mm/day to 253.0 mm/day (recorded in September 1976). According to the records evaluation the driest month was April 1984 with monthly precipitation 0.0 mm/month and the rainiest July 1983 with precipitation 812.0 mm/month. In point of long term average value the driest months are April and March with average monthly precipitation 52.66 mm/month and 56.46 mm/month, the rainiest are September and October with average monthly precipitation 319.99 mm/month and 301.53 mm/month. Total annual precipitation varies from 1465 mm/year to 3031 mm/year with average value 2254 mm/year.

For the Maya King station, there are data series with daily records of precipitation for 196 months (December 1992 – May 2010). Daily precipitation varies from 0.0 mm/day to 241.3 mm/day (recorded in October 2008). According to the records evaluation the driest month was March 1995 with monthly precipitation 6.1 mm/month and the rainiest October 1998 with precipitation 765.2 mm/month. In point of long term average value the driest months are April and March with average monthly precipitation 51.08 mm/month and 59.28 mm/month, the rainiest are August and September with average monthly precipitation 346.9 mm/month and 320.3 mm/month. Total annual precipitation varies from 1763 mm/year to 2571 mm/year with average value 2297 mm/year.

Basic information about statistical evaluation of monthly values of precipitation is summarized in Tab. 9, time behavior of monthly precipitation is pictured on chart (Fig. 7).

Tab. 9 Monthly precipitation

Savannah Forest station												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Number of records	36	35	35	34	34	34	32	32	32	31	34	32
Minimum precipitation	24.7	1.0	1.6	1.0	0.5	15.3	111.8	118.5	152.3	91.2	34.3	42.9
Maximum precipitation	296.4	251.9	204.0	204.5	264.0	755.7	532.9	542.6	537.4	614.9	385.7	394.2
Average precipitation	**128.3**	**81.3**	**55.0**	**49.3**	**107.8**	**305.6**	**324.3**	**352.6**	**358.0**	**295.3**	**210.2**	**167.8**
Melinda Forest station												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Number of records	37	38	38	37	38	38	38	37	37	37	37	35
Minimum precipitation	13.9	2.2	0.0	0.0	0.5	34.2	57.7	75.1	90.4	47.2	3.8	21.0
Maximum precipitation	397.1	277.5	245.6	142.2	476.2	708.2	812.0	443.0	683.4	779.4	509.7	430.2
Average precipitation	**160.8**	**75.6**	**56.5**	**52.7**	**142.7**	**256.9**	**246.8**	**235.9**	**320.0**	**301.5**	**224.6**	**174.0**
Maya King station												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Number of records	18	15	18	17	17	16	17	14	14	16	16	18
Minimum precipitation	28.7	20.7	6.1	9.6	7.8	67.9	195.9	207.4	182.0	105.3	60.7	54.5
Maximum precipitation	233.3	148.0	235.9	208.6	449.3	650.0	444.3	708.3	616.5	765.2	554.5	327.3
Average precipitation	**117.8**	**68.3**	**59.3**	**51.1**	**164.4**	**313.7**	**310.4**	**346.9**	**320.3**	**285.5**	**199.7**	**160.0**

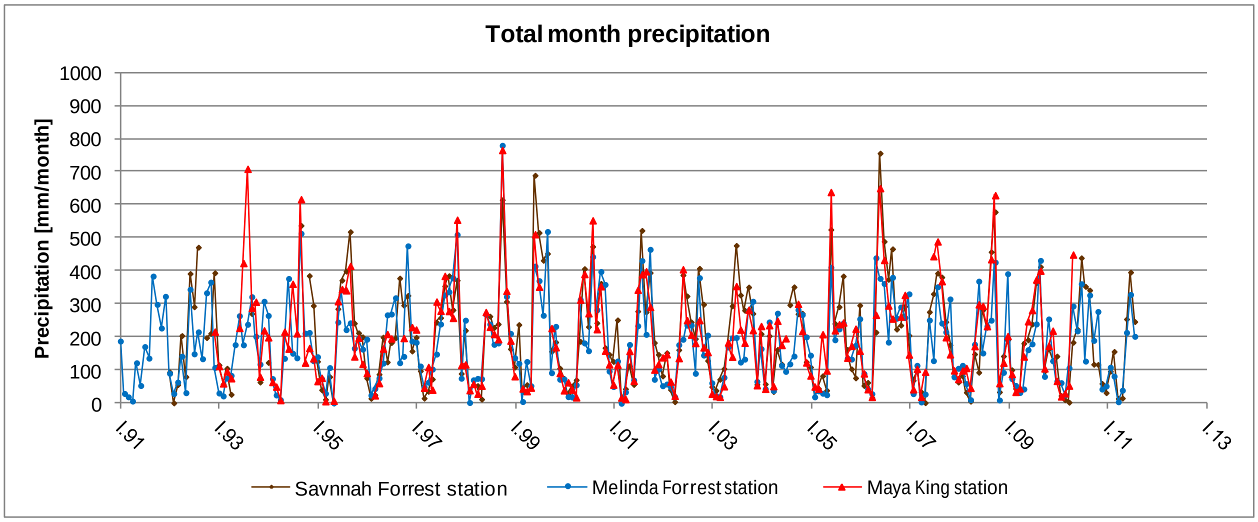

Fig. 7 Monthly precipitation

Evaporation

For the **Melinda Forest** station, there are data series with daily records of evaporation for 277 months (April 1986 – August 2011). Daily evaporation varies from 0.1 mm/day to 21.0 mm/day (recorded in March 1996). According to the records evaluation the lowest evaporation was recorded in January 1990 with monthly evaporation 52.7 mm/month and the highest evaporation in May 2007 with evaporation 166.1 mm/month. In point of long term average value the lowest evaporation occurs during January and December with average monthly evaporation 78.0 mm/month and 86.5 mm/month, the highest evaporation during May and April with average monthly evaporation 132.8 mm/month and 130.8 mm/month. There is not enough data for the evaluation of annual evaporation. Based on average month values annual evaporation value could reach 1300 mm/year.

For the **Maya King** station, there are data series with daily records of evaporation for 186 months (December 1992 – May 2010). Daily evaporation varies from 0.1 mm/day to 12.5 mm/day (recorded in April 1996). According to the records evaluation the lowest evaporation was recorded in December 2001 with monthly evaporation 48.9 mm/month and the highest evaporation in March 2003 with evaporation 167.8 mm/month. In point of long term average value the lowest evaporation occurs during December and January with average monthly evaporation 75.2 mm/month and 82.3 mm/month, the highest evaporation during April and May with average monthly evaporation 134.3 mm/month and 128.9 mm/month. There is not enough data for the evaluation of annual evaporation. Based on average month values annual evaporation value could reach 1280 mm/year.

Basic information about statistical evaluation of monthly values of evaporation is summarized in Tab. 10, time behavior of monthly evaporation is pictured on chart (Fig. 8).

Tab. 10 Monthly evaporation

Melinda Forest station												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Number of records	18	22	25	21	23	17	16	16	9	14	11	15
Minimum evaporation	52.7	73.8	79.2	105.7	98.7	91.1	92.5	87.2	84.3	77.8	63.4	52.4
Maximum evaporation	100.6	108.0	162.4	163.6	166.1	158.9	160.3	138.5	134.8	136.4	111.4	101.4
Average evaporation	**78.0**	**93.7**	**121.7**	**130.1**	**132.8**	**122.6**	**119.7**	**121.0**	**110.2**	**102.1**	**86.5**	**80.9**

Maya King station												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Number of records	15	14	16	15	16	7	8	6	6	7	11	12
Minimum evaporation	58.3	68.1	94.8	100	107.9	85.3	94.7	113.3	77.2	79.4	64	48.9
Maximum evaporation	101.5	113.8	168.7	166.1	159.2	151.3	151.7	131.9	139	124	102.7	100.9
Average evaporation	**82.3**	**94.3**	**124.8**	**134.3**	**129.0**	**125.0**	**113.6**	**121.7**	**104.1**	**97.8**	**80.6**	**75.2**

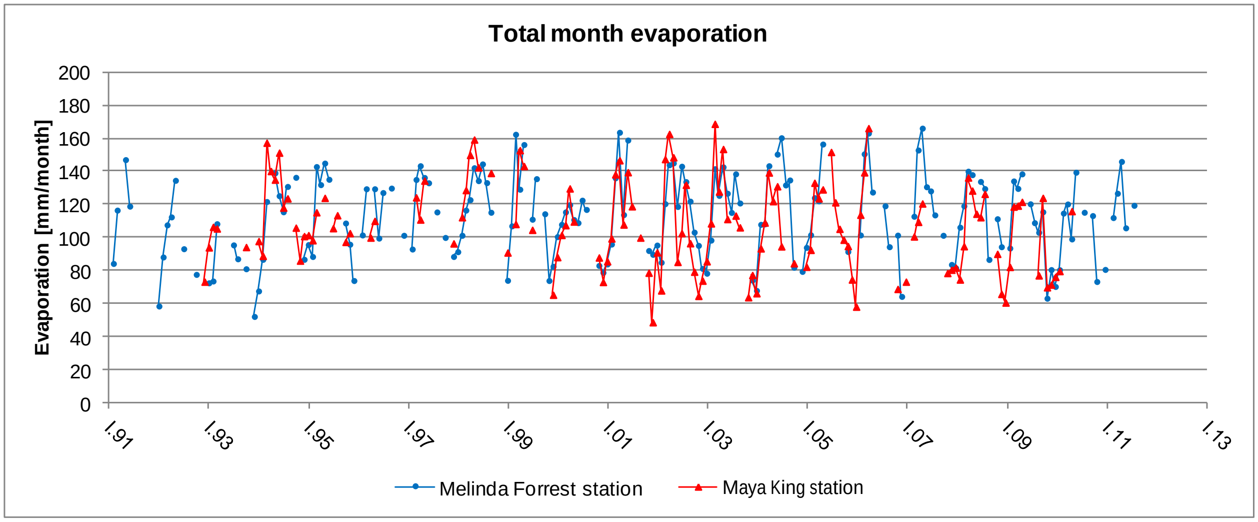

Fig. 8 Monthly evaporation

5.2.2. Role of meteorological data in groundwater assessment

Precipitation is a major component of the water cycle and mostly the only component of water cycle providing groundwater and surface water resources. Precipitation together with temperature and evaporation are main meteorological parameters influencing rate of surface water vertical drainage and groundwater formation rate in the investigated area.

The original precipitation, temperature and evaporation data as basic parameters of water balance were evaluated and then interpreted to determine infiltration of surface water into groundwater bodies. These parameters are also further applied in regional groundwater resource assessment and in conceptual as well as mathematical simulation model.

Climatic conditions are similar over the whole Savannah Province as indicates data assessment at all three climatic stations. Average maximum daily temperature reaches 31°C, minimum temperature 22.5°C. Average annual precipitation is 2325 mm, evaporation 1290 mm. Such quantified average values of climatic parameters are used as input parameters in mathematical model and groundwater resource assessment.

5.3. Geomorphology

The Savannah Groundwater Province lies on the coastal plain in foreland of the Maya mountains. The area is rather flat with few small hummocks. The altitude typically ranges between 20 to 60 m a.s.l. Surface gradually raises westward from sea level to elevation around 70 m a.s.l. at root of Maya mountains. On the slopes of the Maya mountains the altitude quickly raises up to 500 m a.s.l. and steeper slopes are common.

Geomorphological setting, as displayed in Annex 2, Map 2, clearly suggests delineation of the investigated area.

5.4. Hydrology

Belize hydrology network is divided to major river catchments and sub-catchments. The Savannah Province is located in the Southeastern watershed region (Boles, 1999). In total 19 watersheds are included in the investigated area (Fig. 9, Annex 2, Map 5): North Stann Creek, Bocatora Creek, Yemeri Creek, Northern and Southern Lagoon, Black Creek, Mullins River, Sennis River, Big Creek, Mango Creek, Freshwater Creek, Punta Ycacos Lagoon, Monkey River, Pine Ridge Creek, Sittee River, Santa Maria Creek, South Stann Creek, Golden Stream, Deep River, Cabbage Haul Creek.

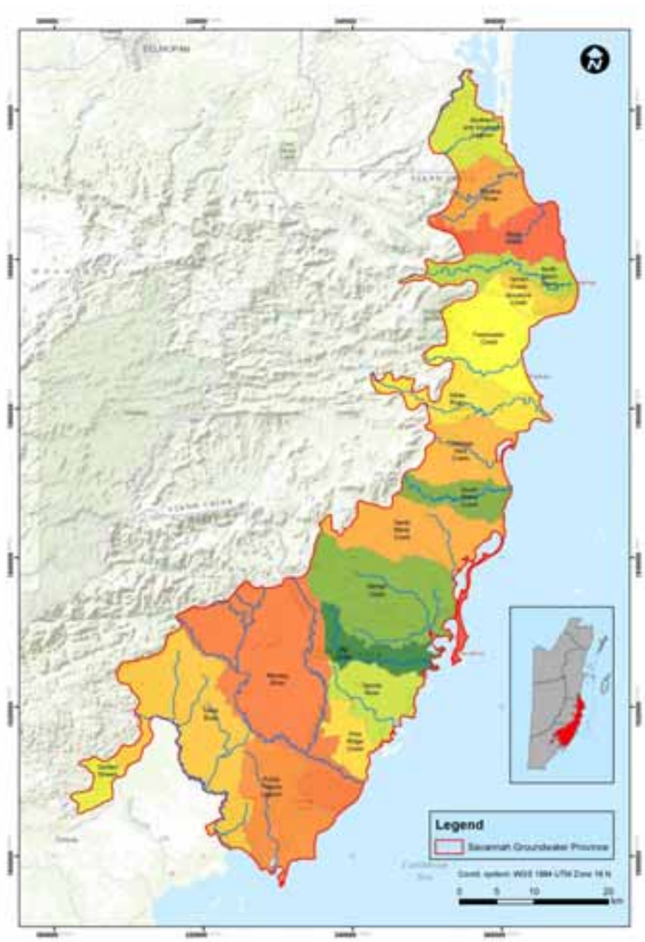

Fig. 9 Watersheds in the Savannah Groundwater Province.

Major water courses in the investigated area are represented by North and South Stann Creek, Sittee River and Monkey River with its tributaries Swasey and Bladen. Watershed area of these major water courses varies in hundreds of square kilometers and flow rate at Caribbean Sea reaches tens of cubic meters (Tab. 11). Major and other main water courses mostly spring beyond Savannah province limits in the Maya mountains and drain central part and southeastern and eastern slopes of the Maya mountains. Water courses are generally discharged into the Caribbean Sea. The flow rate varies depending on the precipitation. There are more small local water courses that mostly spring within Savannah province and drain water into major water courses. Their flow rate significantly depends on precipitation and they could become dry during dry season.

Being a part of a coastal plain, the Savannah Groundwater Province is rich in lagoons, mangrove swamps, deep estuaries and river-mouth bars (Hartshorn et al., 1984). Water from water courses is commonly used as a reliable water source. Surface water is generally suitable for irrigation purposes but in some places is used as drinking water source as well.

Tab. 11 Major water courses in the Savannah Groundwater Province
(http://www.bvsde.paho.org/muwww/fulltext/analisis/belice/Belice01.html)

	Catchment area (km^2)	Flow rate (m^3/s)
North Stann Creek	281.4	15
Sittee River	451.2	14
South Stann Creek	258	9
Monkey River	1 275.40	35-40

Some of water courses were equipped by gauging stations, such as Melinda Forest Station on the North Stann Creek, Kendall Bridge on the Sittee River, South Stann Creek station, Swasey Bridge on the Swasey River and Bladen Bridge on the Bladen River. For short site description, see Tab. 12.

Tab. 12 Hydrological data source

Name	Data source	Description
Sittee River, Kendal	National Meteorological Service, Hydrology Unit	Stream flow for Sittee River, at Kendal Bridge; measured between years 1995 - 2009
Monkey River, Swasey	National Meteorological Service, Hydrology Unit	Stream flow for Monkey River, at Swasey Bridge; measured between years 1993 - 2010
Monkey River, Bladen	National Meteorological Service, Hydrology Unit	Stream flow for Monkey River, at Bladen Bridge; measured between years 1993 - 2007

Data series of daily flow rate from gauging stations were used for evaluation of river flow rate regime and together with meteorological data (precipitation, evaporation, etc.) for evaluation of basic components of water runoff in watersheds. These runoff components and meteorological data (precipitation, evaporation, etc.) one and all are fundamental parameters for water balance assessment within watershed. Parameters of water balance (mainly base flow) create essential input parameters for groundwater modeling and groundwater resources assessment.

Evaluation of base flow from watershed was done firstly by hydrological estimation of water balance and then by hydrograph analysis using method of base flow separation by Kille. Method of hydrological water balance estimation is based on estimation of individual variables of hydrological equation. These variables are representing primarily with precipitation, evapotranspiration, base flow, direct flow. Method of separation by Kille is based on frequency analysis of minimum monthly flow rates in 30 day period over evaluated time.

Minimum monthly flow rates are sorted and placed into exceedance probability chart. Middle part of curve represents average base flow from catchment. Method is suitable for evaluation of regional data with long-term average values. Advantage of this method is fast and easy evaluation, easy availability of basic data, necessity of no additional data, minimizing of subjective intervention.

Hydrological water balance

Simple hydrological water balance equation should be formulated as:

$$Q_b = P - ET - Q_d \pm W$$

where Q_b is base flow, P is precipitation, ET is evapotranspiration, Q_d is direct flow and +/-W is change of water reserves.

The average annual precipitation in Savannah province is 2325 mm/year, average annual evaporation is 1290 mm/year (see section 5.1). Value of annual evapotranspiration is estimated as higher than evaporation, around 1595 mm/year. Considering the fact that Savannah province landscape is very flat with low ratio of consolidated and impermeable surfaces, direct flow will form small part of total water runoff from watershed, 20% by estimation. Parameter +/-W can be neglected for the whole watershed. Solving of equation with above defined parameters gives average value of total water runoff 730 mm/year which gives specific value 23 $L/s/km^2$. Then, the average specific base flow is estimated around 17 $L/s/km^2$.

Hydrograph analysis

Catchment area of Sittee River is 451 km^2 in total, area of sub catchment upward profile at Kendal covers approximately 399 km^2. Sittee River water flow at Kendal gauging station varies from 0.98 m^3/s to 69.3 m^3/s with average flow 32.3 m^3/s (Fig. 10). Based on evaluation of minimum monthly flow rates (Fig. 11) the average value for base flow is 26.4 m^3/s. It represents specific base flow 66.2 L/s/km^2.

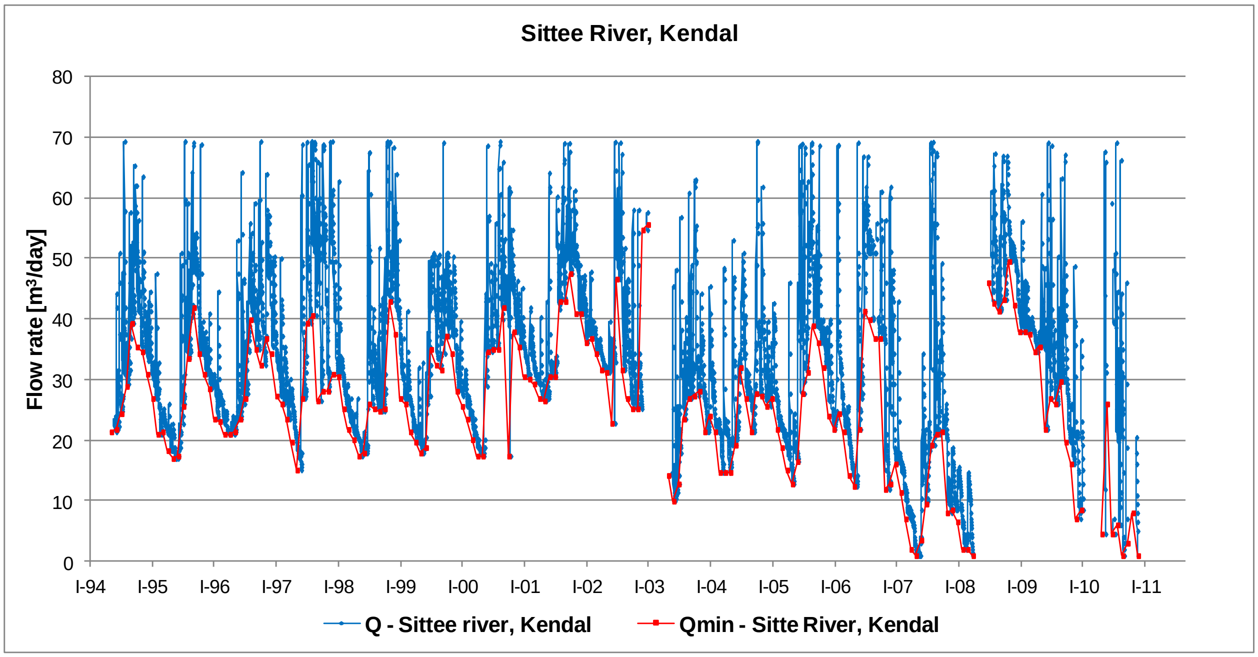

Fig. 10 Sittee River flow rate at Kendal

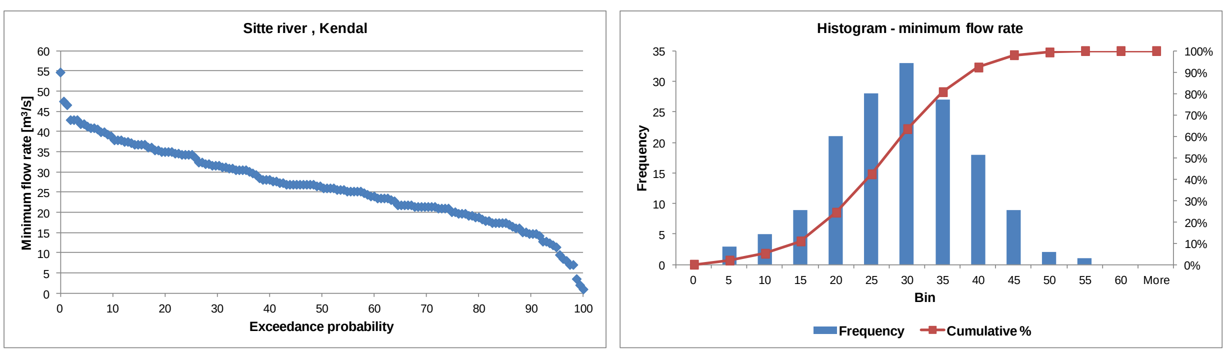

Fig. 11 Sittee River flow rate - statistic

Catchment area of Swasey Branch upward profile at Swasey covers approximately 330 km^2. Swasey Branch water flow at Swasey gauging station varies from 0.006 m^3/s to 277 m^3/s with average flow 22.4 m^3/s (Fig. 12). Based on evaluation of minimum monthly flow rates (Fig. 13) the average value for base flow is 16.4 m^3/s. It represents specific base flow 49.7 L/s/km^2.

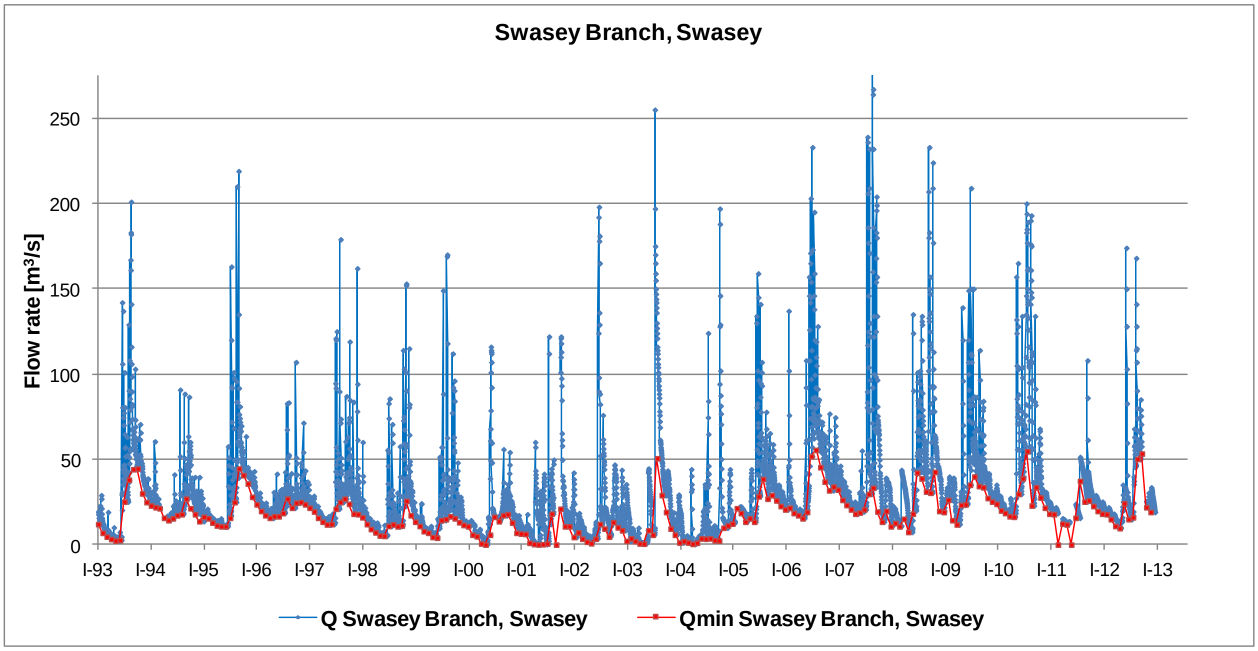

Fig. 12 Swasey Branch flow rate at Swasey

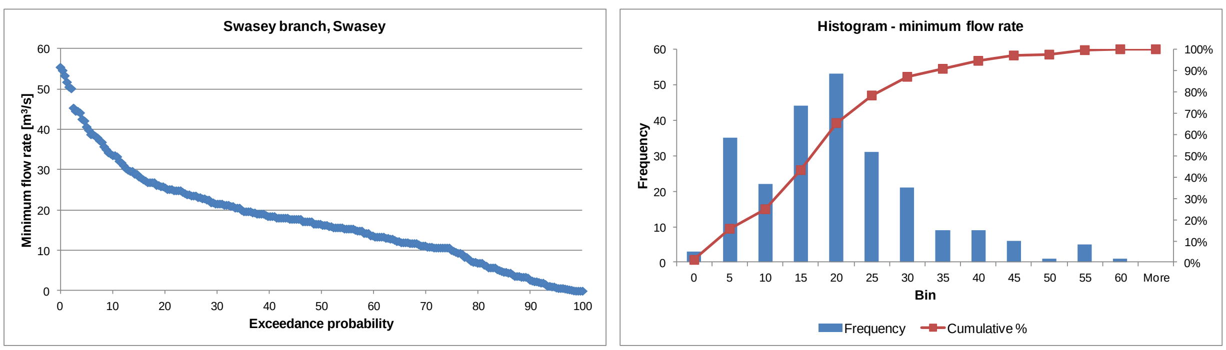

Fig. 13 Swasey Branch flow rate - statistic

Catchment area of Bladen Branch catchment upward profile at Bladen covers approximately 645 km^2. Bladen Branch water flow at Bladen gauging station varies from 0.001 m^3/s to 6641 m^3/s with average flow 3.9 m^3/s (Fig. 14). Based on evaluation minimum monthly flows (Fig. 15) the average value for base flow is 0.9 m^3/s. It represents specific base flow 1.3 $L/s/km^2$.

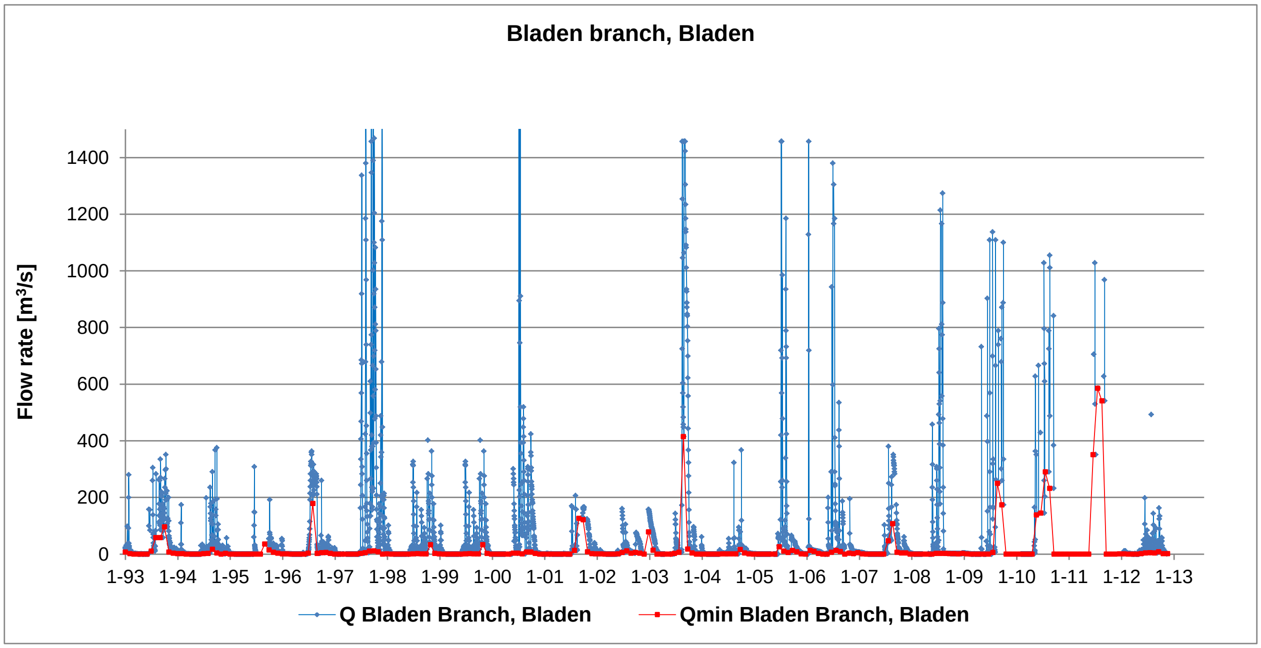

Fig. 14 Bladen Branch flow rate at Bladen

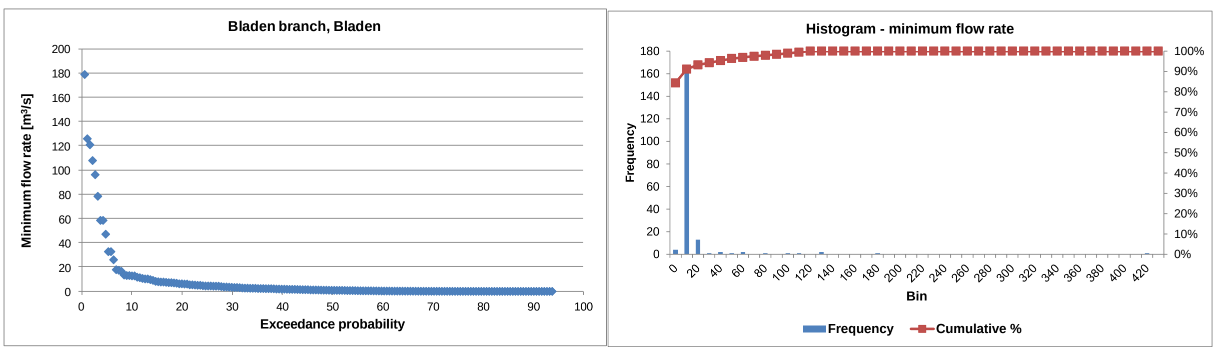

Fig. 15 Bladen Branch flow rate - statistic

Summary Assessment of Base Flow

Hydrograph analysis gives results for average specific base flow 66 L/s/km^2 at Sittee River and 49 L/s/km^2 at Swasey Branch. These results are quite high and are close to specific value of total resources (precipitation) in the area which reaches 72 L/s/km^2 and exceed value 33 L/s/km^2 of internal flow (precipitation less evaporation).

Even considering a hydrograph analysis error, values of specific base flow remain too high in comparison with value of internal flow assessed from climatic data evaluation. Inaccuracy of results is probably caused by incorrect interpretation of daily flow rates.

In case of Bladen Branch hydrograph analysis gives extremely low value of average specific base flow 1.3 L/s/km^2. This value does not correspond to values of specific base flow at Sittee River and Swasey Branch and also will be probably caused by incorrect interpretation of daily flow rates.

Catchment area of Bladen Branch (645 km^2) is approximately twice larger than catchment areas of Sittee River (399 km^2) and Swasey Branch (330 km^2) and all three catchment have similar hydrological characteristic and natural conditions. With respect to similar natural condition of catchments and differences in their areas specific value of base flow at Bladen Branch should be expected near to twice higher than values at Sittee River and Swasey Branch.

Comparison of water balance and hydrograph analysis

Based on analysis of meteorological data with solving of water balance equation specific value of total water runoff (23 L/s/km^2) and specific value of base flow (17 L/s/km^2) from watershed can be considered as values representing average natural conditions within Savannah Province.

Hydrograph analysis gives values of specific base flow varying from 1.3 L/s/km^2 at Bladen Branch to 66 L/s/km^2 at Sittee River. There is no reason for such a significant difference in resulted values especially with respect to similar natural condition of catchments and differences in areas of catchments.

Estimated values for base flow and water runoff acquired by method of hydrologic water balance can be considered as more accurate than values acquired by hydrograph analysis.

The precipitation and evaporation data as basic parameters of water balance were evaluated and interpreted to determine infiltration of surface water in groundwater. The representative specific values of base flow further applied in groundwater assessment and in various models developed within the Project are ranging between 15 L/s/km^2 and 25 L/s/km^2.

5.5. Geology

Belize's geology is known to comprise of an extensive limestone formations. The northern half of Belize rests on the Yucatan Platform. The Yucatan Platform is a tectonically stable limestone shelf of chalk, marl and other sedimentary layers. The site is typical of dolomite limestones, with shallow and poor soils. The Yucatan Peninsula has been subjected to periods of metamorphism, folding, faulting and several sea level changes. The two largest rock groups present are the Paleozoic rocks of the Maya Mountains and the Cenozoic (Miocene to Pleistocene) limestones of northern Yucatan.

Based on the Geological map compiled by Cornec (2002), almost all the Savannah Groundwater Province is located on the Coastal Plain (Annex 2,

Map 4). Within the Coastal plain there are alluvial fans and relict marine terraces. These are pleistocene sediments overlained by more recent floodplains and terraces of the Toledo Flood Plains Land System. The quaternary alluvium deposited in the terrestrial zone is poorly consolidated and readily erodible.

Quaternary to Holocene sediments consist of layers marls, clays, fine to coarse clayey sands, fine to coarse sands mostly unconsolidated, shales, limestone. Origin of these sedimentary formations is coastal and beach. Fine to coarse clayey sands and gravels, sandy and silty clays dominate in higher elevated areas. These are fluvial sediments and terraces and eluvial deposits. Deluviofluvial, deluvial and slope sediments represent with unconsolidated clayey conglomerates, clayey fine to coarse sands silts occur along mountain slopes. The thickness of quaternary sediments varies from few of meters to several tents of meters depending on morphology and tectonic position of site. Quaternary sediments are characterized by quite significant changes in vertical and horizontal lithology.

In Miocene to Paleocene sedimentary formation dominates clayey marls and silty clays, mudstones and limestones. Thickness of these sediments is estimated about 200 m.

Underlying late Cretaceous to Paleocene formation consists of silty and sandy claystones and limestones and shales. These are interbedded with sandy siltstones, fine to coarse sandstones and conglomeratic layers. Origin of these sedimentary formations is deep water and bathyal. Thickness of this formation reaches up to 600 m and should vary according to tectonics.

Basement is formed with Cretaceous shales, limestones and dolomites.

The Savannah Groundwater province is located in the easternmost section of the southern Belize Basin on the coastal plain (Cornec, 2002). This basin is underlain by quaternary and recent deposits namely soils, stream/river deposits and deltaic deposits (Flores, 1952), classified as the Toledo Flood Plains Land System. The quaternary alluvium deposited in the terrestrial zone is poorly consolidated and readily erodible and unconformably overlies the Paleocene-Eocene Toledo Formation.

Tectonically, Belize is located near the junction of the North American and Caribbean tectonic plates, slabs of the earth's crust that have moved past each other over the last 80 million years. Eastward drift of the Caribbean plate resulted in the dominantly structurally-controlled major features of Belize - the Maya Mountains (http://ambergriscaye.com/geology/).

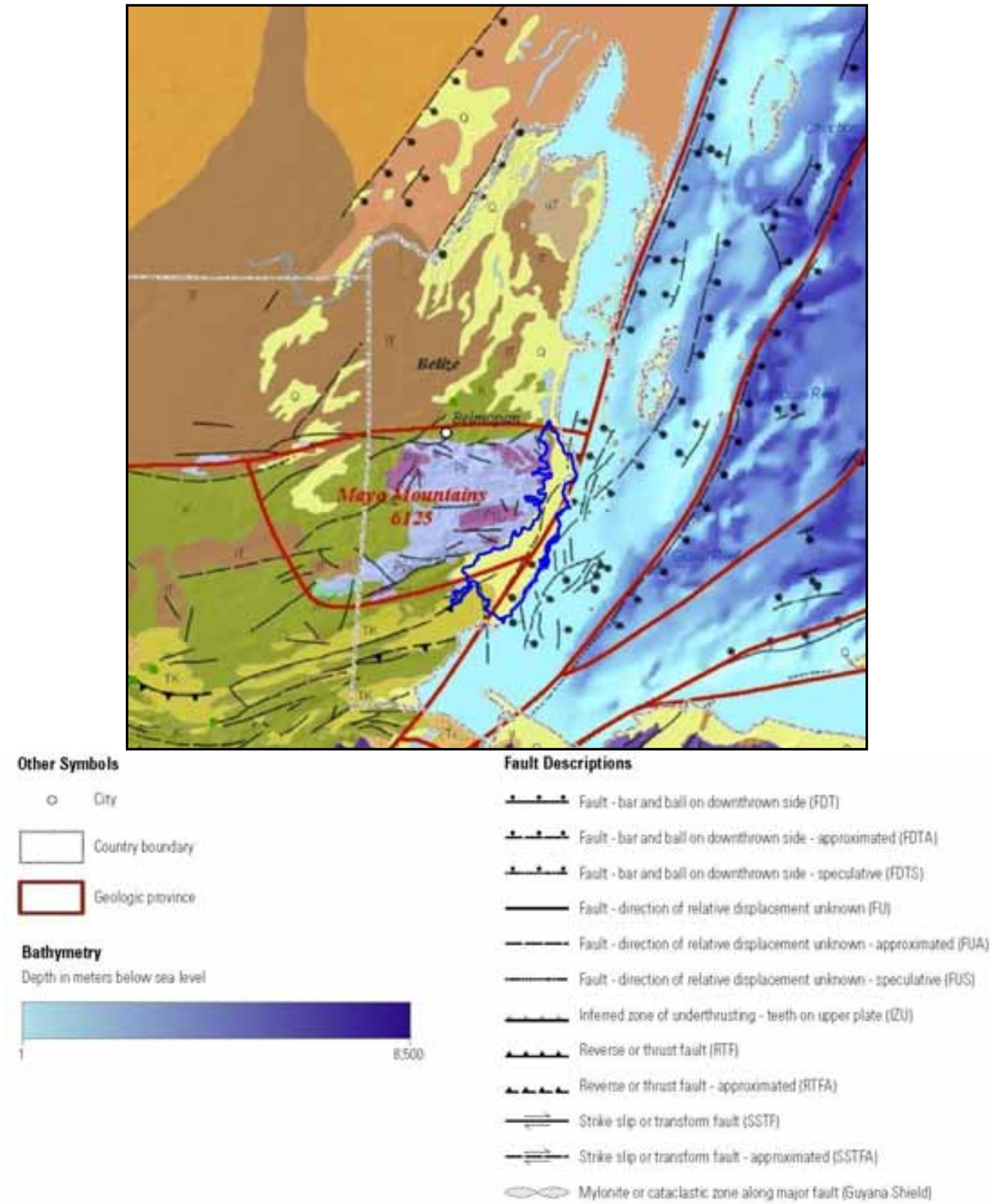

Fig. 16 Tectonics in broader area of Belize. Savannah Groundwater Province boundaries displayed in blue color (modified from USGS, 2004).

Based on regional seismic activity, most of Belize is not known to be a tectonically active. However, the tectonics and faulting represent a significant feature of the studied regional groundwater structure.

5.6. General Hydrogeology

Understanding the aquifer hydraulic properties and hydrochemical characteristics of water is crucial for groundwater planning and management in the study area. Available information on regional geology exploration as well as oil&gas exploration show that in the quaternary, tertiary and upper cretaceous basin sediments that form the Savannah Province multilayered porous aquifer system may be distinguished.

The investigated multilayered aquifer of sedimentary formation is generally formed by clastic sediments (sandstones, sandy gravels) of high permeability and developed over the entire Savannah Groundwater Province area (excluding areas formed by limestone characterized by karst permeability). The thickness of the investigated multilayered aquifer ranging from tens to first hundreds meters together with its favourable hydraulic properties represents extraordinary opportunities for water supply utilization. Multilayered aquifer can be divided in two main sections in a vertical profile, *Quaternary to Holocene section* and *late Cretaceous to Paleocene section*. The vertical profile of each section may include several individual aquifers. These two sections are interbedded with aquitard of Miocene to Paleocene sedimentary formation. Groundwater circulation is very sporadic between sections. Some communication can occur in place where limestones dominate in profile of Miocene to Paleocene aquitard.

Quaternary to Holocene section

Upper part of Quaternary to Holocene section forms phreatic water-bearing system in unconsolidated fine to coarse clayey sands and gravels. This phreatic system is mostly discontinuous and locally developed in depth between 5 - 15 m. Groundwater is recharged with direct infiltration from precipitation. Water-bearing strata of lower part of Quaternary to Holocene section developed in depth between 30 – 60 m are formed with sandy siltstones, fine to coarse sandstones and conglomerates interbedded in sandy claystones and shales. These semi-confined aquifers are recharged by seepage at deep contact of Maya mountains with aquifers or by seepage from upper sedimentary formation. The profile of the Quaternary to Holocene section was subject of investigation during field work and confirmed by drilling of exploratory well HGE-1 and assessment of provided data.

Hydraulic properties of the aquifer system depend on many factors such as the position and thickness of water-bearing layers, ratio of fine grain fraction. The hydraulic conductivity generally ranges between 10^{-4} – 10^{-5} m/s. Yield capacity of extraction wells varies from 0.X L/s to 20 L/s. Lower yields were observed at shallow wells with immediate response to pumping, drought, and rainfall. Higher yields correspond to deeper wells penetrating through several water-bearing layers. The hydraulic testing of exploratory well HGE-1 confirmed the yield of about 9 L/s with drawdown of 13 m.

Late Cretaceous to Paleocene section

Late Cretaceous to Paleocene section forms water-bearing system consisting of calcareous sandstone. Aquifers in this section are confined by a clay aquiclude. The zone of infiltration is outside the Savannah province in Maya mountains. The depth of aquifers (i.e. Cretaceous limestones and dolomites) ranges between hundreds to first thousands meters below the surface. The existence and spatial extent of these sections and aquifers is conditioned by local geological structure. Existence of local aquifers is well documented in San Juan and Monkey River oil well logs. Geophysical profiles for San Juan No. 2 identify two depth levels (120 m, 260 m) with significant groundwater flow which was not confirmed for wells San Juan No 1. and No. 3.

Geological and hydrogeological structure of the aquifers and their hydraulic properties are poorly understood and no sufficient data is available for more detailed evaluation of the structure. These deep aquifers are challenging for further hydrogeological study, exploration and assessment of groundwater regime in deep rock structures.

5.7. Land Use

Belize boasts the highest overall percentage of forest cover of any of the Central American countries (Vreugdenhil et al., 2002). Although, Belize has approximately 63% of the total land area under some form of forest cover, only about 14% of the forests (about 303,000 hectares) are available or appropriate for sustainable forest management for timber production.

In terms of Belize's mangrove cover - which assumes the form of not only of mangrove 'forest' but also of scrubs and savannas, among others, was reported to be 3.4% of land cover (78,133 ha) (UNEP, 2011).

Belizean land is considerably used for agriculture providing roughly 65% of the country's total foreign exchange earnings. Over the last several years agriculture had been one of the most dominant sector contributing to the economic development of Belize. Nowadays, agriculture is second largest industry. Next to the transport sector, the agriculture sector is the second largest importer and user of chemicals in Belize (pesticides and fertilizers) and its related production and processing activities are the largest generators of industrial effluent and solid waste. Irrigation in Belize has been marginal because of its climatic and social conditions. Surface and sprinkler irrigation is being used for citrus and banana production, and surface irrigation is also used for rice and micro-irrigation of papaya production. It is expected that in the coming years more banana plantations will be irrigated where the estimated water withdrawal may be in the range of 240 000 m^3/yr. All of the irrigation systems in Belize are private and were developed with private funds or loans from international cooperation organizations such as the European Union (Ballestero, 2007).

In addition, aquaculture, in particular shrimp farming, is a growing threat to coastal ecosystems. Nutrient pollution, physical alteration of habitat, such as the destruction of mangrove forests, and sedimentation are all impacts of aquaculture experienced in Belize's coastal areas (UNEP, 2011).

Agriculture employs approximately 30% of the total labor forces. About 38% of the total land area is potentially suitable for agriculture use but only perhaps 10 – 15% is used. However, the potential for agricultural potential is not unlimited. The dominant sector in agriculture is sugar industry; other important agriculture sectors are citrus industry, banana farms and cacao – which becoming increasingly important as an export crop (http://ambergriscaye.com/pages/town/factsbze.html). As reviewed, the Savannah Groundwater Province covers 12 aquaculture farms and processing facilities, citrus farms (100 km^2) and banana farms (90 km^2) (Williams, 2011).

See Annex 2, Map 3 for map of land use pattern in the Savannah Groundwater Province.

Tab. 13 Land use / cover distribution in Belize, SP= Savannah Province

Ecosystem	Share for Belize (km^2)	Share for SP (km^2)	Share for Belize (%)	Share for SP (%)	Savannah % of area in Belize
Agricultural uses	4 433.17	471.93	20.04	23.13	10.65
Lowland savanna	1 747.46	635.24	7.90	31.13	36.35
Shrubland	329.01	43.55	1.49	2.13	13.24
Forests	14 222.16	764.60	64.29	37.47	54.49
Water	88.53	12.08	0.40	0.59	13.64
Wetland	1 025.18	86.18	4.63	4.22	8.41
Urban	275.74	26.91	1.25	1.32	9.76
Total	**22121.26**	**2040.50**	**100.00**	**100.00**	

6. Field Work

6.1. Mapping, Measuring, Sampling

Conducting field work verified and supplemented the information collected from the records review. In particular, the site visit was used to confirm locations of wells, acquire GPS co-ordinates of investigated sites, confirmed local land use, surface water body features, obvious sources of potential groundwater contamination (industrial land use, landfills, etc.) and water sampling.

Field work was carried out between January 19, 2014 and February 14, 2014. The entire area of the Savannah Groundwater Province was investigated as documented in Annex 2, Map 7.

In the first stage of field work main activities were focused on mapping and verifying known hydrogeological objects (mainly existing wells). Mesh of these objects formed basic information database of study area. Next step was dedicated to filling up basic information database by exploring areas with low or lack of data about hydrogeology.

Attention was paid not only to existing wells/boreholes but also to other natural and geological phenomena relevant to hydrogeological conditions in area (i.e. surface water bodies, rock outcrops, etc.). During the field work, 173 sites in total were documented in the entire Savannah Province from that 106 documentation points were identified as groundwater or surface water objects. The remaining sites are rock outcrops and sites with significance for geological structure or other (see map in Annex 2, Map 7).

Visited sites by GEOMEDIA are generally classified into 3 categories:

- groundwater sampling sites
- surface water sampling sites
- other (outcrops, etc.) where no sample was taken

Each of the sites was GPS localized and documented. One page document is elaborated for each documentation point describing the type of the point, list of performed measurements and including photo documentation. Complete documentation is available in Annex 8 where one page form was elaborated for each documentation point. In case of wells, information on depth of well, static/dynamic groundwater level and its fluctuation, average pumping rate, geology and archive chemical analysis were collected depending on availability of information or direct site measurement.

During field work, all ground/surface water samples from documented points were taken for analysis of basic chemical indicators (pH, temperature, total dissolved solids, dissolved oxygen, electroconductivity, turbidity). The analyses were carried out by means of GPS AQUAMETER AM-200TM and AQUAPROBE AM-600TM, brand AQUAREADTM.

Measured field data were incorporated into a comprehensive Water Management Database (Annex 9).

Fig. 17 Field equipment

Additionally, 13 samples were analyzed for other relevant chemical parameters in the laboratory of Bowen & Bowen, Ltd. (electroconductivity, pH, total dissolved solid, turbidity, calcium, copper, aluminum, iron, manganese, sodium, fluorides, hydrocarbonates, ammonium, carbonates, chlorides, hardness, alkalinity, nitrates, nitrides, phosphates, salinity, chloride of sodium, sulphates).

The field work contributed to re-assessment of boundary conditions of the Savannah Groundwater Province. Prior to this groundwater assessment, the area of the Savannah Groundwater Province corresponded to 1 842 km^2. Based on the field work observations and detailed geomorphology assessment, the limits of the Savannah Province were adjusted and the current area reaches 2 040 km^2. The difference of the boundary delineation is displayed in Annex 2, Map 8.

6.2. Drilling and Hydraulic Pump Test

Based on the interpretation of available borehole data, including available pump test data as well as deep well-logs, it was advised to drill a hydrogeological exploration well in order to verify geological profile and hydraulic parameters of the upper aquifer by hydraulic testing (pump and recovery tests).

The borehole needed to be cased as permanent hydrogeological object so as to be suitable for subsequent use for monitoring purposes. The monitoring should cover the continuous observation of groundwater levels and hydro-chemical composition. It is expected that this well will represent a pilot monitoring well site in the Savannah Province and thus representing the base for further development of national groundwater regime monitoring network.

The proposed well should cross the vertical profile of the sedimentary formation overlying cretaceous limestones.

The site of the well was selected to reflect the undisturbed groundwater regime of the hydrogeological structure of the upper aquifer. New well should be easily accessible, not affected by other water supply constructions or wells in the broader surrounding or by nearby watercourses. It is recommended that in the vicinity of the proposed well is installed hydro-meteorological station or precipitation station. The field work in January – February 2014 was also aimed at determination of potential sites for drilling.

Several sites have been evaluated as appropriate in terms of expected geological and hydrogeological setting and spatial distribution within the investigated area. The location of potential drilling sites was furthermore verified in terms of proprietary rights. In order to prevent land owner issues, the exploratory well was decided to be drilled within the Crown Land areas, i.e.:

- in Deep River Forest Reserve close to Bladen Branch approx. 4.5 km western from Trio (HGE-1)

The Scientific Collection / Research Permit was received from the Forest Department on June 17, 2014 (included in Annex 4, Document 1).

In order to verify hydraulic properties of encountered aquifer, it was decided to perform hydraulic testing, particularly pump and recovery test. The Department of Rural Development was contracted to carry out drilling and hydraulic testing.

The drilled exploration well HGE-1 is recommended to be used as a pilot well for the groundwater monitoring in the Savannah Province. Formal status as well as organizational and technical operation guidelines of the completed well HGE-1 is proposed in Annex 5.

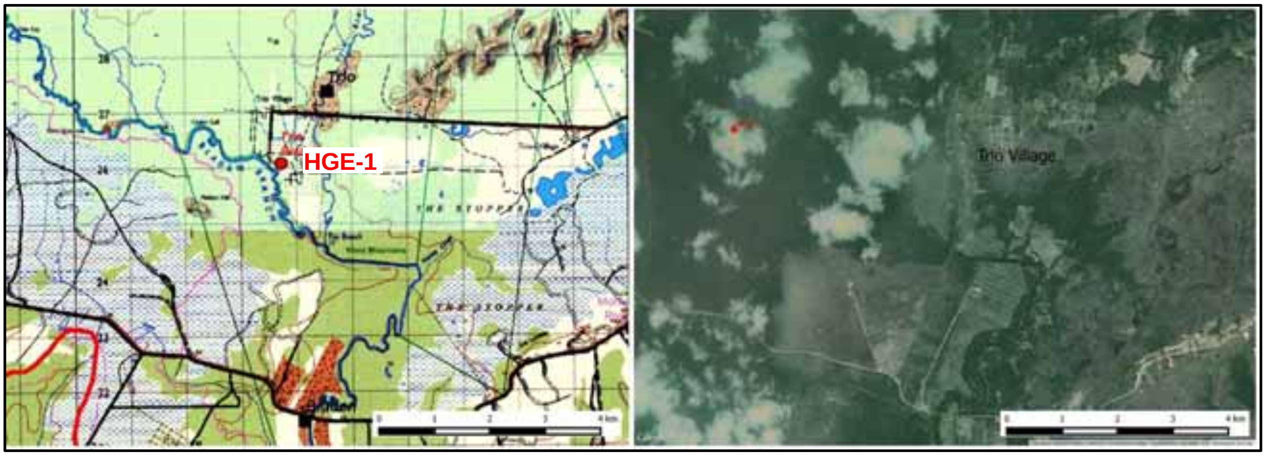

Fig. 18 Location of HGE-1 well.

6.2.1. Drilling

The Deep River Forest Reserve is located in the district of Toledo, Belize south east of the Maya Mountains. It covers approximately 270 km^2. The reserve within the Savannah Groundwater Province is a part of the Deep River watershed. The site is located approximately 150 m from the Deep River on a fluvial terrace (Fig. 18).

The Department of Rural Development utilizes a drilling rig capable of drilling up to 120 m. A rotary bit is utilized for soft material and a hammer bit for hard indurated rock.

Steel casings were utilized so that drilling could proceed and to prevent the collapse of the bore.

Well casings blanks and screens were utilized after the completion of the hole. Approximately 30 m. of casing screens were utilized for the observed water bearing zone. Casing blanks were utilized for the remaining zones, After completion of the well bore it was then gravel packed and cemented.

Fig. 19 Photo documentation from drilling of the HGE-1 borehole in Deep River Forest Reserve.

The first well, HGE-1 in Deep Forest Reserve was drilled between July 14 and 21, 2014 and was officially completed at the depth of 79m. Detailed Well Drilling Report including a detailed geological log and a generalized stratigraphic and hydrogeological section is provided in Annex 4, Document 2.

6.2.2. Hydraulic Pump Test

The 72-hour hydraulic pump testing for the HGE-1 well was carried out using a 10hp submersible pump.

Static water level was measured prior to the start of pumping and during the process in order to determine the rate of drawdown. The pump was placed in the depth of 73 m. Prior to pump testing the initial static water level was 11.5 m below the surface. Within the first 10 minutes the water table dropped to 24.4 m below surface.

Upon completion of hydraulic testing the time taken to return to the starting water level was observed (rate of recovery). 100% recovery percentage was registered after 6 minutes.

Flow rate was observed using a flow meters at different intervals throughout the test namely one minute intervals; 10 minute intervals; 30 minute intervals and hourly intervals.

Detailed hydraulic pump testing record is provided in Annex 4, Document 3.

7. Groundwater Simulation Model

The objective of the mathematical model is to simulate groundwater circulation in the upper sedimentary formation (flow rate and velocity and direction) of the Savannah Groundwater Province and impacts of water abstraction. Groundwater model shall help to define options for water supply ensured from the upper part of aquifer and quantity of total and exploitable groundwater reserves.

Numerical groundwater modeling is applied to provide estimate of the status of the groundwater resource and to set the volume of the groundwater that might be abstracted without damaging local surface aquatic ecosystems and groundwater resources in the long-term.

Groundwater modeling shall be further applied to simulate proposed scenarios of development in groundwater management in the Savannah Groundwater Province, such as growing population centers and large expansion in tourism, aquaculture and agriculture in order to properly asses the availability and sustainability of encountered groundwater resources for public demands. Furthermore, it shall support the proposals for design the groundwater monitoring system.

7.1. Applied Software

The applied software is the industry standard FEFLOW simulation package. For mathematical modeling it was considered as useful to use FEFLOW simulation package because of its very good computing skills, better spatial discretization and optimization of model mesh and more precisely fitting of model mesh to local heterogeneities of hydrogeology and geology elements. MODFLOW as well as FEFLOW is also frequently used powerful industrial standard simulation package based on finite difference method for solving governing equations. Finite difference method uses rectangular numerical mesh that do not allow so precise fitting of model mesh without significant increase of total model nodes and computing time duration. These advantages of FEFOW simulation package were reason for applying FEFLOW instead initially proposed MODFLOW simulation packages.

FEFLOW (Finite Element subsurface FLOW system) is a professional 3D software package for modeling fluid flow and transport of dissolved constituents and/or heat transport processes in the subsurface based on finite element method. This software solves three dimensional and two dimensional, areal and cross sectional, fluid density-coupled, also thermohaline or uncoupled, variably saturated, transient or steady state flow, mass and heat transport in subsurface water resource with or without one or multiple free surface. FEFLOW is suitable for numerous different applications in flow and transport processes simulation in porous media, ranging from lab scale to continental scale.

FEFLOW can be efficiently used to describe the spatial and temporal distribution of groundwater contaminants, to model geothermal processes, to estimate the duration and travel times of pollutants in aquifers, to plan and design remediation strategies and interception techniques, and to assist in designing alternatives and effective monitoring schemes. Through a sophisticated interface communication between FEFLOW and GIS applications such as ArcInfo, ArcView and ArcGIS for ASCII and binary vector and grid formats is available (WASY, 2004).

FEFLOW is capable of solving 2D and 3D problems. A Galerkin-based finite-element numerical method for meshes is used. The mesh should be formed either by cubes or by irregular tetrahedrons. The FEFLOW mesh example is shown in Fig. 20. Dirichlet (1st kind), Neumann (2nd kind) and Cauchy-type (3rd kind) boundary conditions can be specified for flow, mass and heat. A so-called 4th kind of boundary condition exists for singular (pumping or injection) wells. These boundary conditions can be arbitrarily placed at nodal points of a 2D and 3D mesh. All boundary conditions (from 1st to 4th kind) can be specified either as steady-state or transient. All parameters are handled on an element level, i.e., they can differ from element to element, and it is possible to consider those as steady-state or transient quantities. It also allows manipulation of parameters during the simulation. Anisotropy of the hydraulic conductivity is supported for both 2D and 3D.

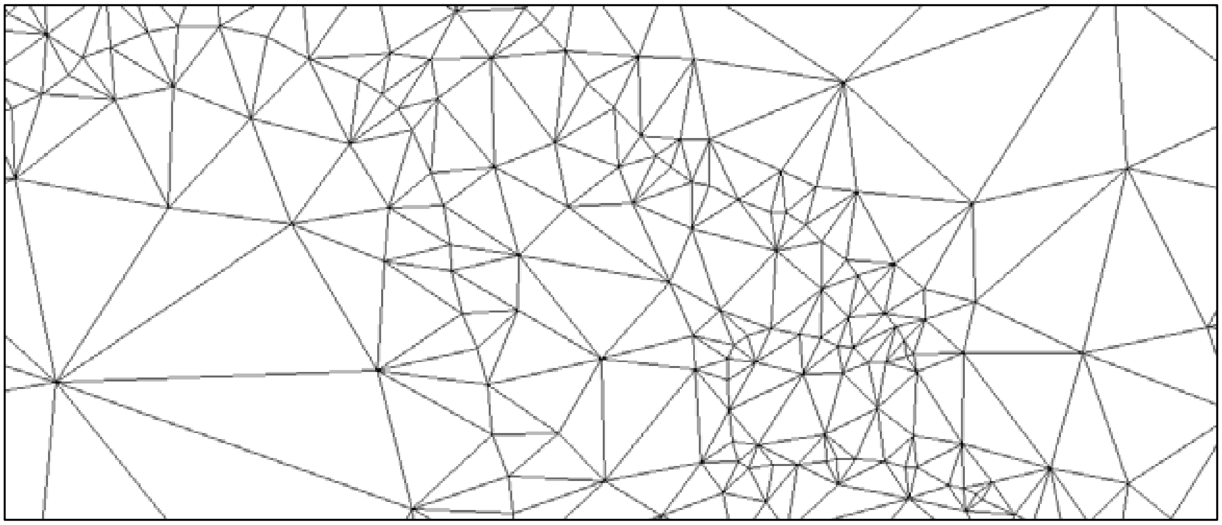

Fig. 20 Example of FEFLOW mesh software interface.

7.2. Conceptual Model

Conceptual model is a first step in construction of mathematical model. A conceptual model is based on a number of assumptions that must be furthermore validated. It represents a complex natural aquifer system and it develops an understanding of groundwater flow directions, sources, and discharge areas. This conceptual model defines the main principles that will be utilized for construction of mathematical model of groundwater flow in the Savannah Province. The construction of the conceptual model represents the initial stage of mathematical modeling process based on archive data acquisition, field work activities and qualified estimates. The conceptual model assigns the geometry of the investigated model area and defines groundwater circulation pattern.

Formulation of conceptual model of hydrogeological structure of the Savannah Groundwater Province has been carried out based on previous data assessment, particularly field work data acquisition. The hydrogeological concept is displayed in Fig. 21 and Fig. 22 showing the prevailing direction of groundwater flow.

The recharge area extends throughout the entire model area – sedimentary basin and surrounding mountains. The direction of groundwater flow is generally from foothills towards the coast. Drainage area is primarily situated along the coast, locally along watercourses and probably towards principal lakes and wetlands with high degree of evaporation from free water surface as well as high evapotraspiration value.

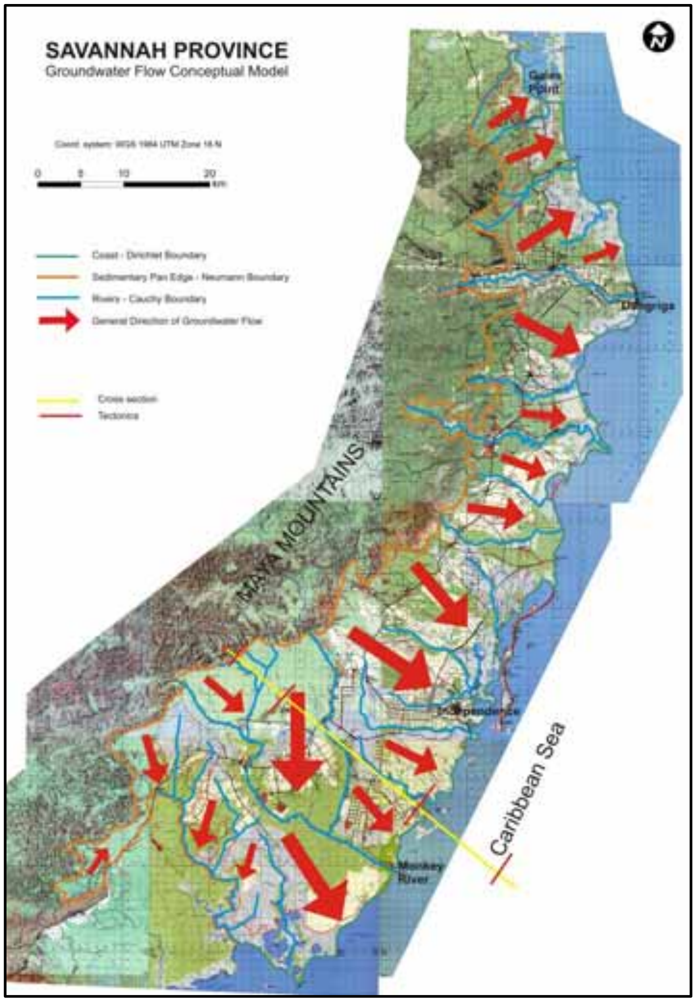

Fig. 21 Groundwater flow conceptual model.

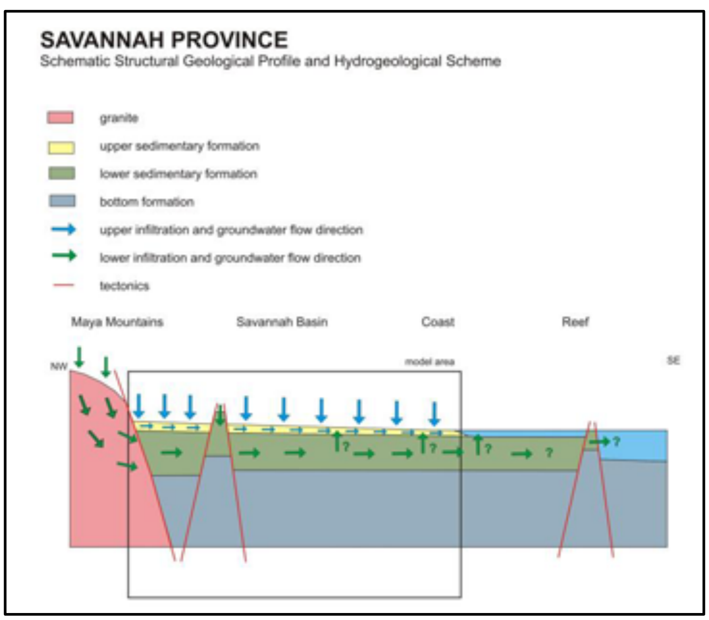

Fig. 22 Schematic structural geological profile and hydrogeological structure of Groundwater Savannah Province. Cross section refers to cross section line marked in Fig. 21.

7.2.1. Model Geometry and Spatial Characteristics

The subject of mathematical modeling will be the area of the Savannah Groundwater Province excluding the Placencia peninsula and the very southern narrow part of the area, as displayed in Fig. 23. These two sections of the defined Savannah Province area were excluded from the hydraulic model as the modeling of these two parts would not bring any reasonable results. Neither of parts reveals significant groundwater extractions nor data abundance.

Model boundary in SW part is set along the Deep River (model area is here extended compared to the Savannah Groundwater Province limits), in N part is set along the Plantation Creek (model area is here extended compared to the Savannah Groundwater Province limits), in N-NW part is locally extended (Gales Point, Mullins River, Alta Vista) as a reason of the assumption that part of the groundwater flow towards the Savannah Province is ensured from the extended sections.

The extension was made towards the groundwater divide. The extent of the modelled area was displayed using GIS tools. The overall modelled area covers the entire Savannah Groundwater Province as specified earlier in the text. Further, as described here above, the area includes several area extensions based on the character of local hydrogeological setting. The model encompasses data also from the close vicinity beyond the Savannah Province boundaries.

The mathematical model corresponds to the entire thickness of the sedimentary formation representing alluvial and sedimentary material of late Cretaceous to recent age. The thickness of layer is uniform or increases towards to the mountainous area respectively. Due to vertically stratified layers of the sedimentary formation the model will be divided into multiple model layers.

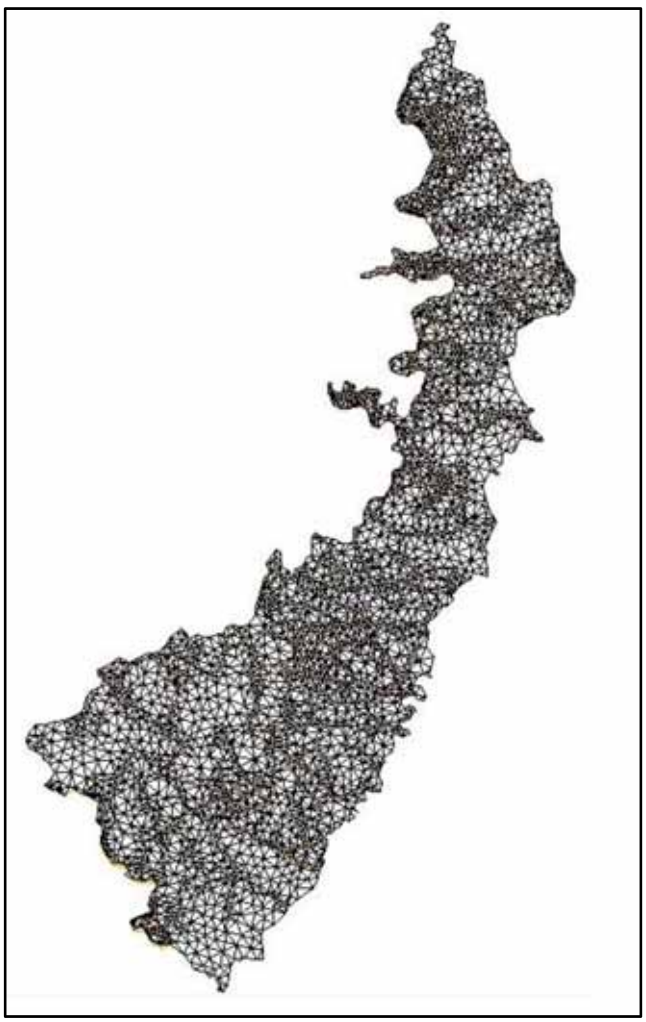

Fig. 23 Area considered for mathematical modeling, preliminary mesh in FEFLOW.

7.2.2. Boundary Conditions

NW border (margin of the sedimentary basin at the foothills) will be represented by the boundary condition of the constant head. Depending on the model calibration results, constant flow rate throughout the modelled area boundaries with local inflow specification will be considered. Constant head applied at SE border will form boundary condition of the coast and areas of coastal lagoons, i.e. drainage boundary. Depending on the model calibration results, constant flow or constant head will be applied at NE and SW border.

Selected main water courses will form inner boundary condition of the first kind (Dirichlet) or the third kind (Cauchy). Following water courses will define boundary condition:

- Deep River
- Monkey River
- Bladen Branch
- Swasey Branch
- Big Creek
- Mango Creek
- South Stann Creek
- Sittee River
- North Stann Creek
- Mullins River
- Plantation Creek

If needed, other smaller water courses will be determined as Cauchy boundary condition of the third kind. Extensive permanent water bodies will form the inner boundary condition of constant water level. Extensive wetlands will eventually form inner boundary condition same as for water bodies (see above).

7.2.3. Balance Scheme of Flow

Model inflow: infiltration of rainfall throughout the entire model area and rarely local inflows across boundary (inflow of groundwater from shallow and deeper part of surrounding mountains along western model area boundaries, vicinity of rivers flowing to the model area originating beyond the area limits).

Model outflow: drainage area along the coastal zone and lagoons, drainage into water courses, groundwater pumping, drainage into lakes and wetlands – according to the definition of evapotranspiration from surface water.

Rainfall infiltration will be represented as a major component of groundwater recharge. Intensity of rainfall infiltration will be interpreted as auxiliary calibration input parameter. Model distribution of rainfall infiltration will reflect climatic data on precipitation, GIS analysis of the modelled area (elevation differences) and type of vegetation cover/ecosystem type. Specification of infiltration rates for different elevations and ecosystems will be subject of further definition of model conditions.

7.2.4. Distribution of Hydraulic Parameters

Model distribution of hydraulic conductivity represents the principal calibration parameter. Generally, the hydraulic conductivity will increase gradually from the edge of the modelled area at the NW foot of the mountains towards the coastal zone.

Findings on the groundwater abstraction and the associated decrease of groundwater levels will be both considered for hydraulic conductivity estimation.

7.3. Mathematical Simulation Model

This section describes creation and calibration of the mathematical model. The modeling process consists of predefined follow-up steps, such as generation of model polygon (boundaries), generation and optimization of mesh and multilayer system, setting of boundary conditions and hydraulic parameters. After having all data incorporated in the model, the calibration process could be prepared. Case scenarios are simulated after calibration targets were achieved.

The model was set as a 3-D groundwater flow.

7.3.1. Model Mesh and Geometry

As described earlier, there are small differences between final model area and Savannah Groundwater Province area. The most significant differences refer to south-western and eastern part of the province, where the Deep River and Soldier or Plantation Creek were set as the borders. Other small differences concern the western part of the province (see Annex 2, Map 13). Such simplification and modification of the model boundary leads to more accurate modeling process as uniquely determined boundary conditions could be identified. The model boundary includes 353 nodes. The distance between individual nodes is approximately 1 km (Annex 2, Map 13). The length of the model boundary (perimeter) is 330.442 km, the model area covers 1.932 km^2.

The model mesh was generated within the model domain. Main river courses, well and borehole sites were included into the model as background information for mesh generation and optimization. Some of the data documented recently by GEOMEDIA during the field work were used in furhter steps of modeling process either as boundary conditions or as observation points during model calibration.

Created model mesh (see Annex 2, Map 14) is refined in the vicinity of rivers, model boundaries and calibration points. This approach enables to set boundary condition very properly, calibration process is accurate and total number of nodes is optimized.

The model is vertically divided into 6 layers, whereas the mesh has horizontally uniform shape in each slice. The entire model mesh consists of 39516 pentahedral elements formed by 25039 nodes. This means that there are 6586 elements in each mesh layer and 3577 nodes in each horizontal layer. The first layer elevation corresponds to the surface elevation of the modelled area. The elevation data were obtained from USGS (U.S. Geological Survey). The base of model creates horizontal plane with elevation 400 m b.s.l. 3D model showing modeled polygon with its layers is displayed below in Fig. 24.

Tab. 14 Yield of documented wells used as well boundary condition in the first model layer.

ID	Village	Type	Subtype	yield (l/s)	yield (m3/d)
0012	Trio	Drilled well	agricultural	6.8	587.52
0013	Monkey River	Drilled well	public supply	4.75	410.4
0021	Bella Vista	Drilled well	public supply	1.85	159.84
0024	Cowpen	Drilled well	public supply	1.15	99.36
0050	San Isidro	Drilled well	agricultural	5.7	492.48
0058	Sagitun	Drilled well	agricultural	6.1	527.04
0060	Sagitun	Drilled well	agricultural	1.9	164.16
0062	Sagitun	Drilled well	agricultural	15.2	1313.28
0071	San Pablo	Drilled well	agricultural	6.1	527.04
0073	San Pablo	Drilled well	agricultural	10.2	881.28
0075	Cowpen	Drilled well	public supply	3.8	328.32
0074	Cowpen	Drilled well	agricultural	5.7	492.48
0078	Kanatic Resort	Drilled well	public supply	7.9	682.56

ID	Village	Type	Subtype	yield (l/s)	yield (m3/d)
0083	Sittee	Drilled well	exploratory	12.9	1114.56
0086	Sittee	Drilled well	exploratory	30	2592
0087	Sittee	Drilled well	public supply	11.5	993.6
0091	South Stan Creek	Drilled well	agricultural	15	1296
0092	South Stan Creek	Drilled well	agricultural	15	1296
0093	South Stan Creek	Drilled well	agricultural	15	1296
0105	Independence	Drilled well	public supply	13.5	1166.4
0106	Independence	Drilled well	public supply	7.57	654.048
0107	Independence	Drilled well	public supply	17	1468.8
0110	Independence	Drilled well	agricultural	1.5	129.6
0148	Silk Gras	Drilled well	public supply	8	691.2
0153	Hope Creek	Drilled well	agricultural	0.06	5.184
0156	Pomona	Drilled well	public supply	4	345.6
0158	Pomona	Drilled well	domestic	15	1296
0160	Hope Creek	Drilled well	agricultural	5.3	457.92
0162	Silk Gras	Drilled well	public supply	1.6	138.24

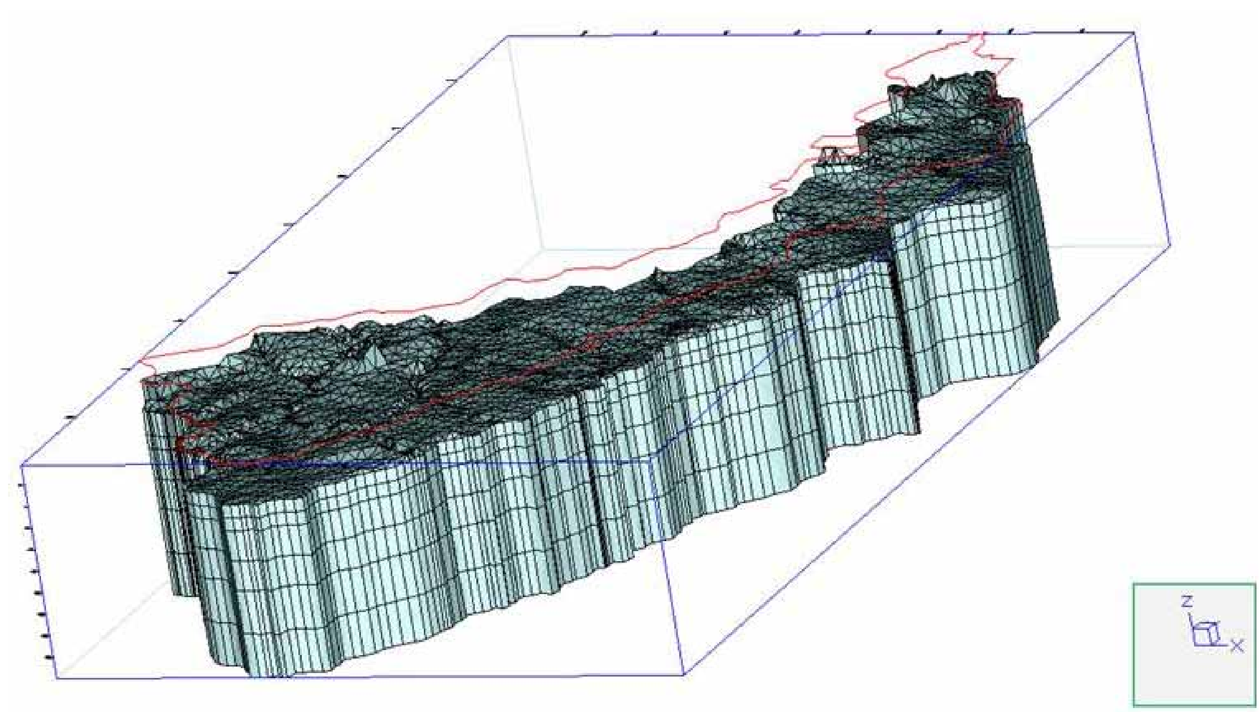

Fig. 24 Model 3-D mesh of the Savannah Groundwater Province.

The first two model layers represent phreatic water-bearing system of Quaternary to Holocene sediments, the third and the forth model layer represents aquitard of Miocene to Paleocene sedimentary formation and the deepest two layers represent late Cretaceous to Paleocene formation with interbedded water-bearing strata - this approach is close to real conditions and brings more accurate modeling results.

7.3.2. Boundary conditions

In the model, three types of boundary conditions were used:

- the first type boundary condition (Dirichlet)
- the second type boundary condition (Neumann)
- well boundary condition

Dirichlet boundary condition was set along the coast with the hydraulic head value 0 m a.s.l. representing sea level. Dirichlet boundary condition was also used to represent rivers within the model area. The boundary conditions values describing rivers correspond to its surface water level elevation. These boundary conditions were set as constant values. Dirichlet boundary condition along with Neumann boundary condition was also used for estimation of inflow into the model area along the western boundary. Hydraulic head value at this boundary was specified during calibration.

Well boundary conditions were used to describe yield of the documented wells. The list of wells used for definition of well boundary conditions is shown in Tab. 14. All boundary conditions used in the model are shown in Annex 2,

Map 15.

7.3.3. Hydraulic Parameters

Each layer in the model has its unique properties: hydraulic conductivity, infiltration (for upper layer only), density ratio, storativity, storage compressibility and transfer ratio properties. These characteristics were set for each layer according to available data.

Model area was, for conductivity setting, divided into two areas in the first two layers representing phreatic water-bearing system of Quaternary to Holocene sediments. One area near to the west border describes geological condition along Maya mountains and the second area in the rest of model domain.

Horizontal conductivity value $1*10^{-5}$ m/s was set up for area of Maya mountain foothills and $9*10^{-5}$ m/s for the rest of the area. Vertical conductivity was set as 10 times lower.

The third and the fourth model layers representing aquitard of Miocene to Paleocene sedimentary formation had uniform horizontal conductivity value $7*10^{-7}$ m/s and vertical $6*10^{-8}$ m/s. Last two model layers had uniform horizontal conductivity value $1*10^{-6}$ m/s and vertical ten times lower.

The upper layer was characterized by given infiltration values. The setting of infiltration values was based on different ecosystem characteristics. Infiltration was computed based on total precipitation. The entire model area was divided into 7 ecosystem categories with following estimated infiltration values:

- Savanna: 1.1 mm/d
- Urban 1.3 mm/d
- Agriculture 1.5 mm/d
- Mangrove 1.7 mm/d
- Scrubland 1.9 mm/d
- Forest 2.1 mm/d
- Wetland/Seagrass 0.1 mm/d

Map showing each ecosystem of Savannah Groundwater Province as set in FEFLOW mesh is shown in Annex 2, Map 3.

7.3.4. Calibration Process and Model Results

The calibration process is the crucial part of the mathematical modeling. The main aim of these steps is to set the real conditions and simulate as accurately as possible the current situation. Calibration process was made based on combination of groundwater level and flow rate criteria.

Groundwater level criterion results from comparison of measured hydraulic head and hydraulic head computed by the model. Hydrogeological objects (wells) with measured hydraulic head values during field work in Savannah Groundwater Province were used as calibration points (Annex 2, Map 7, Annex 8, Annex 9). Flow rate criterion is based on comparison of flow rates measured at significant hydrological and hydrogeological objects (i.e. rivers and streams flow rate, springs discharge) with computed balance of these objects. Criterion flow rates of Sittee River, Bladen Branch and Swasey Branch were used for the calibration.

The calibration should reach similar measured and computed values by changing model input parameters. The exact values for measured and computed hydraulic head values are never reached and slight discrepancies have to be expected. Described calibration steps give idea about the character of the hydraulic head in the model.

Difference between measured and computed hydraulic head at observation points is documented in Fig. 25. The figure shows that model calibration gives relatively good matching between measured and computed hydraulic head. Average difference in hydraulic head is 1.1 m with standard deviation 4.9 m. Considering the fact that documentation point elevation was measured with error caused by portable GPS accuracy, reached deviation in model calibration can be acceptable and with regard to groundwater level criterion the model calibration can be considered as satisfactory.

Model water balance for Sittee River, Bladen Branch and Swasey Branch gives flow rate values 0.12 m^3/s, 2.03 m^3/s and 0.81 m^3/s respectively. These values represent amount of groundwater drained by rivers. Flow rate values related to watershed model area suggest values of specific base flow around 17 $L/s/km^2$ for all three rivers. This value corresponds to value 15 $L/s/km^2$ estimated by hydrological water balance. With regard to flow rate criterion the model calibration can be considered as satisfactory.

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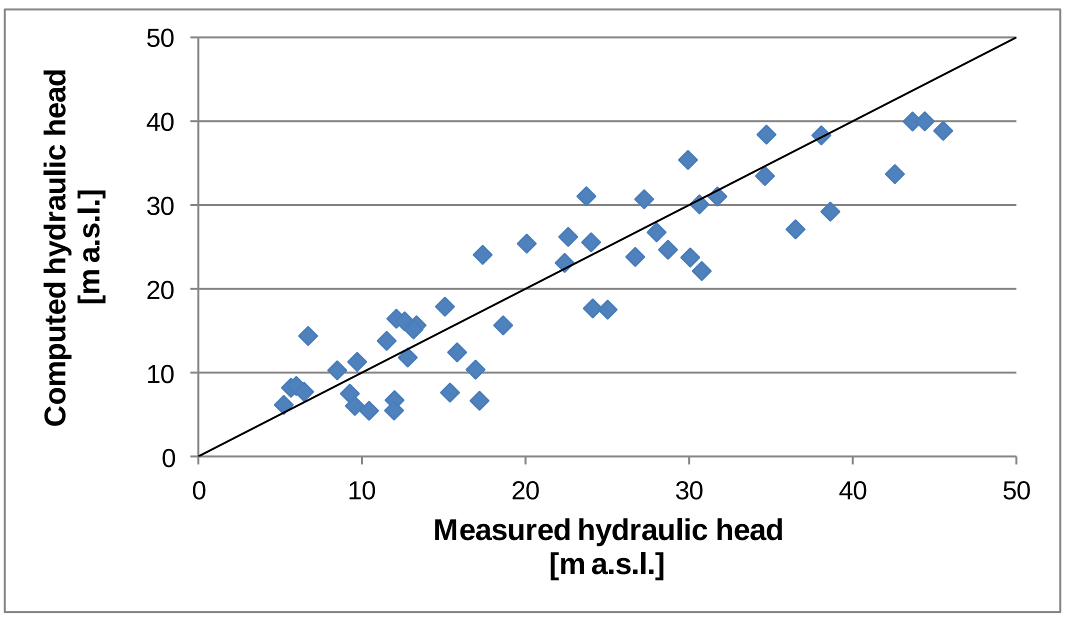

Fig. 25 Groundwater level criterion matching.

Groundwater level varies from 1 m a.s.l. along coast to 50 m a.s.l. at parts with the highest surface elevation at Maya mountain foothills (Annex 2, Map 17). Groundwater flow direction generally heads eastern towards Caribbean Sea. Groundwater flow direction is locally effected around major rivers.

Based on model calibration, total amount of water entering the Savannah Groundwater Province area is $2.93*10^6$ m^3/d. This number consists of surface infiltration over the entire area ($2.9*10^6$ m^3/d) and groundwater inflow from Maya mountains ($2.1*10^4$ m^3/d). Value $2.93*10^6$ m^3/d represents total natural renewable water resources of Savannah Groundwater Province. Groundwater in Savannah Groundwater Province is partially drained by rivers ($1.76*10^6$ m^3/d) and partially into Caribbean sea ($1.13*10^5$ m^3/d).

Water balance was also computed severally for all 18 watersheds in the simulated area (Fig. 9, Annex 2, Map 5). Values of single components of water balance participating on groundwater creation (Inflow from river / boundary, Inflow from precipitation, Flow from neighboring watersheds) and groundwater runoff (Outflow to river / boundary, Groundwater extraction, Flow to neighboring watersheds) are quantified in Tab. 15.

Tab. 15 Water balance parameters – current situation.

Watershed	Area (m^2)	Inflow from river / boundary (m^3/d)	Inflow from precipitation (m^3/d)	Outflow to river / boundary (m^3/d)	groundwater extraction (m^3/d)	Flow from (+) / to (-) neighboring watersheds (m^3/d)
Big Creek	61.30	0	95 586	146 704	4 726	53 684
Black Creek	77.13	0	114 605	80 028	0	-37 941
Bocatora Creek	16.84	0	31 177	30 754	0	-1 266
Cabbage Haul Creek	86.24	5 197	124 124	117 972	4 389	-10 351
Deep River	213.28	1 142	332 034	382 690	0	40 986
Freshwater Creek	119.47	2 102	177 149	193 109	991	10 210
Mango Creek	202.89	0	273 935	261 249	4 497	-15 665
Monkey River	372.70	9 384	622 905	543 331	3 469	-102 899
Mullins River	77.98	0	131 024	138 217	0	3 724
North Stan Creek	64.31	667	100 108	107 379	2 969	6 937
North. and South. Lagoon	83.05	899	134 018	158 942	0	20 620
Pine Ridge	44.08	0	67 653	52 167	410	-17 022
Punta Ycacos	137.92	0	148 809	138 358	0	-14 541
Santa Maria	132.82	0	206 623	187 601	527	-24 210
Sennis River	82.09	0	97 281	134 450	0	34 850
Sittee River	79.26	3 708	121 992	110 845	2 799	-15 429
South Stan Creek	57.21	665	94 307	81 055	5 909	-10 653
Yemeri Creek	21.73	0	33 782	34 528	0	-157

7.4. Water Management Simulation Scenarios

Several simulation scenarios were investigated for Savannah Groundwater Province in order to follow different water management development. The formulated scenarios reflect potential effects of global climate change (Scenario A) as well as man-made impacts in local and regional scale.

Development scenarios introduced in this report should contribute to a sustainable regional development (agriculture, tourism) resilient and adapted to global climate change.

Belize and mainly coastal areas have to deal with tourism increasing and thus with higher demand of drinking water. In some areas, new touristic resorts will be built up with new water supply needs. Since drinking water will be obtained from groundwater sources, it is necessary to set the amount of groundwater that can be pumped to non-threaten groundwater supply and surroundings wells for municipality support. Single case studies include:

A. Decrease of infiltration in the whole model area
B. Increased extraction in Independence village
C. Increased extraction around Riversdale
D. New touristic resorts
E. Saltwater intrusion

Detailed description of these case studies is given in chapters below. Areas B,C, D and E selected for simulation scenarios are displayed in Fig. 26.

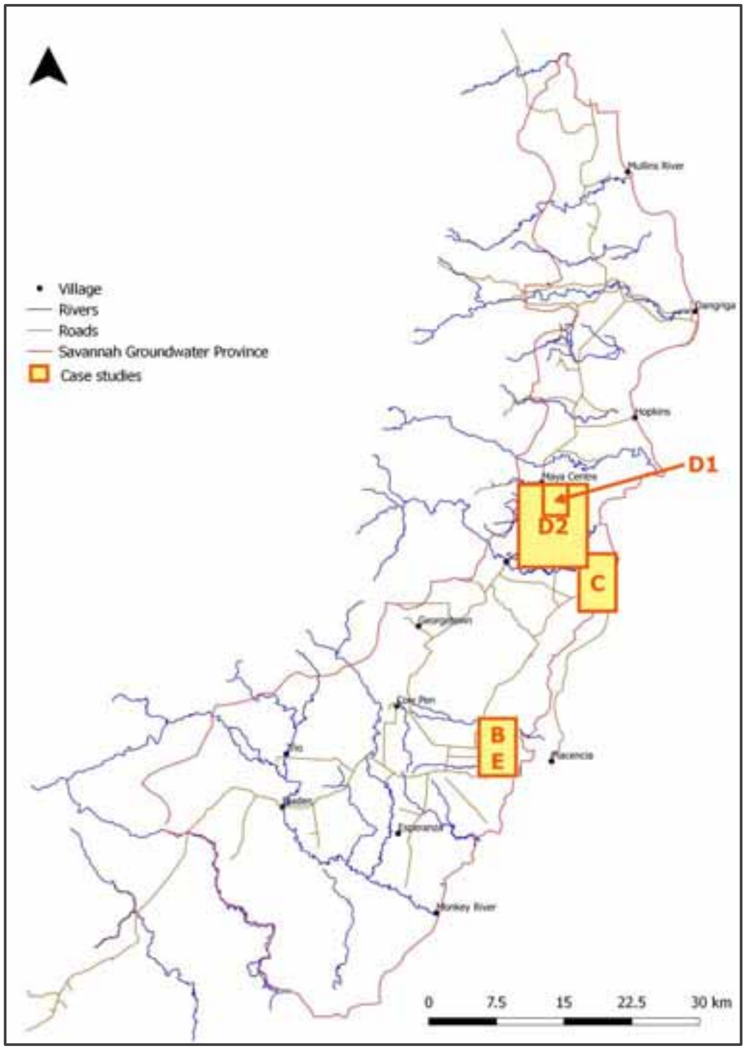

Fig. 26 Areas of simulation scenarios.

A. Decrease of infiltration in the whole model area

In this scenario, infiltration was uniformly decreased by 10% compared to standard values mentioned above.

Based on model calibration, total amount of water entering the Savannah Groundwater Province area is $2.93*10^6$ m^3/d. This number consists of surface infiltration over whole area ($2.9*10^6$ m^3/d) and groundwater inflow from Maya mountains ($2.1*10^4$ m^3/d). Groundwater in Savannah Groundwater Province is partially drained by rivers ($1.76*10^6$ m^3/d) and partially into Caribbean Sea ($1.13*10^5$ m^3/d).

Infiltration decrease significantly affects total water balance over the whole area of Savannah Groundwater Province. Due to this fact total natural resources decrease to value $2.6*10^6$ m^3/d causing the decrease of groundwater inflow into rivers ($1.36*10^6$ m^3/d) and sea ($1.05*10^6$ m^3/d). Natural resources decrease causes drawdown of groundwater head over whole Savannah Groundwater Province. The highest drawdown about 1.7 m can be encountered along the western boundary of Savannah Groundwater Province and the influence (drawdown) slowly decreases towards Caribbean Sea, where the influence is minimal. The average drawdown over Savannah Groundwater Province is 0.6 m.

Water balance of single watersheds was also computed in this scenario to exemplify changes caused by decreased infiltration. Values of single components of water balance influenced by decreased infiltration are quantified in Tab. 16.

Tab. 16 Water balance parameters - decreased infiltration.

Watershed	Area (m^2)	Inflow from river / boundary (m^3/d)	Inflow from precipitation (m^3/d)	Outflow to river / boundary (m^3/d)	groundwater extraction (m^3/d)	Flow from (+) / to (-) neighboring watersheds (m^3/d)
Big Creek	61.30	0	82 035	127 900	4 726	50 591
Black Creek	77.13	0	99 420	86 535	0	-12 885
Bocatora Creek	16.84	0	31 081	16 213	0	-14 869
Cabbage Haul Creek	86.24	6 421	106 995	103 583	4 389	-5 443
Deep River	213.28	1 370	279 387	293 118	0	12 361
Freshwater Creek	119.47	2 676	158 133	176 264	991	16 446
Mango Creek	202.89	131	237 898	225 043	4 497	-8 489
Monkey River	372.70	10 311	575 161	484 306	3 469	-97 697
Mullins River	77.98	0	121 500	123 516	0	2 016
North Stan Creek	64.31	1 339	90 080	91 545	2 969	3 094
Northern and Southern Lagoon	83.05	1 104	123 246	146 333	0	21 983
Pine Ridge	44.08	0	62 657	55 385	410	-6 861
Punta Ycacos	137.92	0	132 884	128 176	0	-4 708
Santa Maria	132.82	420	172 938	171 601	527	-1 230
Sennis River	82.09	0	88 963	124 804	0	35 841
Sittee River	79.26	4 141	106 329	99 966	2 799	-7 705
South Stan Creek	57.21	1 050	73 268	69 984	5 909	1 576
Yemeri Creek	21.73	0	29 820	36 677	0	6 857

The influence of groundwater caused by decreased infiltration rate is documented on groundwater level contour maps of Savannah Groundwater province in Annex 2, Map 18.

B. Increased extraction in Independence village

There is significant drinking water source for Placencia, Independence and Big Creek villages close to Independence village. Drinking water is extracted from 3 supply wells. This scenario suggests increase of population and demand of drinking water. The extraction rate will therefore increase 3 times compared to the current pumping rate, i.e. from 3288 m^3/d to 9864 m^3/d.

Model result shows, that the increased pumping rate causes significant drawdown of groundwater level in the vicinity of supply wells. The drawdown increases by 4.58 m compared to drawdown at current pumping rate and the length of affected area extends 3 km towards the coast. The impact of increased pumping rate on groundwater outflow from the area was also monitored, The groundwater outflow decrease resulting from model simulation is only 1048 m^3/d that does not correspond with the increased pumping rate. It means that current groundwater resources in area are not sufficient for such extraction increase. According to the model simulation, the area with affected groundwater head extends to Big Creek Branch and leads to induced infiltration from Big Creek to groundwater body. It means that the increased extraction rate would not be fully covered by groundwater resources but would be significantly covered also by surface water (Big Creek).

It is supposed that in real conditions induced infiltration from Big Creek will be limited due to hydraulic resistivity of river-basin sediment. So real drawdown will be higher and influenced area will probably reach to sea cost and could result in saltwater intrusion.

The recommendation for this area is to thoroughly assess impacts of increased groundwater extraction and consider possibility to construct another well for groundwater extraction in different area and far from current extraction wells.

The impact of the increased pumping on groundwater level is documented in groundwater level contour map comparing the current situation and simulated scenario (Fig. 27).

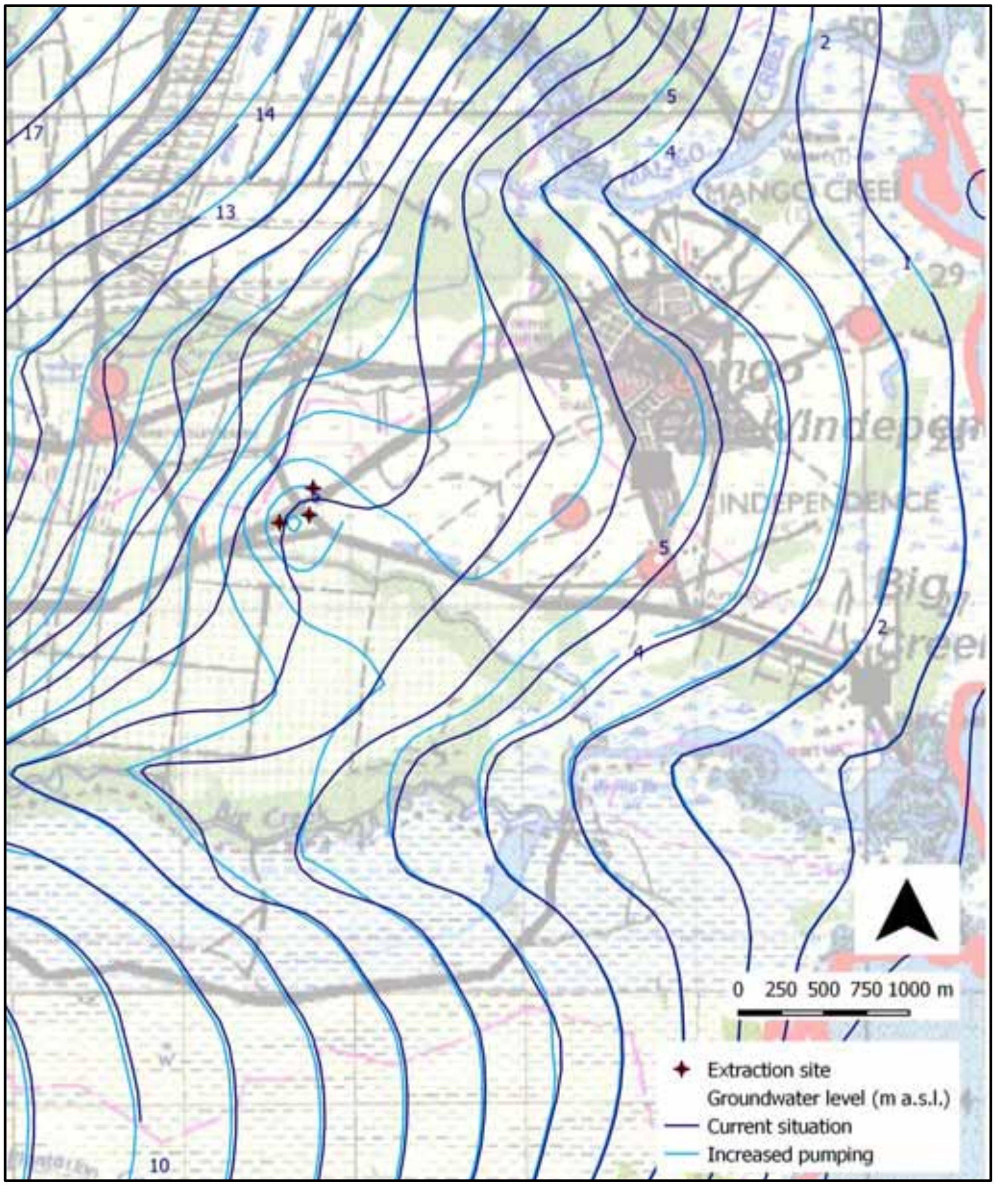

Fig. 27 Groundwater level contour map. Simulation scenario – increased extraction in Independence

C. Increased extraction around Riversdale

There is significant drinking water source for Riversdale Village. New pumping well was simulated near the village. This scenario supposes population increase as well as increasing drinking water demand. The value of 130 m^3/d was set as simulated pumping rate for this area.

Model result shows, that the drawdown of groundwater level in new well reaches 1.04 m and the affected area is quite limited. The impact of increased pumping rate on groundwater outflow from the area was also monitored. The computed groundwater outflow decrease 132 m^3/d corresponds to increased pumping rate. It means that current groundwater resources in area are sufficient for building of new groundwater extraction point.

The impact of the increased pumping on groundwater level is documented in groundwater level contour map comparing the current situation and simulated scenario (Fig. 28).

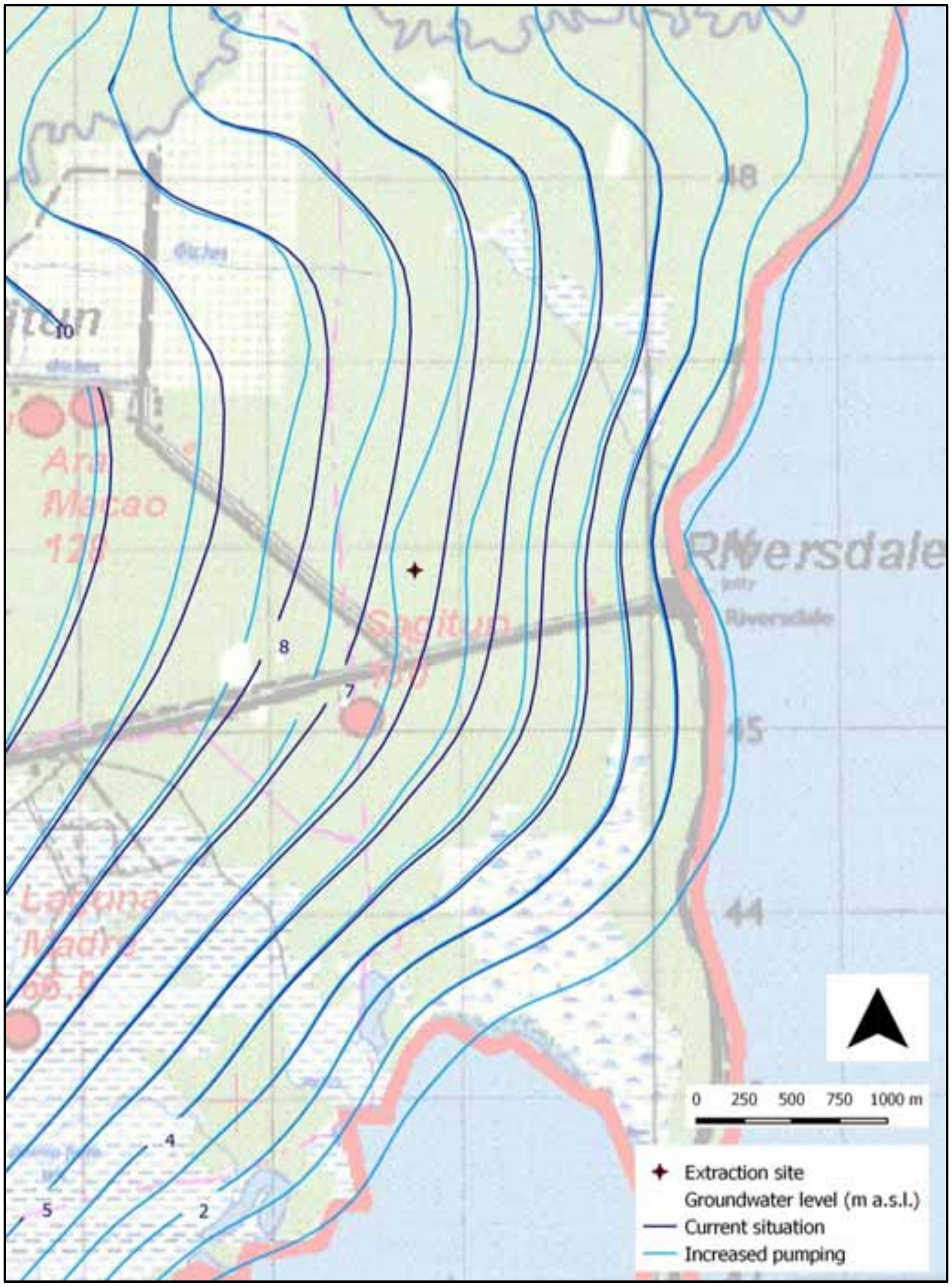

Fig. 28 Groundwater level contour map. Simulation scenario – increased extraction in Riversdale

D. New touristic resorts

As published in EIA reports of Belize, 2 new resorts, i.e. All Pine Resort and .Hughes Estate West Area Resort, are planned to be built in the country.

- **D1 - All Pine Resort**

In the All Pines Area, Stann Creek District, Belize, new touristic resort is planned to be build. This resort is approximately 3 km south of Maya Center Village. According to EIA report, the estimated water demand is 142.5

m^3/d of drinking water. Groundwater is planned to be pumped from two wells placed in shallow aquifer less than 30 m deep. The impacts of pumping to groundwater sources below this level are subject of assessment.

Total pumping rate 142.5 m^3/d was equally divided between two wells, each with pumping rate 71.25 m^3/d. The model results show that the impact on hydraulic head around new groundwater source is small. The drawdown in wells reaches 0.6 m. According to results, it might be assumed that pumping rate of 142.5 m^3/d has only minimal impact on hydraulic head and on outflow from the area as well.

The impact of the increased pumping on groundwater level is documented in groundwater level contour map comparing the current situation and simulated scenario (Fig. 29).

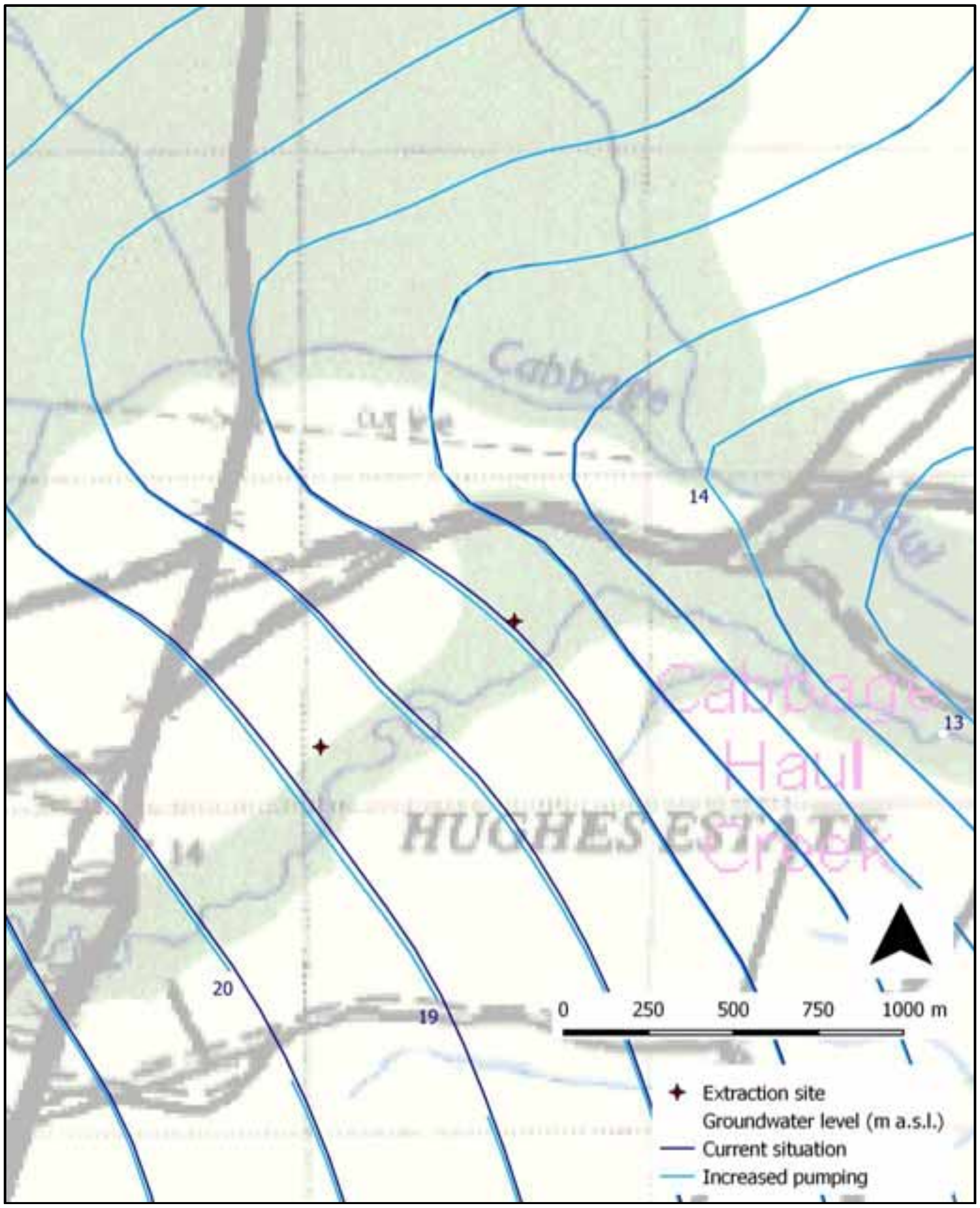

Fig. 29 Al Pine resort - groundwater level map

- **D2 - Hughes Estate West Area Resort**

In the Hughes Estate West Area, Stann Creek District, Belize, new touristic resort is planned to be build. This resort is on the coastal plain of the Caribbean Sea. The area covers approximately 20.15 km^2. According to EIA report, the estimated pumping rate of drinking water is 988 m^3/d. This amount of water is planned to be pumped from 3 wells in total, it means that pumping rate for each well was set to 330 m^3/d.

Model result shows, that the maximum drawdown of groundwater level in new wells is around 3.1 m and the affected area extends only in the close surrounding of the well. Results show that the pumping rate 988 m^3/d in total causes only minimal impact on hydraulic head and on outflow from the area.

The impact of the increased pumping on groundwater level is documented in groundwater level contour map comparing the current situation and simulated scenario (Fig. 30).

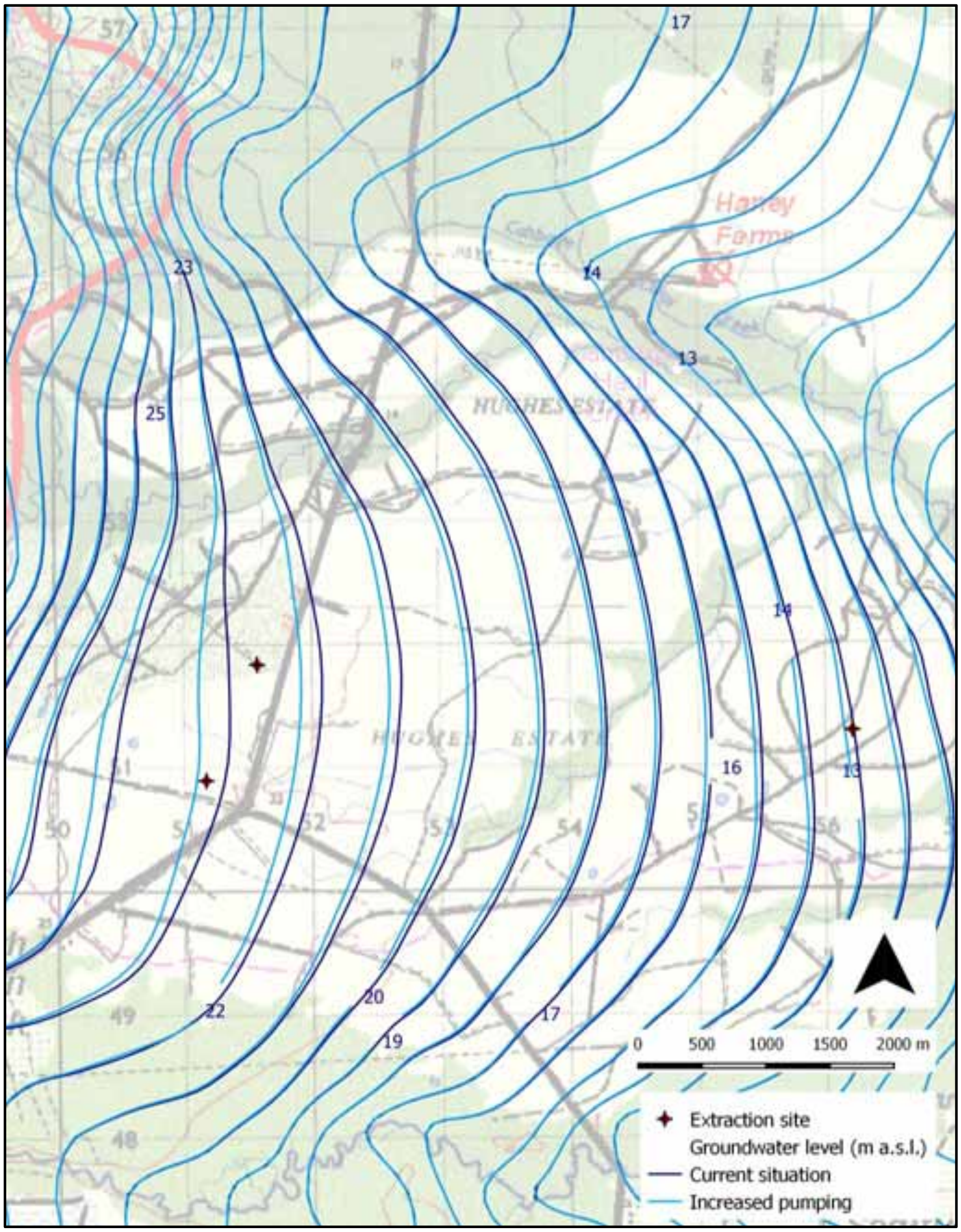

Fig. 30 Hughes Estate resort - groundwater level map

E. Saltwater intrusion

The last scenario focused on assessment of saltwater intrusion into freshwater aquifer along coastal part of Savannah Province. Generally, freshwater in Savannah province aquifers moves downgradient and discharges to low-lying coastal areas and into the sea. But groundwater extraction or changes in groundwater recharge (e.g. decreased infiltration) reduces the weight of the overlying freshwater body, which can decrease or even reverse the seaward flow so that seawater moves landwards into the freshwater aquifer. Saltwater intrusion scenario was evaluated in the same area as scenario of increased extraction in Independence village (Fig. 26). In order to evaluate the intrusion of seawater it was necessary to implement new 3D density-dependent steady state flow and transport model.

New model mesh was adopted for transport simulation. Numerical mesh was refined over simulated area. Subject of simulation was only uppermost phreatic water-bearing system of Quaternary to Holocene sediments (the first two model layers of the original model) due to freshwater source existence. Flow characteristics (hydraulic conductivity, infiltration, storativity etc.) of model layers remained unmodified. The boundary conditions were adopted according to previous calibrated model. Dirichlet boundary condition was set along the coast with the hydraulic head value 0 m a.s.l. representing sea level (no tidal fluctuation was considered) and along western boundary with the hydraulic head value 10-15 m a.s.l. (according to groundwater level in calibrated model). Neumann constant flux (zero flow) was set along northern and southern boundary of model domain.

For this model, solute transport concentrations are expressed as chloride concentration (Cl). Chloride concentration was selected due to its conservative nature and tracer-bearing capacity. The boundary conditions are Dirichlet constant concentration, where freshwater is in contact with seawater along eastern model boundary, the chloride concentration is set to 100 and 13.000 mg/L in the freshwater and seawater, respectively. As no direct measurement of dispersivity was made, the longitudinal and transverse dispersivity were set to 50 m and 5 m respectively. Molecular diffusion was assumed as 1.00×10^{-9} m^2/s.

Current situation of groundwater regime within simulated area is shown on groundwater level contour map in Fig. 31). Three saltwater intrusion subscenarios reflecting changes in hydrogeological condition were investigated:

- Saltwater intrusion in the current state
- Increased groundwater extraction in Independence village
- Impact of the sea level rise

Distribution of chloride concentration for above mentioned seawater intrusion scenarios was investigated along the cross section connecting Independence water source with the coast as displayed in Fig. 31.

As obvious from Fig. 32, model result shows sharp decrease of chloride concentration from the coast towards inland in the current state (solid line). The zone affected by increased chloride concentration extends to a distance of 500 m from the coast. However, significant drawdown of groundwater level caused by increased groundwater extraction in Independence village source influences groundwater runoff. This leads to decrease of seaward groundwater flow and makes penetration of saltwater towards inland easier (dashed line). In this case the zone affected by increased chloride concentration extends to a distance of 1100 m from the coast. The same effect shows sea level increase (dotted line) where zone of influence extends to a distance of 1300 m from the coast. It is necessary to note, that the sea level rise scenario does not reflect transgression of coastal line landwards. In case of transgression, i.e. the shift of the coastal line, the extent of the affected zone would be the same and shifted deeper landwards.

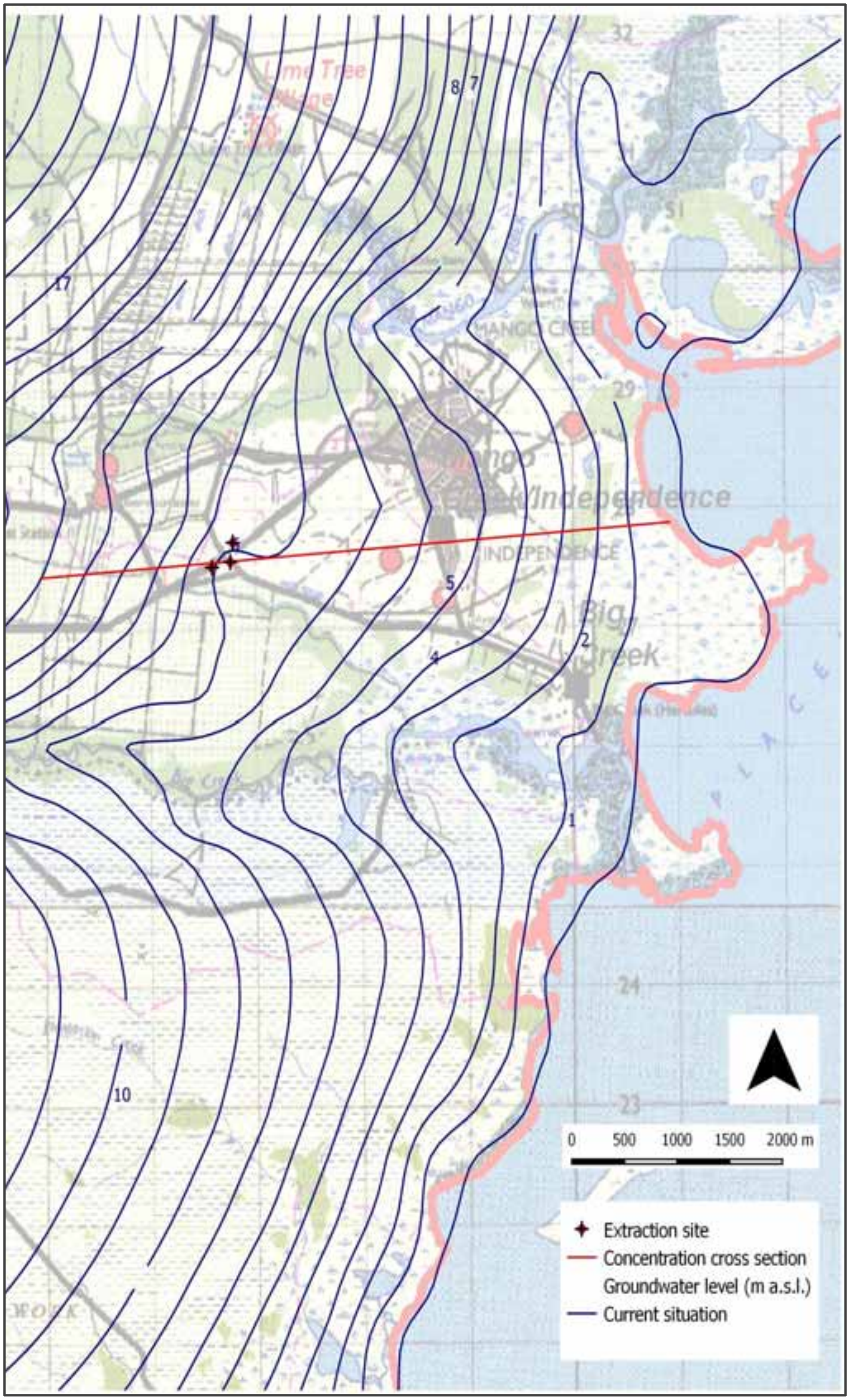

Fig. 31 Groundwater level contour map. Simulation scenario – saltwater intrusion.

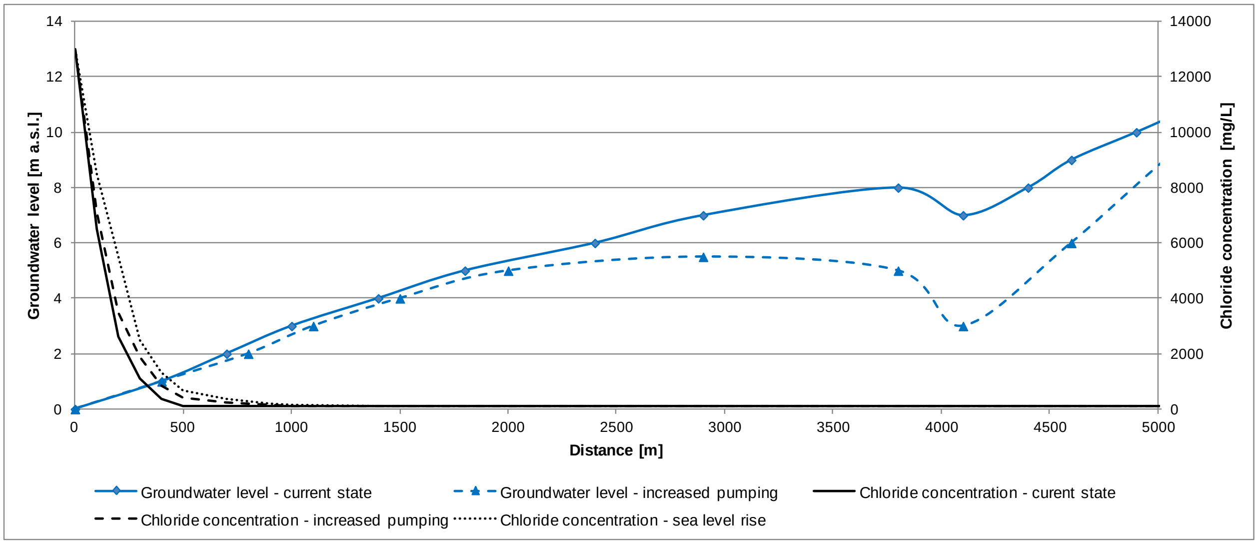

Fig. 32 Groundwater levels and chloride concentrations along the cross section as specified in Fig. 31 reflecting different seawater intrusion scenarios.

8. Groundwater Assessment

8.1. Quantitative Groundwater Assessment

Performed assessment of climatic and hydrological data and model solution shows that the Savannah Groundwater Province has relatively high natural resources and favourable conditions for groundwater resources capacity. Specific value of precipitation is estimated around 73 L/s/km^2 from which approximately 15 - 20 L/s/km^2 is the enrichment of groundwater resources capacity. According numerical modeling, the enrichment of groundwater resources corresponds to 17 L/s/km^2.

According to model solution the Savannah Groundwater Province can be divided in two parts, the northern and the southern part, with different groundwater capacity. Boundary between these two parts can be set along boundary between Big Creek and South Stann Creek watershed. The northern part of the Savannah Groundwater Province is less wide in comparison with southern part. The area along Mayan mountain foothill with less permeable sedimentary formation covers much larger area. This means that the specific groundwater resources capacity in the northern part will be lower than average value.

Groundwater is mostly exploited from shallow part of the aquifer system to the depth of 60 m mostly. Well yield varies from negligible decimal liters per second to 15 - 20 L/s and depends on well depth, well geological position and number of crossed water-bearing layers. Current total groundwater exploitation in the Savannah Groundwater Province averages around 500 L/s (by estimation) and creates only 2% of total groundwater renewable resources capacity. In point of this view the Savannah Groundwater Province is not overexploited and has big potential for future groundwater resources utilization expansion.

However, utilization of groundwater in agriculture as well as public supply sources is often centralized in small areas. If the water supply wells were sited close to each other, the aquifer system could be locally overexploited either continuously or in the periods of enhanced groundwater demand. This overexploitation could negatively impact areas downward of groundwater flow. This impact would lead to the decrease of the yield of groundwater source, significant drawdown of groundwater head affecting surface ecosystems, saltwater intrusion and overall aquifer damage close to coastal areas. As obvious, the construction of new groundwater sources or yield increase of current sources in such affected areas has to be thoroughly assessed.

Similar effects as described in previous paragraph can be caused by drainage. Especially wide spread drainage systems have significant impact on groundwater resources capacity in the area. Draining system accelerates surface and subsurface runoff from the area and decreases ratio of infiltrated surface water into groundwater. This process decreases total amount groundwater resources capacity and consequently available groundwater resources.

8.2. Qualitative Groundwater Assessment

A standard groundwater chemical analysis should as a minimum comprise values for temperature, electroconductivity, pH, the four major cations (Na^+, K^+, Mg^{2+}, Ca^{2+}) and four major anions (Cl^-, HCO_3^-, SO_4^{2-}, NO_3^-), in other words eleven variables (Appelo and Postma, 2007).

Construction of Piper and Stiff diagram was possible only for 13 samples (S1-S13) analyzed in detail in laboratory (Bowen & Bowen, Ltd. laboratory, Fig. 33). This set of samples includes both surface water and groundwater considering the following:

- 3 surface water samples: S1, S7, S12
- 10 groundwater samples: S2, S3, S4, S5, S6, S8, S9, S10, S11, S13

The Tab. 17 shows the extract of documentation points including sampling points S1 – S13.

Tab. 17 Extract from the database of documentation points including samples S1-S13. Siting of sampling points S1-S13 are given in a map in Annex 2, Map 9.

Tag	ID	X	Y	District	Village	Sample	Type
S-1	134	358826	1897359	Belize	Gales Point	Surface water	Watercourse
S-2	141	360448	1880340	Stann Creek	Hope Creek	Groundwater	Borehole
S-3	148	356173	1863885	Stann Creek	Silk Gras	Groundwater	Borehole
S-4	153	362618	1879350	Stann Creek	Hope Creek	Groundwater	Borehole
S-5	156	355749	1879952	Stann Creek	Pomona	Groundwater	Borehole
S-6	162	357352	1867452	Stann Creek	Silk Gras	Groundwater	Borehole
S-7	96	313692	1818801	Toledo	Medina Bank	Surface water	Watercourse
S-8	95	310393	1812474	Toledo	Tambran	Groundwater	Hand pump - bore
S-9	9	327017	1821752	Toledo	Bladen	Groundwater	Borehole
S-10	35	340681	1840611	Stann Creek	Georgetown	Groundwater	Borehole
S-11	42	346713	1845585	Stann Creek	Santa Rosa - Santa Cruz	Groundwater	Well
S-12	122	348896	1848918	Stann Creek	South Stan Creek	Surface water	Watercourse
S-13	166	354212	1879889	Stann Creek		Groundwater	Borehole

ATTN: Mgr. Vaclav Frydrych/ GEOMEDIA

Date: February 19th 2014

Sample ID: GEOMEDIA

Date: 14th February 2014

INORGANIC CHEMISTRY

PHYSICAL	UNIT	METHOD	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13
CONDUCTIVITY	us/cm	CONDUCTIVITY (probe)	159.6	62.6	556	156.7	168.6	322	290	543	556	284	36.6	50	44.2
pH	unit	pH/ISE meter (probe)	7.25	5.28	7.37	6.52	6.38	7.72	7.90	7.26	7.80	7.51	6.32	6.56	5.86
TOTAL DISSOLVED SOLIDS (TDS)	ppm	CONDUCTIVITY (probe)	79.8	31.3	278	78.4	84.3	161.1	145.1	266	278	142	18.3	25.0	22.1
TURBIDITY	ntu	Nephelometric -Tungsten	0.818	0.104	0.173	0.103	0.162	0.097	7.51	0.857	0.247	0.152	0.734	2.07	0.733
METALS	**UNIT**	**METHOD**													
CALCIUM (Ca)	ppm	UV VIS Spectro/ Titration	28.7	2.1	129	15	62	85	158	242	118	129	3.2	6.5	2.3
COPPER (Cu)	ppm	Bicinchoninate/ UV VIS Spectro	0.02	0.04	0.12	0.05	0.05	0.02	0.01	0.01	0.02	0.01	0.02	0.02	0.05
ALUMINUM	ppm	Aluminon/UV VIS Spectro	0.025	0.023	0.104	0.050	0.054	0.020	0.014	0.016	0.002	0.006	0.012	0.006	0.029
IRON, TOTAL	ppm	UV VIS Spectro	0.07	0.07	N/D	0.01	0.02	0.01	0.09	0.21	0.02	0.10	0.02	0.20	0.13
MANGANESE	ppm	Periodate Oxidation/UV VIS Spectro	0.008	0.032	0.016	0.003	0.005	0.022	N/D	0.019	0.008	0.014	0.002	0.012	0.047
MAGNESIUM(Mg)	ppm	UV VIS Spectro / Titration	24.4	5.9	24	11	4	69	36	48	68	17	2.8	4.7	7.4
SODIUM	ppm	Probe	12.59	7.95	58.4	22.7	6.23	12.50	3.72	15.53	69.0	10.16	5.65	7.03	4.86
NON-METALS	**UNIT**	**METHOD**													
FLUORIDE (F)	ppm	SPADNS/UV VIS Spectro	0.12	0.06	0.20	0.13	0.04	0.09	N/D	0.08	0.02	0.15	0.08	0.10	N/D
INORGANIC COMPOUNDS	**UNIT**	**METHOD**													
BICARBONATE (HCO_3)	ppm	Titration	45.8	2.3	121	26	66	154	154	332	110	160	4	16.3	2.9
AMMONIA	ppm	Salicylate / Probe	N/D	N/D	N/D	N/D	N/D	N/D	0.01	N/D	N/D	0.05	N/D	0.19	N/D
CARBONATE (CO_3)	ppt	Titration	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
CHLORIDE (Cl)	ppm	Mercuric Nitrate	19.3	8.4	20	24.7	3.9	3.5	0.7	0.7	53	0.9	2.7	3.5	6.9
TOTAL HARDNESS (as $CaCO_3$)	ppm	EDTA Titration/ UV VIS Spectro	53.1	8.0	153	30	79	162	194	290	186	146	6.0	11.2	9.7
M ALKALINITY (as $CaCO_3$)	ppm	Sulfuric acid titration	45.8	2.3	121	26	66	154	154	334	110	160	4.0	16.3	2.9
NITRATE	ppm	Cadmium Reduction/ UV VIS Spectro	2	11.3	1.4	5.8	7.7	1.1	2.8	1.8	1.8	1.8	9.2	2.0	7.7
NITRITE	ppm	Diazotization/ UV VIS Spectro	0.004	0.006	0.005	0.016	0.006	0.008	0.006	0.005	0.002	0.015	0.007	0.011	0.009
PHOSPHATE (PO)	ppm	PhosVer / Orthophosphate/ UV VIS	1.07	1.71	2.39	3.67	1.77	1.92	1.15	3.29	1.44	2.09	0.76	2.22	1.2
SALINITY	ppt	Mercuric Nitrate titration	0.033	0.014	0.035	0.043	0.006	0.006	0.001	0.001	0.093	0.001	0.004	0.006	0.012
SODIUM CHLORIDE (NaCl)	ppm	UV VIS Spectro / Titration	31.84	13.86	33	40.75	6.435	5.775	1.155	1.155	87.4	1.485	4.451	5.775	11.385
SULPHATE (SO_4)	ppm	Sulfa Ver 4/ UV VIS Spectro	1	0	10	1	2	2	6	1	6	2	0	0	0

Lab Techs: Remy Can
Rohan Ramharak

Abbreviations/Consideration
CFU: Colony Forming Units
TNTC: Too numerous to count
CG: Confluent Growth
ND: Not Detected
NT: Not Tested
NA: Not applicable

Fig. 33 Record of laboratory results of samples S1 – S13, Bowen&Bowen Ltd.

Chemical archive data collected from existing sources could not be subject of detailed chemical study as one or several key parameters necessary for Piper/Stiff plot construction were missing. For future analysis it is highly recommended to include analyses of all standard parameters necessary to Piper/Stiff diagram construction (Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, HCO_3^-, SO_4^{2-}, NO_3^-) facilitating the water type characterization.

Water chemistry data acquired from all available existing sources were incorporated into an extensive Water Management Database. General statistics of these data is given in Annex 3.

Water analyses done in the field using field measurement tools as described in section 6.1, have been used for major statistic evaluation and general overview of the basic water quality, as described later in sections 8.2.1 and 8.2.2.

As obvious from the Piper and Stiff diagram, sampled water reveals differences in chemical composition.

However, there are no significantly different characteristics between groundwater and surface water samples. This is a result of predominant shallow groundwater circulation which is in the investigated upper part of the aquifer system considerably mixing with surface water bodies.

The overall proportion of cations and anions in samples S1-S13 groundwater is displayed in Fig. 34.

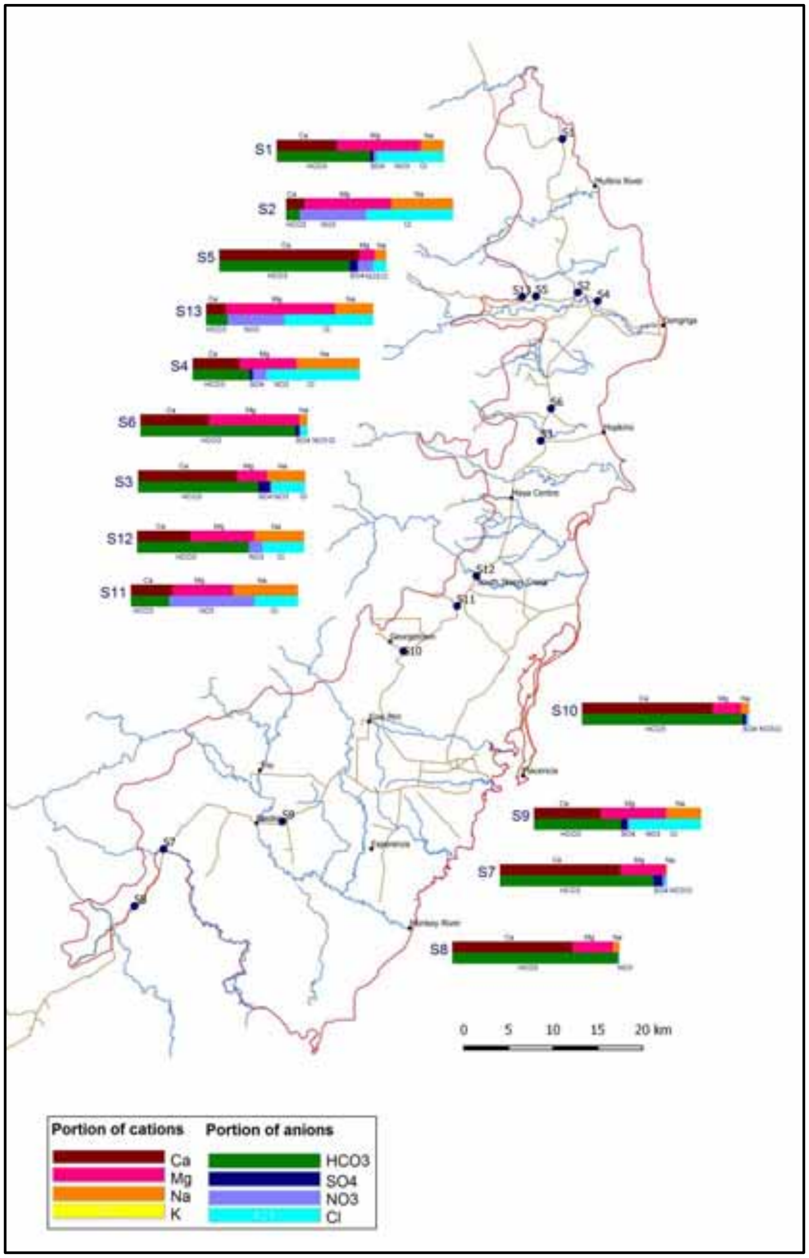

Fig. 34 Proportion of ions for sampled surface water (S1, S7, S12) and groundwater (rest of samples).

8.2.1. Surface Water

This section describes surface water quality based on following data:

- Detailed analyses S1-S13 (Bowen & Bowen, Ltd. Bowen & Bowen, Ltd.)
- Field analyses using field measurement tools (GEOMEDIA Ltd., see section 6.1)

Surface water analysed in detail in Bowen & Bowen, Ltd. laboratory was sampled at three sites so as to cover the investigated area in a regular manner:

S1 – Gales Point (in the north of the Savannah province)
S7 – Medina Bank (in the south of the Savannah province)
S12 – South Stann Creek (in the middle of the Savannah province)

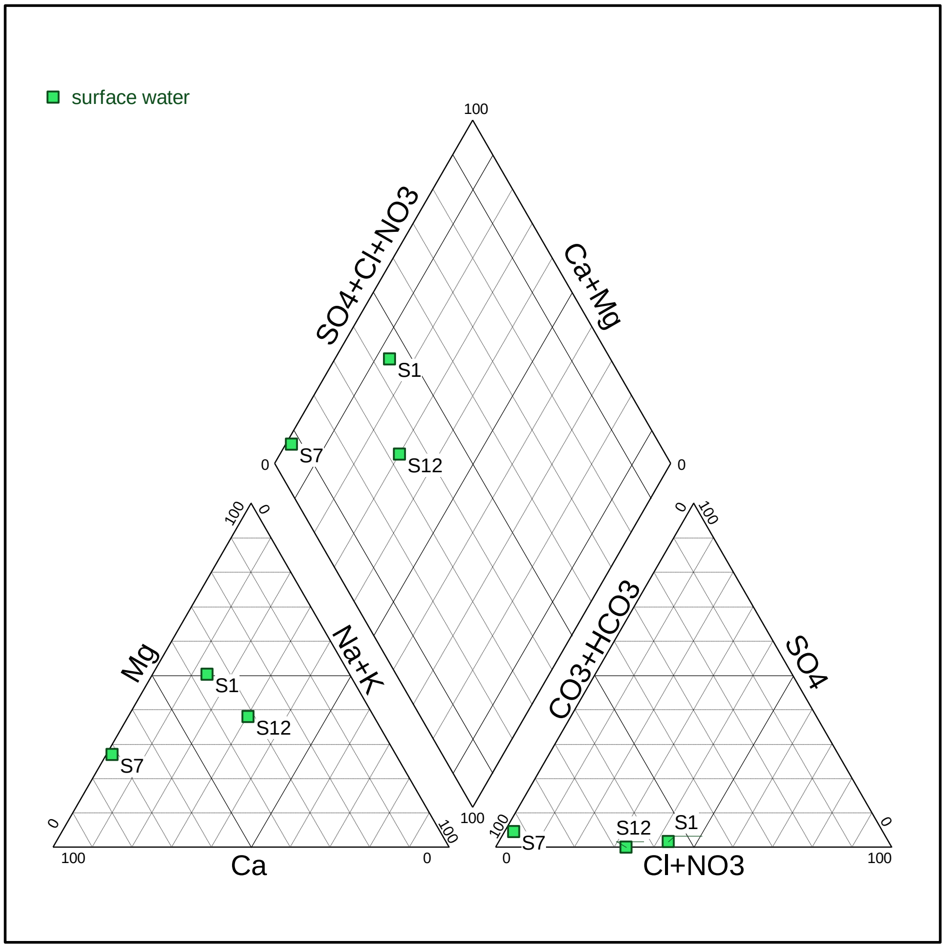

Fig. 35 Piper diagram for surface water samples S1,S7, S13 in the Savannah Groundwater Province.

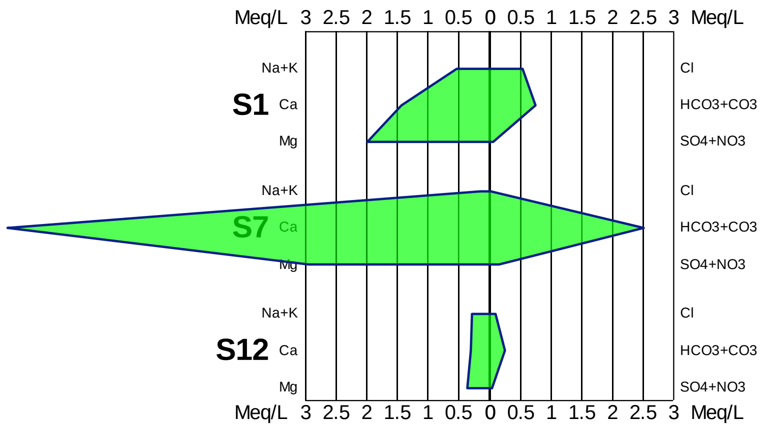

Fig. 36 Stiff diagram for surface water samples S1, S7 and S 12 in the Savannah Groundwater Province

As evident from Fig. 35 and Fig. 36, the chemistry of surface water is different for each site. All three samples are rich in bicarbonates. The similarity in chemical composition might be found for samples S1 and S12. They are both of $Mg(HCO_3)$ character although S1 reveals higher cationic concentration. S1 was taken in the proximity of the sea coast explaining the elevated values of chloride concentration compared to other surface water samples (19,3 ppm, i.e. 0.54 meq/L). On the other hand, sample S7 is typically $Ca(HCO_3)$ water, contains no chlorides (absence of sea-salt aerosols due to higher distance from the sea coast) and also reveals the highest degree of mineralization suggesting probable interaction with groundwater aquifer.

Results of 34 analyzed surface water samples carried out in field by GEOMEDIA Ltd. were generally compared to drinking water limits (see section 4.5.3). All measured parameters complied with drinking water parameters. Only two samples revealed slightly lower pH value. Complete data set is subject of the comprehensive Water Management Database in Annex 9. The chemical parameters are also given for each sample in the field notes in Annex 8.

Tab. 18 Basic statistics of surface water field analyses carried out by GEOMEDIA (34 samples, January 31 – February, 11, 2014)

SURFACE WATER	Temperature (°C)	pH	DO (ppm)	Conductivity (uS/cm)	Resistivity (ohms/cm)	TDS (ppm)	Salinity (ppt)
Minimum	24,3	6,29	3,24	10	3448	6	0
Maximum	29,4	8,16	8,67	287	90909	186	0,14
Median	26,35	7,11	7,705	42,5	22475	27	0,02
Mean	26,51	7,24	6,47	77,12	24062	50	0,03
Standard Deviation	1,00	0,48	2,01	80,78	16546	53	0,04

8.2.2. Groundwater

This section describes surface water quality based on following data:

- Detailed analyses S1-S13 (Bowen & Bowen, Ltd. Bowen & Bowen, Ltd.)
- Field analyses using field measurement tools (GEOMEDIA Ltd., see section 6.1)
- Detailed analysis of the water sample from drilled well HGE-1 (Bowen & Bowen, Ltd. Bowen & Bowen, Ltd.)

Groundwater analyzed in detail in Bowen & Bowen, Ltd. laboratory was sampled at ten sites:

S2 – Hope Creek
S3 – Silk Gras
S4 – Hope Creek
S5 - Pomona
S6 – Silk Gras
S8 – Tambran
S9 - Bladen
S10 - Georgetown
S11 – Santa Rosa – Santa Cruz
S13 - Pomona.

Sample S8 was taken from the hand pump bore, S11 from a well and the rest of samples originate from boreholes.

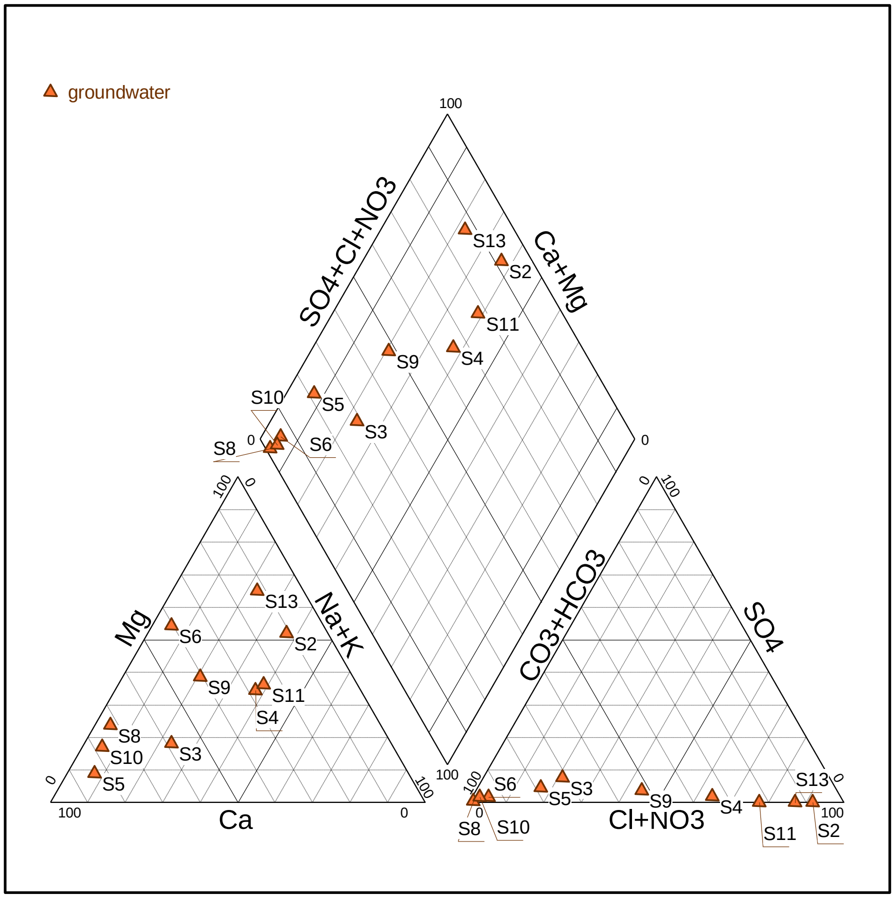

Fig. 37 Piper diagram for groundwater samples S1,S3-S6,S8-S11,S13 in the Savannah Groundwater Province.

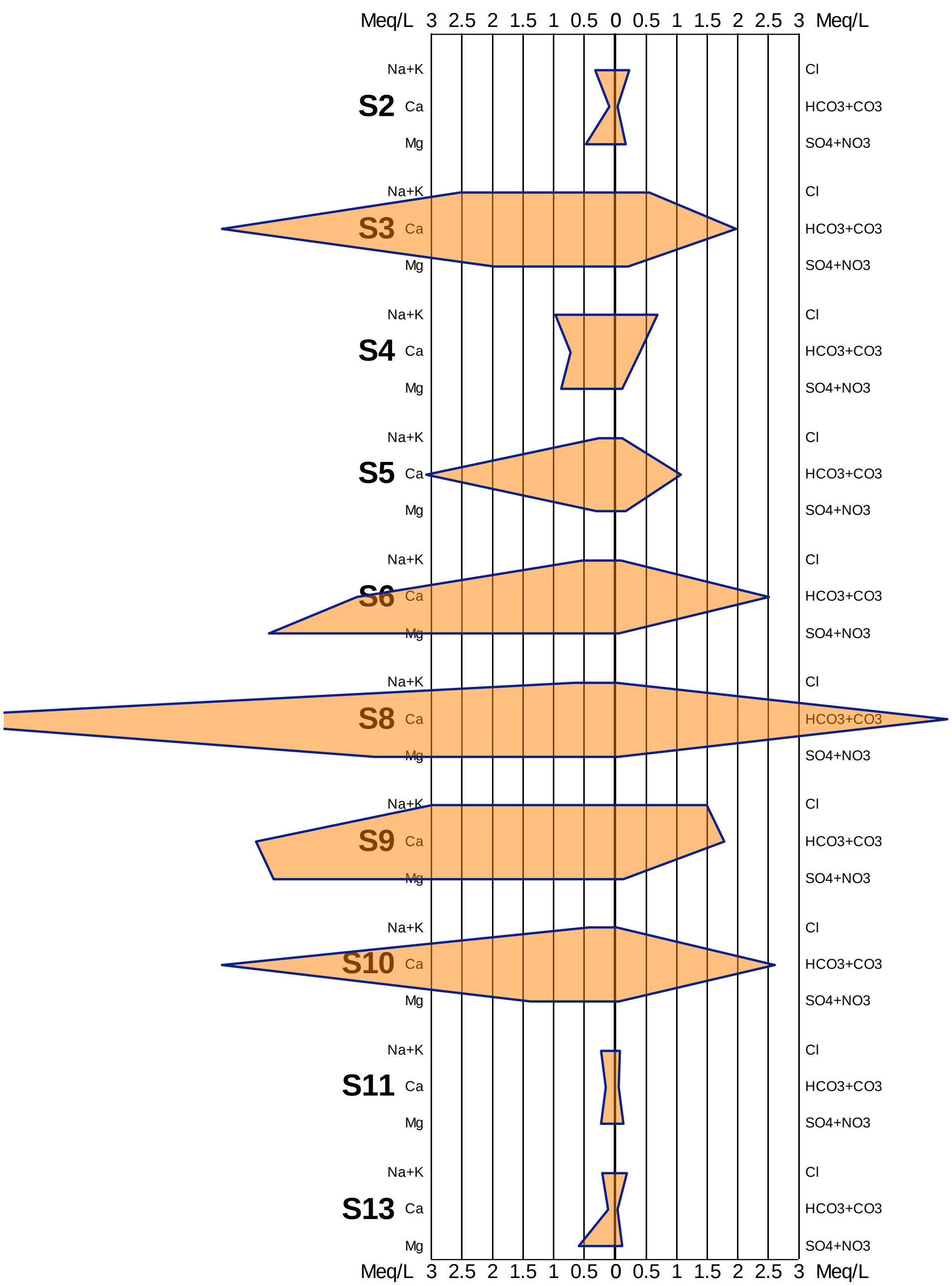

Fig. 38 Stiff diagram for groundwater samples S1, S3-S6, S8-11, S13 in the Savannah Groundwater Province

Although it is rather difficult to classify groundwater samples into several groups as some of them are less distinctive, all measured groundwater samples can be generally classified into two major groups (Fig. 37, Fig. 38):

1) *(Ca)(Mg)HCO3 (calcium-magnesium-bicarbonate) type*
   Most of the samples (S3, S5, S8, S9 and S10) reveal Ca(HCO3) character. Sample S6 is classified rather into Mg(HCO3) group. Sample S9 belongs due to increased Mg concentration to Ca(Mg)(HCO3) group. Generally speaking, samples originating from deeper horizons reveal high ion content. As evident from both Piper and Stiff diagram (Fig. 35, Fig. 36) none of groundwater samples reveals sodium-bicarbonate or sodium-sulphate character.

2) *(Ca)(Mg)(Na)Cl(NO3) (calcium-magnesium-sodium-chloride-nitrate) type*
This group of groundwater is characterized by less distinctive chemical composition. Concentration of individual ions is lower and overall chemical composition results from different processes including contamination. This feature was identified for samples S2, S4, S5, S11, S13.
As obvious from the spatial distribution of sampling sites, samples S2, S4, S5 and S13 correspond to the area around Hope Creek and Pomona. The boreholes used for sampling are situated within agricultural area which may explain vulnerability for contamination by anthropological sources.

Tab. 19 Basic statistics of groundwater detailed analyses carried out by Bowen&Bowen Ltd. (7 samples, February 14, 2014)

GROUNDWATER	Conductivity (us/cm)	pH	TDS (ppm)	Calcium (ppm)	Manganese (ppm)	Sodium (ppm)	Bicarbonate (ppm)	Chloride (ppm)	Alkalinity (ppm)	Nitrate (ppm)	Sodium chloride (ppm)	Sulphate (ppm)
Minimum	36,6	5,28	18,3	2,1	0,002	4,86	2,3	0,7	2,3	1,1	1,155	0
Maximum	556	7,8	278	242	0,047	69	332	53	334	11,3	87,4	10
Median	284,00	7,02	142,00	85,00	0,01	10,16	110,00	6,9	110,00	1,80	6,44	2,00
Mean	281,70	6,82	141,00	83,00	0,02	19,93	105,00	12,2	105,00	4,60	19,00	2,50

Considering the results of 76 analyzed groundwater samples in field it may be considered that sampled groundwater do not reveal anomalous values. The analyses were generally compared to drinking water limits (see section 4.5.3). Based on this, 44 samples reveal lower pH, 7 samples exceeded the standard conductivity. Only one samples exceeded the standard value of TDS. Complete data set is subject of the comprehensive Water Management Database in Annex 9. The chemical parameters are also given for each sample in the field notes in Annex 8.

Tab. 20 Basic statistics of groundwater field analyses carried out by GEOMEDIA (76 samples, January 25 – February, 13, 2014)

GROUNDWATER	Temperature (°C)	pH	DO (ppm)	Conductivity (uS/cm)	Resistivity (ohms/cm)	TDS (ppm)	Salinity (ppt)
Minimum	25,6	4,9	2,22	19	955	12	0
Maximum	30,3	7,79	8,01	978	47619	635	0,48
Median	28,1	6,375	4,795	100,5	9302	65	0,05
Mean	28,06	6,36	4,65	164,07	14272	106	0,08
Standard Deviation	0,91	0,72	1,56	180,95	12825	118	0,09

The third source of groundwater analysis acquired during the project was the water sampled from newly drilled well HGE-1 nearby Bladen / Trio village in Deep River Forest Reserve. The record of laboratory results is given in Fig. 39. The only parameter slightly exceeding the limit for drinking water according a Canadian standard (see section 4.5.3) is magnesium. However, the elevated magnesium concentrations are not harmful to human health.

ATTN: GEOMEDIA

Sample ID: GEOMEDIA

Date: 15th August 2014

INORGANIC CHEMISTRY

PHYSICAL	UNIT	METHOD	RESULT
			HGE1
CONDUCTIVITY	us/cm	CONDUCTIVITY (probe)	369
pH	unit	pH/ISE meter (probe)	7.02
TOTAL DISSOLVED SOLIDS (TDS)	ppm	CONDUCTIVITY (probe)	186.4
TURBIDITY	ntu	Nephelometric -Tungsten	0.317
METALS	UNIT	METHOD	
CALCIUM (Ca)	ppm	UV VIS Spectro/ Titration	122
COPPER (Cu)	ppm	Bicinchoninate/ UV VIS Spectro	<0.04
ALUMINUM	ppm	Aluminon/UV VIS Spectro	0.008
IRON, TOTAL	ppm	UV VIS Spectro	0.04
MANGANESE	ppm	Periodate Oxidation/UV VIS Spectro	0.013
MAGNESIUM(Mg)	ppm	UV VIS Spectro / Titration	69
SODIUM	ppm	Probe	6.3
NON-METALS	UNIT	METHOD	
FLUORIDE (F)	ppm	SPADNS/UV VIS Spectro	0.28
INORGANIC COMPOUNDS	UNIT	METHOD	
BICARBONATE (HCO_3)	ppm	Titration	178
AMMONIA	ppm	Salicylate / Probe	0.02
CARBONATE (CO_3)	ppt	Titration	ND
CHLORIDE (Cl)	ppm	Mercuric Nitrate	9.7
TOTAL HARDNESS (as $CaCO_3$)	ppm	EDTA Titration/ UV VIS Spectro	191
M ALKALINITY (as $CaCO_3$)	ppm	Sulfuric acid titration	178
NITRATE	ppm	Cadmium Reduction/ UV VIS Spectro	1.2
NITRITE	ppm	Diazotization/ UV VIS Spectro	0.007
PHOSPHATE (PO)	ppm	PhosVer / Orthophosphate/ UV VIS Spectro	1.7
SALINITY	ppt	Mercuric Nitrate titration	0.002
SODIUM CHLORIDE (NaCl)	ppm	UV VIS Spectro / Titration	2.47
SULPHATE (SO_4)	ppm	Sulfa Ver 4/ UV VIS Spectro	3

Fig. 39 Laboratory results of sample from HGE-1 well, Bowen&Bowen Ltd.

8.3. Groundwater Vulnerability and Quality Protection

8.3.1. Groundwater Quality Risks

Groundwater might be generally vulnerable to numerous pollutants (qualitative changes) as well as excessive pumping leading to groundwater overuses (quantitative changes). Vulnerability of groundwater quality in the Savannah Province reflects geologic and hydrogeological setting determining the thickness and properties of the vadose zone cover layer. The interaction of groundwater with surface water is another vulnerability factor as surface water represents a source of pollution.

The Savannah Groundwater Province consists of multi-layered aquifer system. Groundwater level in the upper part of the sedimentary formation is throughout the investigated area observed mostly nearby the surface. Unsaturated zone consists of thin layer of sandy rocks. Soil-protection layer which generally forms efficient barrier for pollutant infiltration into groundwater is locally absent. Upper part of aquifer is generally assessed as highly vulnerable to external factors. Cover layer of impermeable clayey rocks occurs only locally and protects groundwater body from pollution and forms confined groundwater level (e.g. Ara Macao).

With regard to the very low population density and low number and extent of industrial companies, the total risk of upper part of aquifer pollution is evaluated as low. The quality of groundwater is not affected by anthropogenic activities. The potential risk of pollution represents agriculture or rather the potential use of chemical substances in agriculture and insufficient safeguarding of groundwater wells.

Deeper aquifers lie in depths of tens and hundreds meters below the surface covered by impermeable layers (aquitards). Recharge area of lower aquifer is located in Maya Mountains with no inhabitants and negligible risk of groundwater pollution caused by human sources. Lower aquifer is for that reason generally considered as low vulnerable to external factors.

On the other hand, karst aquifer represents highly vulnerable environment due to significant karst permeability, intensive groundwater circulation (character of pipe flow) and low filtration capability.

Observation during the field work enabled the identification of several occurrences of inappropriate municipal waste disposal and waste water disposal representing the risk for groundwater quality, such as following:

- Wild landfills are situated in the close vicinity of drinking water supply objects. Municipal waste management is generally considered to represent qualitative risks for groundwater (Fig. 40).

Fig. 40 Wild landfills in the Savannah Groundwater Province. Example from Independence (left) and Swasey wetlands (right).

- Domestic waste water is discharged into the immediate vicinity of water resources (Fig. 41).

Fig. 41 Municipal waste water in the vicinity of the groundwater well, Golden Stream.

- Industrial waste water is discharged into the vicinity of water resources, e.g. waters containing chemical substances for bananas treatment before dispatching (Fig. 42).

Fig. 42 Industrial waste water from banana washing discharged into water course, Banana farm No. 27.

- The significant potential sources of pollution such as oil stations and oil reservoirs were observed in the close vicinity of water resources (Fig. 43).

Fig. 43 Oil station close to groundwater source (behind the tank), banana farm.

- One of the most significant qualitative risks for groundwater resources is inappropriate filling up of old abandoned water wells with municipal waste. Local inhabitants are not informed about patterns of groundwater circulation, water resources as well as groundwater protection. Old water resources need to be safeguarded. Any unsafeguarded well represents a serious risk for groundwater in terms of its quality.

Fig. 44 Abandoned wells filled up with waste, Cowpen.

Groundwater quantity, as a subject of the field observation, is assumed not to be negatively affected so far. However, several pumping sites are equipped with submersible pump with not adequate output (often too high) which is leading to permanent decrease of water level corresponding to the level of suction basket (e.g. public supply well in Pomona ID 0156). Nevertheless, this situation is of only technical character without permanent negative impacts on the groundwater system.

As a reason of high aquifer permeability the drawdown of groundwater table level at pumping sites reaches generally low values in the range of first meters. The cone of depression covers only the very close vicinity of the pumping sites. Regarding considerable amount of precipitation in the investigated area the overuse of the studied aquifer is considered to be low probable.

A specific issue is pumping of groundwater in coastal areas. Excessive or inappropriate way of groundwater withdraw might cause intensive intrusion of saline water into fresh water aquifer leading to deterioration of groundwater resource quality.

Saline water intrusion has been a rare occurrence (e.g. Mullins River ID. 0138).

8.3.2. Mitigation Measures for Individual Groundwater Risks

Based on the fieldwork findings, several areas of major risks of groundwater quality have been identified. These are listed here below. In the same time, the risk description is accompanied by proposal of appropriate mitigation measures.

The following recommendations need to be supported by organization of public educational events focusing on both general hydrogeological principals as well as respecting the water resources in terms of its protection against contamination and its sustainability.

A) Municipal waste management

Wild landfills have been identified in the vicinity of important drinking water supply objects. A great amount of sites polluted by municipal waste was encountered, especially in the close vicinity of municipalities and communities as well as at the edges of wetlands and water bodies.

It is highly recommended to implement the municipal waste management central registration system. The municipal waste producers should have access to the information how to treat and dispose the waste as well as the access to the site designated for the waste disposal. For that reason it is essential to ensure the central collection of the municipal waste, the waste transportation system as well as the monitored waste storage at secure landfills. Furthermore, it is recommended to implement the waste separation and waste recycling system.

The existing wild landfills are to be disposed of as soon as possible and it is necessary to take up measures to prevent new wild landfill development.

B) Industrial waste storage

Industrial waste represents one of the most serious risks to groundwater vulnerability. The most effective way to eliminate the uncontrolled hazardous waste management is the implementation of hazardous waste classification system (official catalogue of different hazardous waste categories issued by state authorities), the implementation of hazardous waste producers register and hazardous waste management register. The hazardous waste management producers must be able to declare treatment with the hazardous waste in accordance with environmental, groundwater, surface water and water resources protection principles. The hazardous waste must be disposed at adequately secured sites and it is necessary to keep the documentation record.

C) Mining and quarrying

Mining and quarrying represent risk for groundwater vulnerability mainly for two reasons. The first one is the potential release of hazardous substances into groundwater due to the extraction of raw materials (e.g. heavy metals, sulphates, petroleum products). Secondly, sand and gravel surface extraction might lead to the exposure of the groundwater level at the surface and therefore exposure to the direct contamination. The exposure of the groundwater level does not primarily mean the direct risk for the groundwater quality, however it is important to prevent potential input of contaminants into such artificially created lakes. It is essential to develop system of groundwater monitoring objects in the close vicinity of the mining area.

D) Discharge of municipal wastewater

Municipal wastewater is generally discharged into water courses, rock environment, on the surface or into the sewage systems. The shallow groundwater table in the whole investigated area is potentially threated by municipal wastewater discharge. The wastewater treatment plant and sewage systems need to be constructed, especially in the areas with increased population density. The same concerns small local wastewater treatment plant in rural areas with lower population density.

The discharge of municipal wastewater into the nearby water sources especially in the vicinity of public and drinking water supply objects needs to be reduced. In general, municipal wastewater represents lower risk for groundwater quality than other potential sources of pollution. Nevertheless in rural areas the municipal wastewater represents a significant risk of water resources contamination. For that reason it is recommended to build a system which would be easy to follow for every household.

E) Industrial production and industrial wastewater discharge

Industrial wastewater must be disposed of in a safe controlled manner under the supervision of the public authorities. It is necessary to build a state registration system for industrial wastewater producers, registration of chemical composition and dangerousness of wastewater and a control system for discharged wastewater after previous treatment. In areas of industrial production with a serious risk of groundwater pollution it is important to develop sophisticated system of groundwater monitoring objects and prepare emergency plans to prevent the consequences of serious industrial accidents.

F) Agricultural production

An agricultural production does represent a main source of groundwater pollution in a global scale. The pollution results primarily from a large-scale application of chemical substances to protect plants or plant products from harm caused by pests (pesticides, fungicides…), large-scale application of fertilizers and antibiotics and other drugs from animal farms. It is necessary to ensure effective state control focused on a compliance with technological processes for the use of chemical substances, fertilizers and pharmaceuticals in agriculture, especially in the areas with the shallow groundwater level.

G) Handling with substances representing a risk for groundwater and surface quality

Unsafe disposal of hazardous substances represents mainly a risk of short term accident. The best possible way of prevention of such accidents and their consequences is safe disposal of substances hazardous to water quality and environment. Hazardous substances, such as certain chemicals and pesticides, must be subject of state registration and control system concerning the storage, transportation, utilization and disposal of unused supplies of hazardous substances. The central storehouse of chemicals is obliged to draw up emergency plan in case of emergencies as well as develop system of groundwater monitoring objects.

H) Inadequate protection of water resources

Protection of water resources covers both the protection of surface and groundwater resources against any contamination. It is important to ensure that each public drinking water source has a manager supervising the water resource and deciding appropriate measures to keep the water resources clean, in good technical conditions, to ensure necessary maintenance and preventive measures to protect the resource (prevention from infiltration of contaminants in the close vicinity).

Considering significant resources for collective drinking water public supply, it is particularly essential to set protection zones. The principle of the protection zone lies in the prevention of groundwater in the area between the recharge zone and the discharge zone, i.e. extraction point against any contamination. These protection zones are subject of specific land use regime, e.g. agricultural management without use of chemicals considerate the environment and water resources. Abandoned water resources need to be properly secured and disposed of so as not to become a source of contamination.

Furthermore, a system of groundwater monitoring sites must be developed in the close vicinity of important drinking water supply sources.

8.4. Current Groundwater Use

Practically all existing water supply objects identified and documented within the Project activities are to exploit upper part of fresh groundwater aquifer. As observed in the field, an abstraction well reaching the depth of 30m in average is adequate to obtain sufficient amount of water for water supply in the range of litres to tens litres per second throughout the Savannah Province.

Most groundwater wells were equipped by submersible pumps with a constant output corresponding usually to 5 L/s. It is highly recommended to adjust the submersible pump output/flow rate of each well to local hydrogeological conditions.

It might be concluded that the current water supply ensured by exploitation of the upper part of aquifer is negligible compared to the total groundwater reserves in this aquifer. The potential for further exploitation of fresh water within the Savannah Groundwater Province is considered to be very high. Balance assessment of the Savannah Groundwater Province is subject of more detailed study of groundwater regime and mathematical modeling.

The water supply provided from the deeper aquifers would require significant technological and economical demands. Based on available data so far, the exploitation of the deeper aquifers in the Savannah Province is not expected to be perspective in terms of short or medium-term water supply. This is particularly true for the interior areas with abundant groundwater resources of the upper aquifer. The potential use of the deeper aquifers could be considered within coastal areas characterized by sea water intrusion into the freshwater upper aquifer (e.g. Ara Macao).

9. Water Management Database

9.1. General Description

One of the major tasks of the groundwater assessment project in Savannah Groundwater Province was to use existing data from different governmental agencies and departments, private water management companies or other organizations in Belize. Further data were acquired in the field by GEOMEDIA during the project duration.

Quite a bit set of data was acquired but the data character is very heterogenous. The challenge for all concerned agencies is presenting information in an easily, preferably unified comprehensible format to policy makers or the public. Also, after collecting the data sets it was needed to develop a way to effectively store and retrieve the information.

For the abovementioned reasons, available and relevant data, i.e. observations and data measured and observed by GEOMEDIA during the project as well as historic information provided by local GOB and private agencies were integrated together and a Water Management Database (WMD) was built using Microsoft Office Excel package. This assures on one hand a very universal application platform, on the other hand assures the robustness in utilization. The WMD integrates multitude of data from the fields of geology, hydrogeology and hydrochemistry.

The purpose of the WMD is to provide information for integrated and coordinated regional water management by governmental, public and private organizations. Further purpose of the WMD is to provide data for scientific and research activities.

The WMD is provided in paper format as well as in electronic file (.xls) so as it could be continuously improved and enriched by new data in future (Annex 9).

Proposed Guideline for maintenance and operation of the WMD is enclosed in Annex 6.

9.2. Applied Data

WMD includes only data with exact coordinate localization or data where coordinates could be easily estimated based on map reading or field knowledge.

Provided archive data that were sometimes missing key information on the measurement or sampling localization were excluded from the database as it could introduce significant errors in the data sets and cause further misunderstanding in data reading. Missing coordinates could be often replaced by estimates or by new geographical measurement if the measurement or sampling was easy to identify based on other provided information. If it was not the case, these data were not used as a database input. The example of this situation is data set from Ministry of Health including water analyses. The information did not include coordinates and even the description of the sampling point did not help to identify the well. This is recommended for further consideration and to be consequently added into WMD. Other reason for excluding these data from the WMD is the character of sampled water often representing tap water or samples from rudimentary water system. Such samples might have modified chemical composition due to increased potential of pollution and not representing raw groundwater parameters.

Special group of data is formed by data acquired from the Department of Rural Development. They were all included in the WMD despite the fact that missing coordinates or other identifiers did not allow the exact identification of the well in space. Therefore, these data may be duplicated with other data having assigned coordinates. In practice it means that one well might possess two different ID numbers because one ID was assigned to a well identified by GEOMEDIA and the other by Rural Development and in reality both records may refer to the same well. This has to be kept in mind for further WMD processing and it is recommended to additionally fill in missing coordinates and if possible to harmonize the ID numbers.

Tab. 21 provides the final list of data suppliers together with information on the amount of applied data in WMD compared to total amount of records obtained from local authorities or measured in field.

Tab. 21 List of processed hydrogeological data – comparison of total amount of data and applied in WMD.

Data Source	Data description	Total number of records	Number of records applied in WMD
GEOMEDIA Ltd.	Field chemical analyses	113	113
	Field hydrogeological measurements	84	84
	Laboratory analysis (Bowen&Bowen Ltd.)	13	13
	Well log data, pump test, geological profile, laboratory chemical analysis (HGE-1)	1	1
Ministry of Labour, Local Government and Rural Development, Department of Rural Development	Water well log reports, Stan Creek District	38	38
	Water well log reports, Toledo District	17	17
Public Utilities Commission	Chemical well data, Stan Creek District	4	4
	Hydrogeological characteristics (yield, GW level)	3	3
	Basic Information about 4 wells and chemical data for 1 well, Ara Macao Resort (Report TNCE, 2006)	4	4
Ministry of Health	Groundwater and surface water chemical data, Stan Creek District	92	2
	Groundwater and surface water chemical data, Toledo District	10	0
Belize Aquaculture Ltd.	Chemical data for 5 wells (time series)	76	76
	Chemical data for one surface water sample (time series)	11	11
Belize Water Service Ltd.	Chemical data for 1 wells (Dangriga Village) – raw and treated water	2	1
Public Health Bureau (The Ministry of Health)	Chemical data for 3 wells, Stan Creek District	3	3
Banana farms	Chemical data for banana farms	108	108

9.3. Data Processing

The original source data were processed and validated. The data processing is based on evaluation of the data accuracy and relevancy. The data validation is based on environmental and geo-scientific statistical methods.

The aim of the WMD was to integrate as much data as possible acquired from local authorities or measured in field. The numbers of data are given in Tab. 21. The data fields in WMD cover a range of different parameters that may be measured or identified for each documentation point. As obvious, the applied data have different character and do not cover all data fields. In general, missing information is represented by a blank cell in the WMD except of the chemistry data. Missing chemical analysis is recorded as NT (=not tested). In case the value is expressed as < the record is indicated as ND (not detected).

9.4. Database Schema

All aspects of our data required developing an appropriate database structure. Data are stored in excel data sets and organized into a schema with five main data sets, as displayed in Fig. 45.

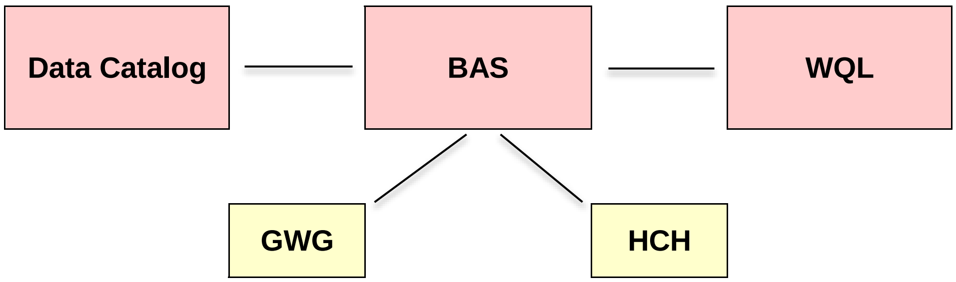

Fig. 45 Water Managment Database Schema (Data Catalog-data overview, BAS - basic data, WQL - water quality limits, GWG – groundwater and geology, HCH – hydrochemistry).

These five data sets are interconnected and together, they form compact database. This approach ensured to create dynamic, functional and useful utility for better monitoring and understanding of groundwater and surface water.

Fields describing the same information in different data sets have the same name, format and uses the same coding.

9.4.1. Data Catalog

The Data Catalogue provides an explanation how the data are organized and an overview of all applied data by introducing monitored and evaluated values. Data Catalog includes for sections such as following: List of data sets, List of fields, Abbreviations and applied Units:

- „List of data sets“ provides the description of BAS, GWG, HCH and WQL data sets.
- „List of fields“ provides description of applied field for BAS, GWG and HCH data sets.
- „Abbreviations“ provides a list of applied abbreviations within the WMD.
- „Units" provides a list of applied units within the WMD.

9.4.2. BAS – Basic data

The BAS data set lists all objects that are subject of the WMD. Applied data fields in BAS are described in Data Catalog including specification of the data format, units, comment on possible values and detailed explanation. Here, it is also described whether unique object is further included in GWG data set, HCH data set or both.

9.4.3. GWG – Groundwater and Geology

The GWG data set describes those objects listed in BAS that possess information on hydrogeology and (or) geology. Applied data fields in GWG are described in Data Catalog including specification of the data format, units, comment on possible values and detailed explanation.

9.4.4. HCH - Hydrochemistry

The HCH data set describes those objects listed in BAS that possess information on hydrochemistry. Applied data fields in HCH are described in Data Catalog including specification of the data format, units, comment on possible values and detailed explanation.

9.4.5. WQL – Water Quality Limits

The WQL data set was created alongside hydrochemistry data in order to compare the analyses with general standard values. Introduced water quality limits are established according to Water Health Organisation's drinking water standards, Guidelines for Canadian Drinking Water Quality and United States Environmental Protection Agency standards. This table also suggests if the applied standard refers to recommended or maximum levels.

9.5. Future use of the Water Management Database

As proposed in Guidelines for maintenance and operation in Annex 6, the WMD is to be housed by NIWRA. Organizations acquiring relevant data related to hydrogeology, geology or hydrochemistry shall act as nodes for data input. As proposed WMD should be further maintained and continuously extended. New measurements or parameters can be easily added to any WMD data set. Added data might cover not only Savannah Province area but also other regions in Belize. This approach shall ensure continuously updated data set used for any further groundwater assessment or groundwater monitoring.

10. Conclusions and Recommendations

The project deals with qualitative and quantitative assessment of groundwater resources in Groundwater Savannah Province. The proposed groundwater assessment provides a set of raw data and their qualitative and quantitative interpretation.

This project has also examined the resilience of groundwater to climate change in Belize. Groundwater possesses a high resilience to climate change in Belize and should be central to adaptation strategies. Moreover, reliance on groundwater is likely to increase as rainfall becomes more variable and demand for water becomes greater.

The assumptions of the groundwater flow were implemented into a mathematical model. Numerical groundwater models provide a powerful quantitative tool to aid the optimization and management of water resources in an economic, sustainable and environmentally responsible manner.

The Project has been further followed and supported by a number of national and local stakeholders, representatives of whom are listed in the Annex 1. Various parts of the Project were suitable as basis for know-how transfer and capacity building, in the interaction among the project team and the stakeholders. The opportunities included especially the field work and drilling as well as data collection and review in the developed Water Management Database.

The know-how transfer and capacity building shall continue after the Project completion in the following areas:
- groundwater monitoring;
- data management and assessment;
- simulation modeling of groundwater development scenarios.

10.1. Data Management, Integration and Assessment

The success of any groundwater assessment study, to a large measure depends upon the availability and accuracy of collected, measured, recorded data required for that study. Identifying the data needs of a particular study and collection or monitoring of required data constitute integral parts of any groundwater assessment and simulation modeling study.

The water quantity and quality was assessed based on following data sources:
- Existing collected data
- Field data

Data were collected from existing available national reports as well as from international sources. The collected data relevant for comprehensive assessment of the groundwater potential are covering the areas of topography, land use, meteorology, hydrology, geology and hydrogeology.

The field work considerably contributed to the current characterization of the Savannah Groundwater Province by including new measurements and findings in the area. The hydrogeological well HGE-1 was drilled in Deep River Forest Reserve under supervision of GEOMEDIA with the aim to contribute to the current knowledge of the upper part of freshwater aquifer in terms of geological structure and hydrogeological properties. The guideline for maintenance and operation of the HGE-1 well is proposed in Annex 5.

All available archive data and new measurements were processed with emphasis to the identification of complex relationships and interactions of various components of geo-hydrological environment by means of GIS database as well as numerical modeling and integrated into an extensive Water Management Database. The Water Management Database (Annex 9) was developed to effectively store and retrieve the information about the selected documentation point. The database is developed using Microsoft Office Excel package and is submitted in electronic format along with this Final Report in Annex 9. The guideline for maintenance and operation of the Water Management Database is proposed in Annex 6.

10.2. Groundwater Quantity, Quality and Protection

The current exploitation of the investigated aquifer was preliminary evaluated as not excessive compared to the total groundwater reserves in this aquifer. The potential for further exploitation of fresh water in this aquifer could be considered to be rather high. However, it is recommended to adjust pumping rate to local conditions.

Annual precipitation in Savannah province averages 2325 mm/year and annual average evaporation varies around 1300 mm/year. Value of evapotranspiration necessary for the model purposes is considered to be higher than given evaporation. Considering climatic and hydrological conditions within the area, value of total natural runoff 730 mm/year giving specific value of 23 L/s/km^2 the average specific base flow can be estimated around 17 L/s/km^2.

The assessment of geological and groundwater data, numerical simulation as well as field observations resulted in the re-assessment of the outlined hydrogeological boundary of the Savannah Province.

The field work enabled to identify several occurrences of inappropriate municipal waste disposal and waste water disposal representing the risk for groundwater quality. Based on this a set of mitigation measures and recommendations were formulated in order to ensure the protection of groundwater bodies. Key proposed mitigation measures are as following:

- It is recommended to accept adequate measures for protection not only quantitative parameters of the hydrogeological structure reflecting the development of new water resources but also for protection of groundwater and surface water quality
- It is recommended to accept adequate measures to improve municipal waste management in order to prevent wild landfills development endangering the aquifer qualitative parameters;
- It is recommended to accept adequate measures to improve the waste water management in order to prevent waste water discharge into fresh water aquifer;
- It is recommended to develop educational activities in order to explain the vulnerability of groundwater and surface water resources;
- It is recommended to ensure qualified treatment with old and unused water resources which could represent the source of groundwater pollution;
- It is recommended to delineate the boundaries of water resource protection area for each water supply object according to the hydrogeological setting;
- It is recommended to conduct a survey of significant potential sources of groundwater pollution and adopt measures for treatment of substances causing groundwater and surface water pollution;
- It is recommended to set up conditions for application of chemical substances in agriculture to minimize impact to groundwater quality.

A number of agencies monitor water quality and quantity in Savannah Groundwater Province for their own purposes and no comprehensive set of information is currently available. For that reason it is recommended that the HGE-1 well drilled in the Project framework becomes the inaugural groundwater monitoring station for the province and outfitted with necessary technologies to make monitoring more efficient. Continuous monitoring at proposed well would significantly improve knowledge on the freshwater aquifer and would enable to draw further recommendations for exploitation of the concerned aquifer system.

Collected records on water chemistry from existing data sources in Belize do not generally contain complete water quality information. In order to ensure accurate data interpretation, it is highly recommended to develop water monitoring system and unify the regularly analysed parameters. Recommended minimum set of measured parameters includes pH, temperature, salinity, TDS, mineralization, Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, HCO_3^-, SO_4^{2-}, NO_3^-.

10.3. Groundwater Model

Groundwater models can be applied to a range of problems to aid water companies, regulators and other abstractors optimise water resource management and planning.

The objective of the mathematical model is to simulate regional groundwater circulation in the upper sedimentary formation (flow rate and velocity and direction) groundwater resources balance of the Savannah Groundwater

Province and impacts of water abstraction. Numerical groundwater modeling is applied to provide estimate of the status of the groundwater resource and to set the volume of the groundwater that might be abstracted without damaging local surface aquatic ecosystems and groundwater resources in the long-term.

The field work observation resulted in a general definition of the conceptual model. This assumption was further adjusted by model calibration and validated according model simulation.

Based on model calibration, total amount of water entering the Savannah Groundwater Province area is $2.93*10^6$ m^3/d (17.5 $L/s/km^2$). This number consists of surface infiltration over whole area $2.9*10^6$ m^3/d (17.5 $L/s/km^2$) and groundwater inflow from Maya mountains $2.1*10^4$ m^3/d (240 L/S). Value $2.93*10^6$ m^3/d represents total natural renewable water resources of Savannah Groundwater Province. Groundwater in Savannah Groundwater Province is mostly drained by rivers ($1.76*10^6$ m^3/d) and coastal areas are drained directly into Caribbean sea ($1.13*10^5$ m^3/d). Exploitable resources can be estimated to value 6 - 10 $L/s/km^2$.

For Savannah Groundwater Province, several case studies were performed. Model scenarios indicate that utilization of groundwater resources in some areas is close to resource limits and further increase of groundwater extraction might cause aquifer structure overexploitation, as confirms simulation of the extraction increase of the Independence groundwater source. Model scenarios also indicate that the negative changes of parameters influencing groundwater recharge can cause decrease of exploitable groundwater resources. These parameters include not only amount of precipitation but also landscape utilization that can change water regime and ratio of surface water infiltration into groundwater. The saltwater intrusion model scenario shows that the zone affected by increased chloride concentration extends to a maximum distance of 1300 m from the coast (the case of sea level increase).

The guideline for maintenance and operation of the Groundwater Model is proposed in Annex 7.

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Annexes

Annex 1 **List of persons contacted in the frame of the Project**

Annex 2 **Maps**

Annex 3 **Statistics**

Annex 4 **Well Documentation – HGE-1**

Annex 5 **Proposed Operation Guidelines – Exploration and Monitoring Well**

Annex 6 **Proposed Operation Guidelines – Water Management Database**

Annex 7 **Proposed Operation Guidelines – Groundwater Model Savannah Province**

Annex 1

List of project partners

Organisation	Name	Involvement in the Project
United Nations Development Programme	Ms. Diane Wade	client – stakeholder
United Nations Development Programme	Ms. Ismirla Andrade	stakeholder, project administration
United Nations Development Programme	Mr. Colin Gillett	stakeholder, project coordination
Ministry of Natural Resources and Agriculture, Policy Coordination and Planning Unit	Dr. Paul Flowers	stakeholder
Ministry of Natural Resources and Agriculture, Policy Coordination and Planning Unit	Mr. Nelson Link	stakeholder
Ministry of Natural Resources and Agriculture, Hydrology Unit	Ms. Rhona Lopez	stakeholder, support in build-up of the project database
Ministry of Natural Resources and Agriculture, Policy and Planning Unit	Ms. Tennielle Williams	government, support in build-up of the project database
Ministry of Natural Resources and Agriculture, Mining Unit	Mr. Edward Swift	government
Ministry of Natural Resources and Agriculture, Mining Unit	Ms. Michelle Alvarez	government
Ministry of Natural Resources and the Environment, Forest Department	Mr. Marcelo Windsor	government
Ministry of Energy, Science and Technology and Public Utilities, Geology and Petroleum Department	Mr. Andre Cho	government, support in build-up of the project database
Ministry of Energy, Science and Technology and Public Utilities, Geology and Petroleum Department	Mr. Pedro Cho	government, support in build-up of the project database
Ministry of Energy, Science and Technology and Public Utilities, Geology and Petroleum Department	Mr. Craig Moore	government, support in build-up of the project database
Ministry of Forestry, Fisheries and Sustainable Development, Department of the Environment	Mr. Martin Alegria	stakeholder
Ministry of Forestry, Fisheries and Sustainable Development, Department of the Environment	Ms. Maxine Monsanto	government, support in build-up of the project database
Ministry of Forestry, Fisheries and Sustainable Development, Department of the Environment	Mr. Leonides Sosa	government, support in build-up of the project database
National Meteorological Service, Climatology Section	Ms. Catherine Cumberbatch	Government agency, support in build-up of the project database
Ministry of Labour, Local Government and Rural Development, Department of Rural Development	Mr. Hilbert Lopez	stakeholder, support in build-up of the project database supplier – drilling services

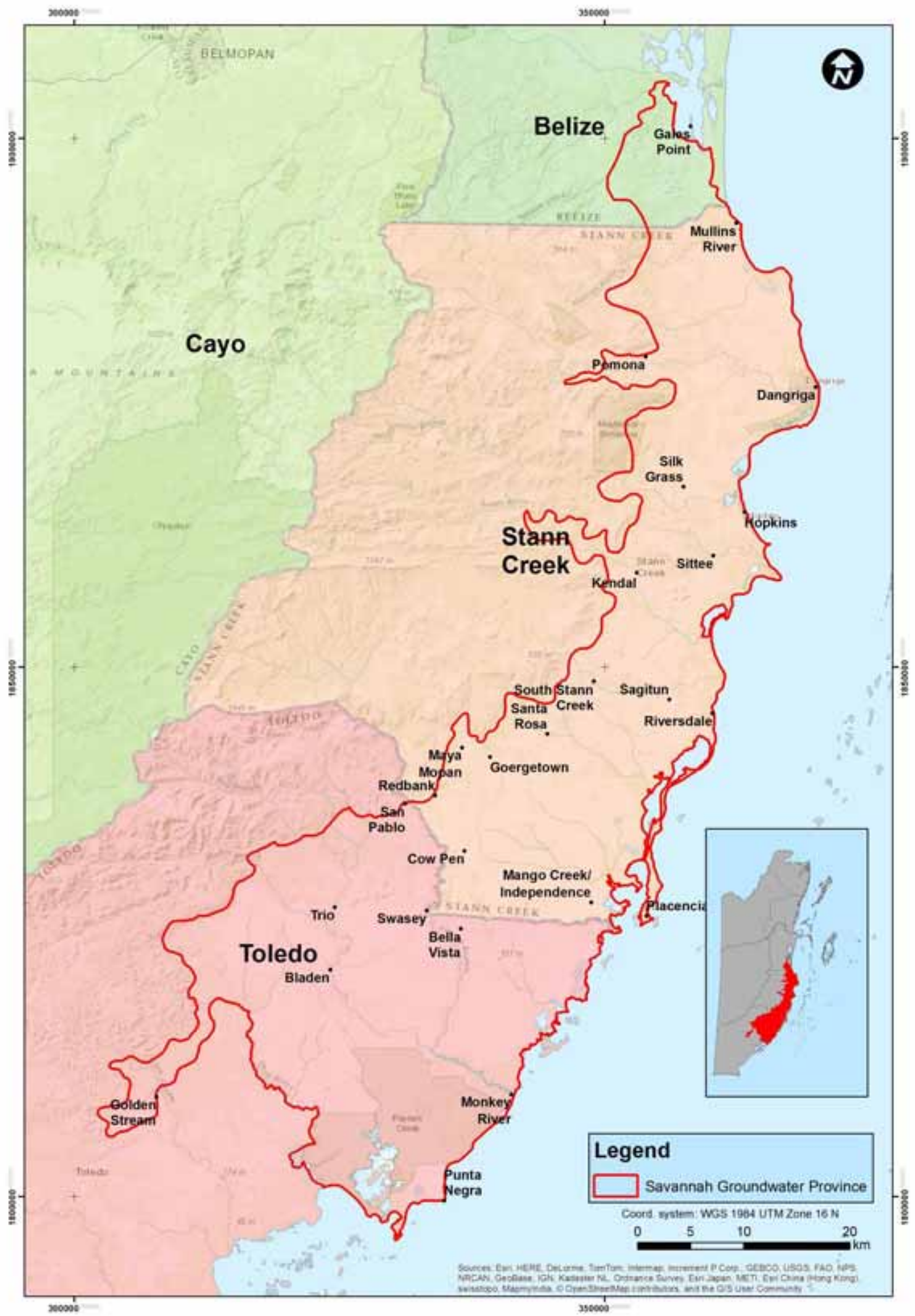
Organisation	Name	Involvement in the Project
Ministry of Labour, Local Government and Rural Development, Department of Rural Development	Mr. Ernest Banner	stakeholder, support in build-up of the project database supplier – drilling services
Ministry of Agriculture and Fisheries	Mr. Ricardo Thompson	government
Ministry of Health	Mr. Anthony Flowers	stakeholder, support in build-up of the project database
Ministry of Health	Mr. Mark Bernard	stakeholder
National Meteorological Service, Hydrology Unit	Mr. Dennis Gonguez	stakeholder, support in build-up of the project database
Public Utilities Commission	Mr. Rudolph Williams	government agency, support in build-up of the project database
Caribbean Community Climate Change Centre	Dr. Kenrick Leslie	stakeholder
National Climate Change Office	Mr. Colin Mattis	stakeholder
National Climate Change Office	Ms. Ann Gordon	stakeholder
Coastal Zone Management Authority and Institute	Mr. Vincent Gillet	Quasi-government agency, interested party support in build-up of the project database
Independent Consultant, Galen University	Mr. Ramon Frutos	interested party
Belize Water Service Ltd.	Mr. Keith Hardwick	stakeholder, support in build-up of the project database
Princess Petroleum Ltd.	Mr. Keon Garbutt	interested party
Princess Petroleum Ltd., geologist	Mr. Max Mohamed	interested party
Bowen&Bowen, Ltd. laboratory	Mr. Manuel Lanza	supplier – lab services
Agricultural Development & Services Ltd.		local stakeholder
Amelia Johnson's Farm	Magadallen Che	local stakeholder
AquaMar Limited	Michael Duncan	local stakeholder
Belize Aquaculture Limited	Isabelle Gayot Andre Reneau	local stakeholder
Big Creek Group	Gustavo Carillo	local stakeholder
Caribbean Producers Belize Limited (CPBL)	Jerry Williams	local stakeholder
Citrus Growers Association	Thomas Tate Thurman Williams	local stakeholder
Delta Pride Farms (Farm 14)		local stakeholder
Go Bananas 06 Ltd.	Freddy Bonilla Jevany Molina	local stakeholder
Go Bananas Farm 04	Javier Francho	local stakeholder
Go Bananas Farm 08	Giovanni Reyes	local stakeholder
Green Gold Farm Ltd (Farm 16)		local stakeholder
Mayan King Banana Farms (Farms 05, 06 & 27)	Miguel Monroy	local stakeholder
Royal Mayan Shrimp Farm	Marie Longsworth	local stakeholder
Sanctuary Belize/Kanatik Resort	Frank Costanzo-Connelly	local stakeholder
Sagitun Farms (Farm 07)		local stakeholder
Tropical Agriculture Investment ltd.	Arnold Torres	local stakeholder

Organisation	**Name**	**Involvement in the Project**
Village Council - Bella Vista	Glenda Banegas (Water Board Office) Tomas Bonilla (Water Board Office)	local stakeholder
Village Council Water Board – Hope Creek	Thomas Tate Evaristo Cruz	local stakeholder
Village Council Water Board – Monkey River Village Council - Monkey River	Keserine Garbut Richard Pitts (Village Council Chairman)	local stakeholder
Village Council Water Board - Pomona	Mr. Wagner	local stakeholder
Village Council Water Board- Bladen	Augustine Shaw	local stakeholder
Village Water Board - Cow Pen	Mr. Garcia (pump operator)	local stakeholder

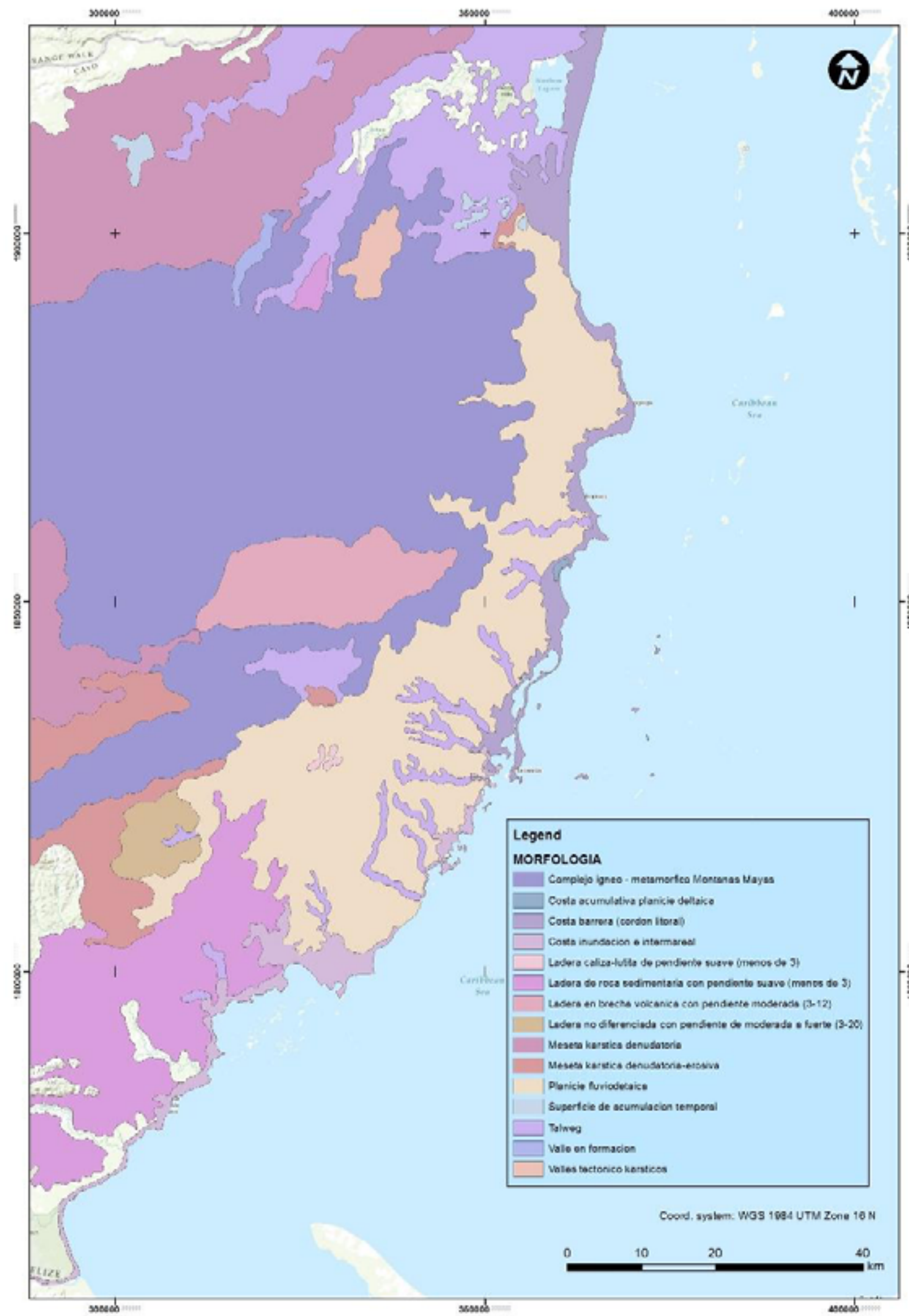
Annex 2

Maps

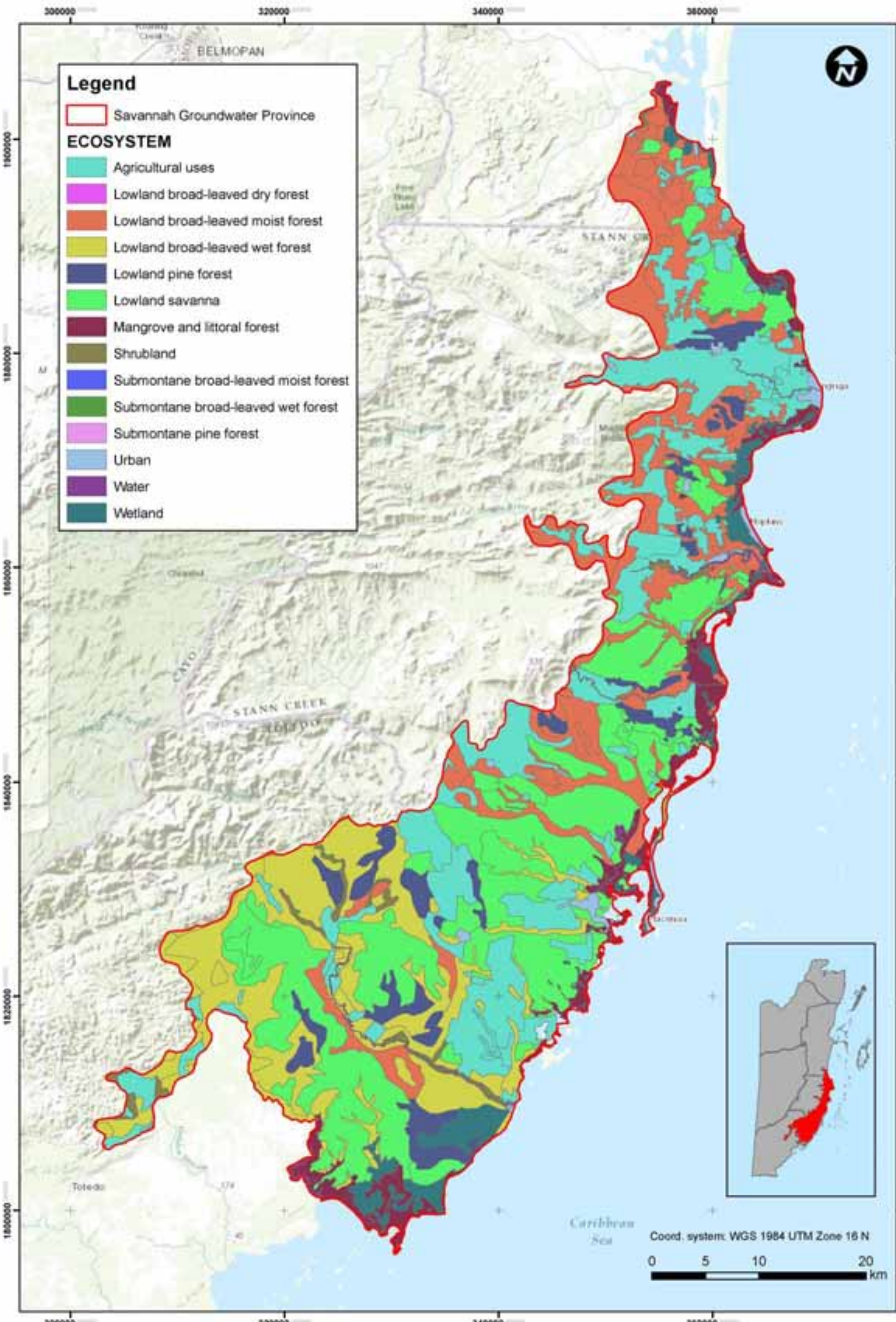
Map 1 District map – detailed view Savannah Groundwater Province.



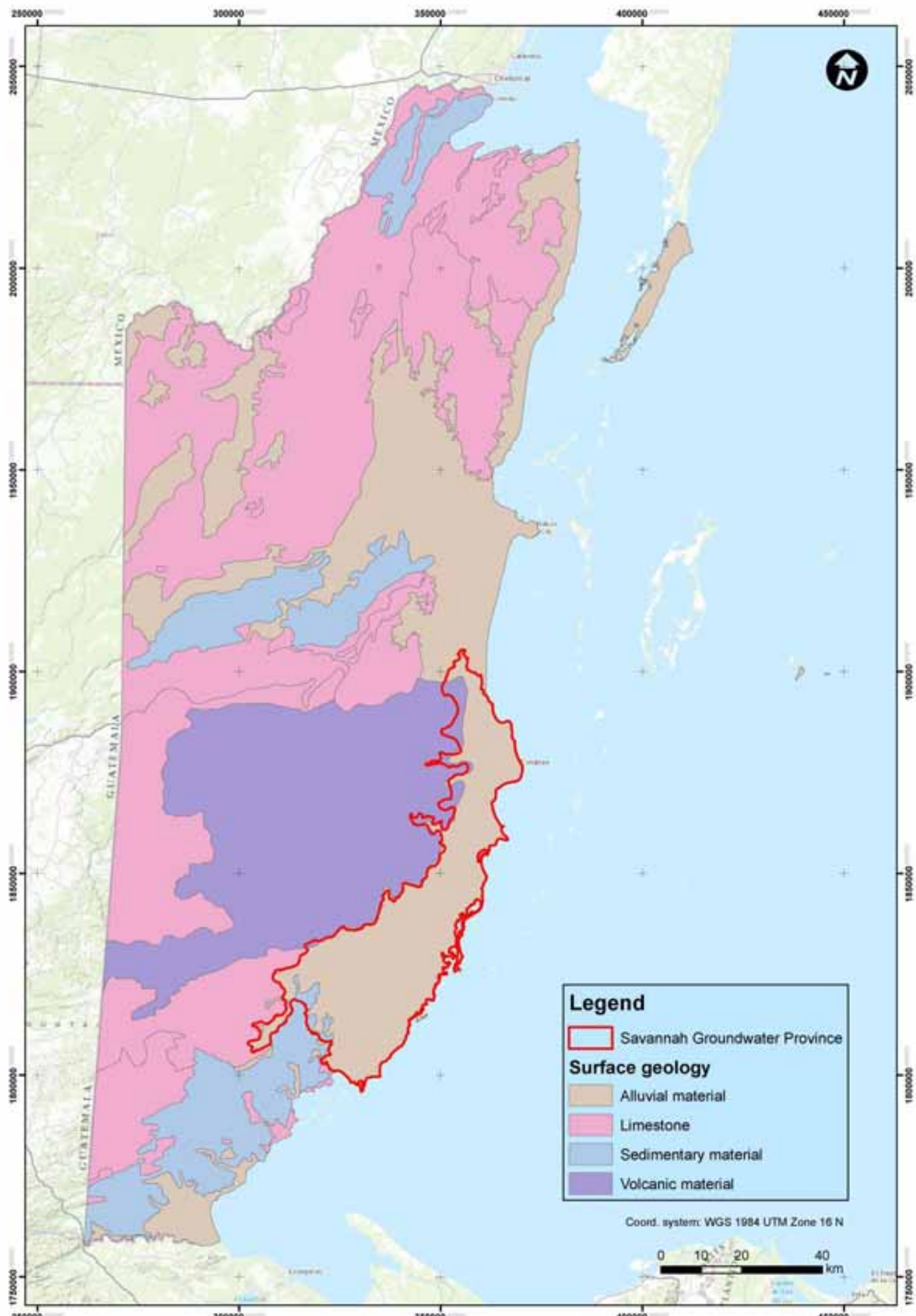
Map 2 Geomorphology of southern Belize delineating the Savannah Groundwater Province.



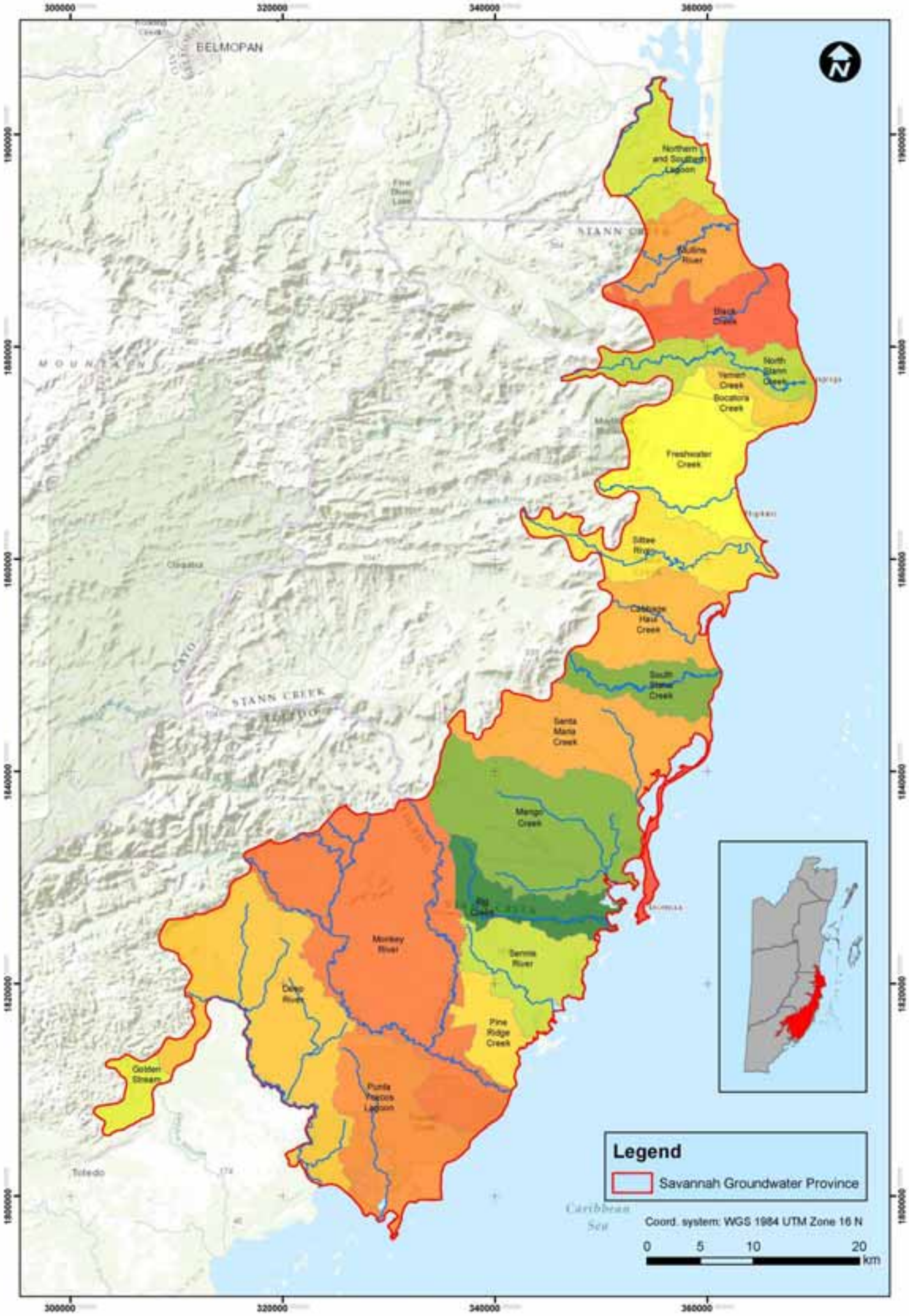
Map 3 Land use of the Savannah Groundwater Province.



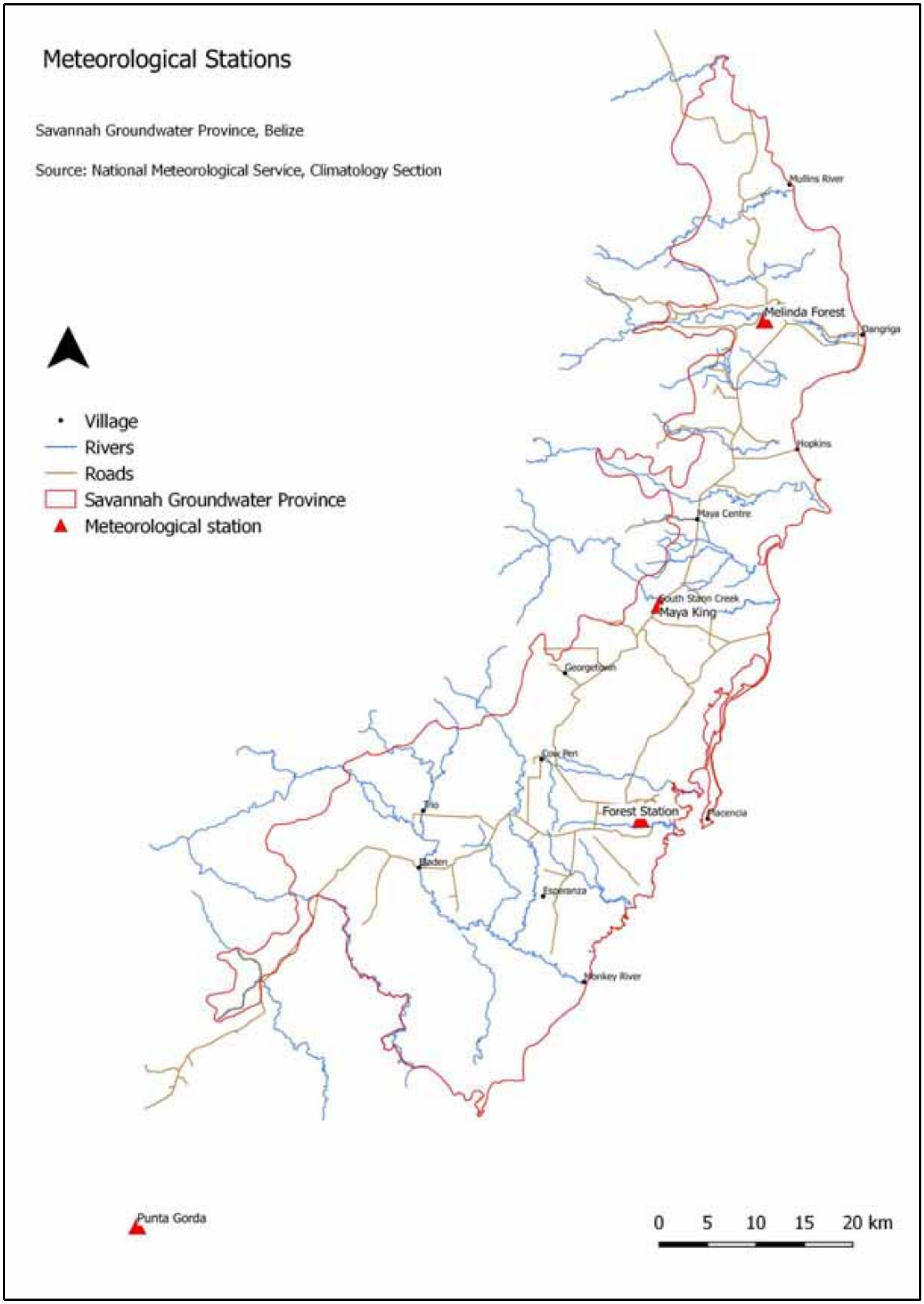
Map 4 Simplified geology of the Savannah Groundwater Province.



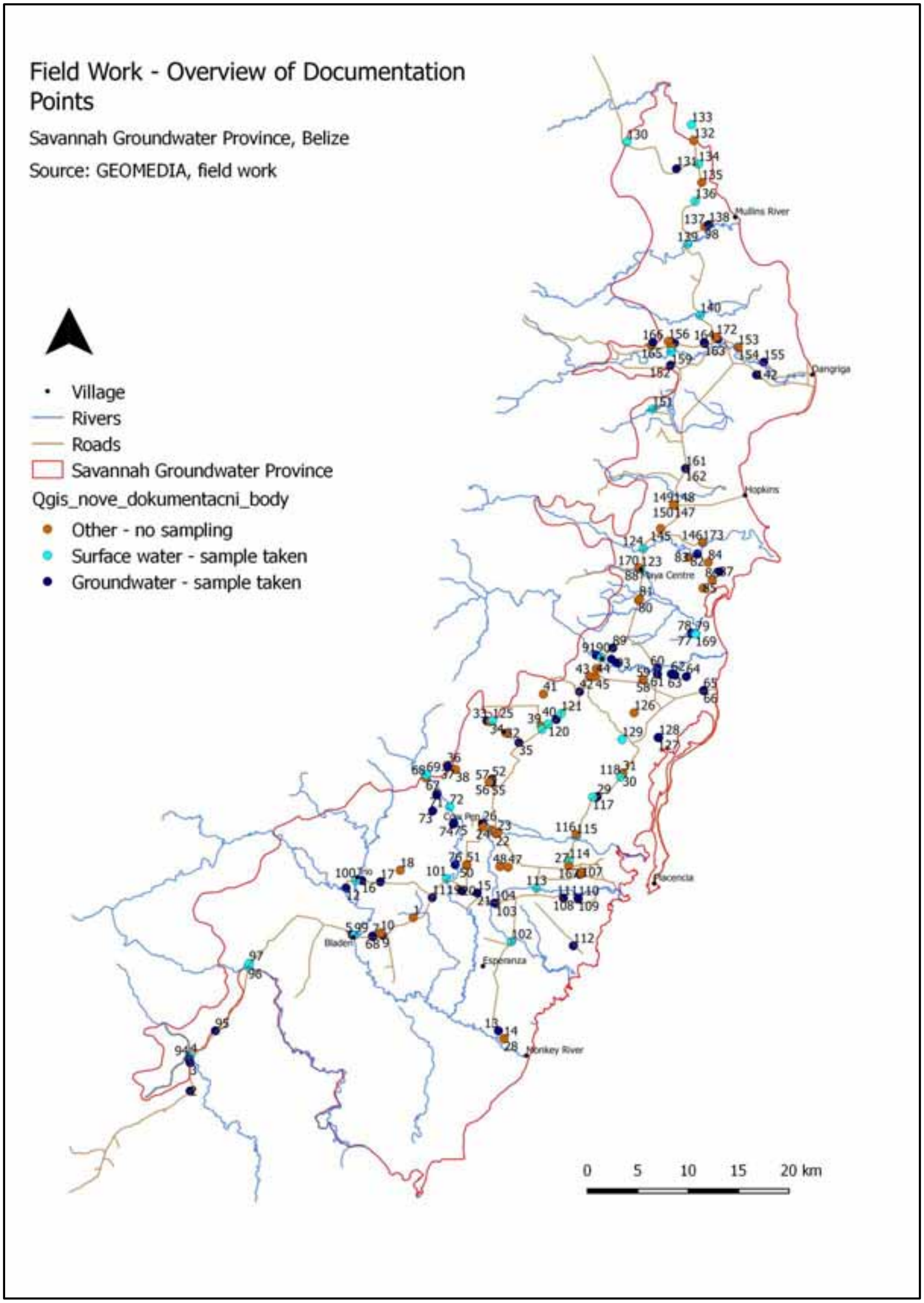
Map 5 Watersheds in the Savannah Groundwater Province.



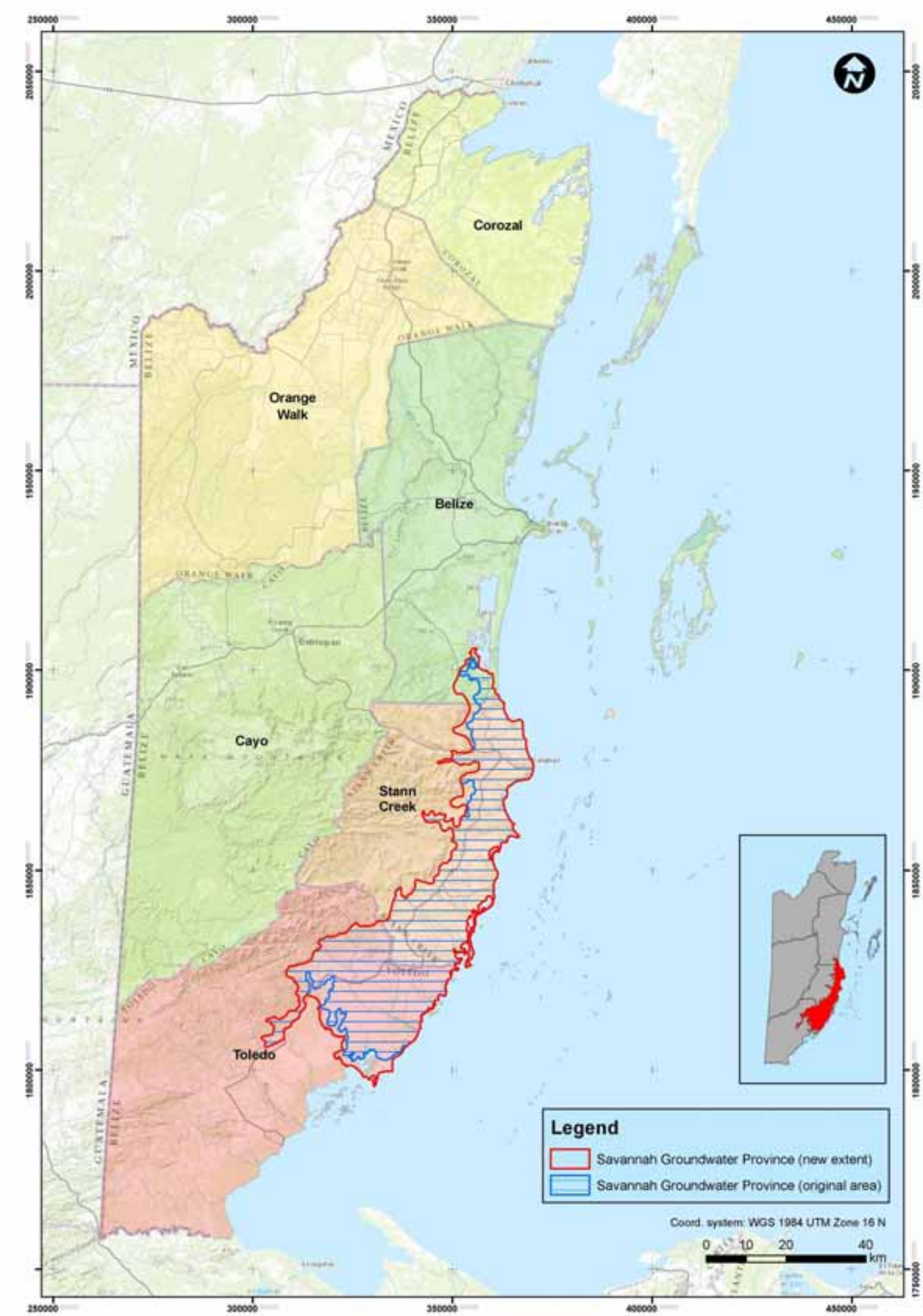
Map 6 Distribution of main meteorological stations



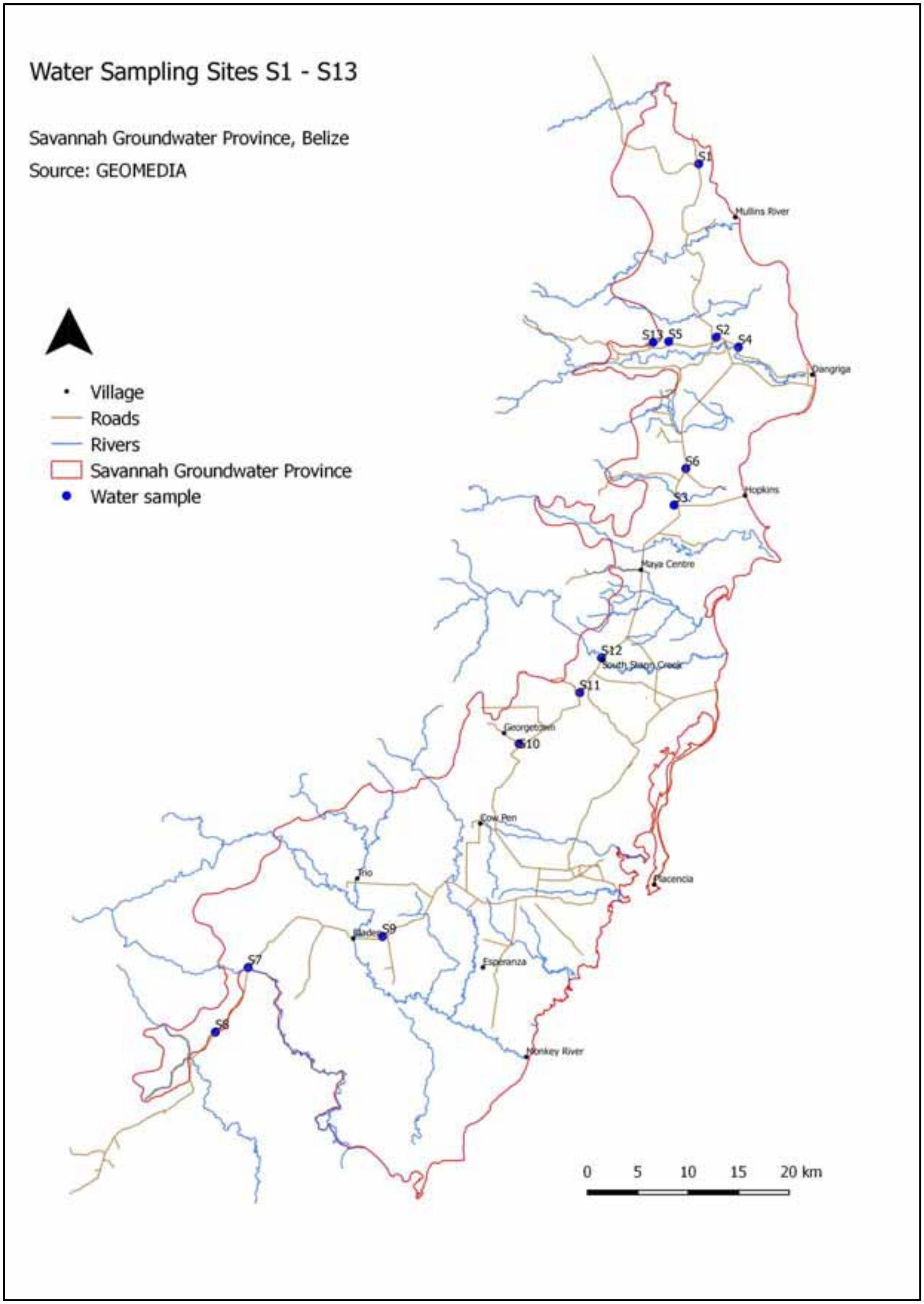
Map 7 Field work - overview of documentation points



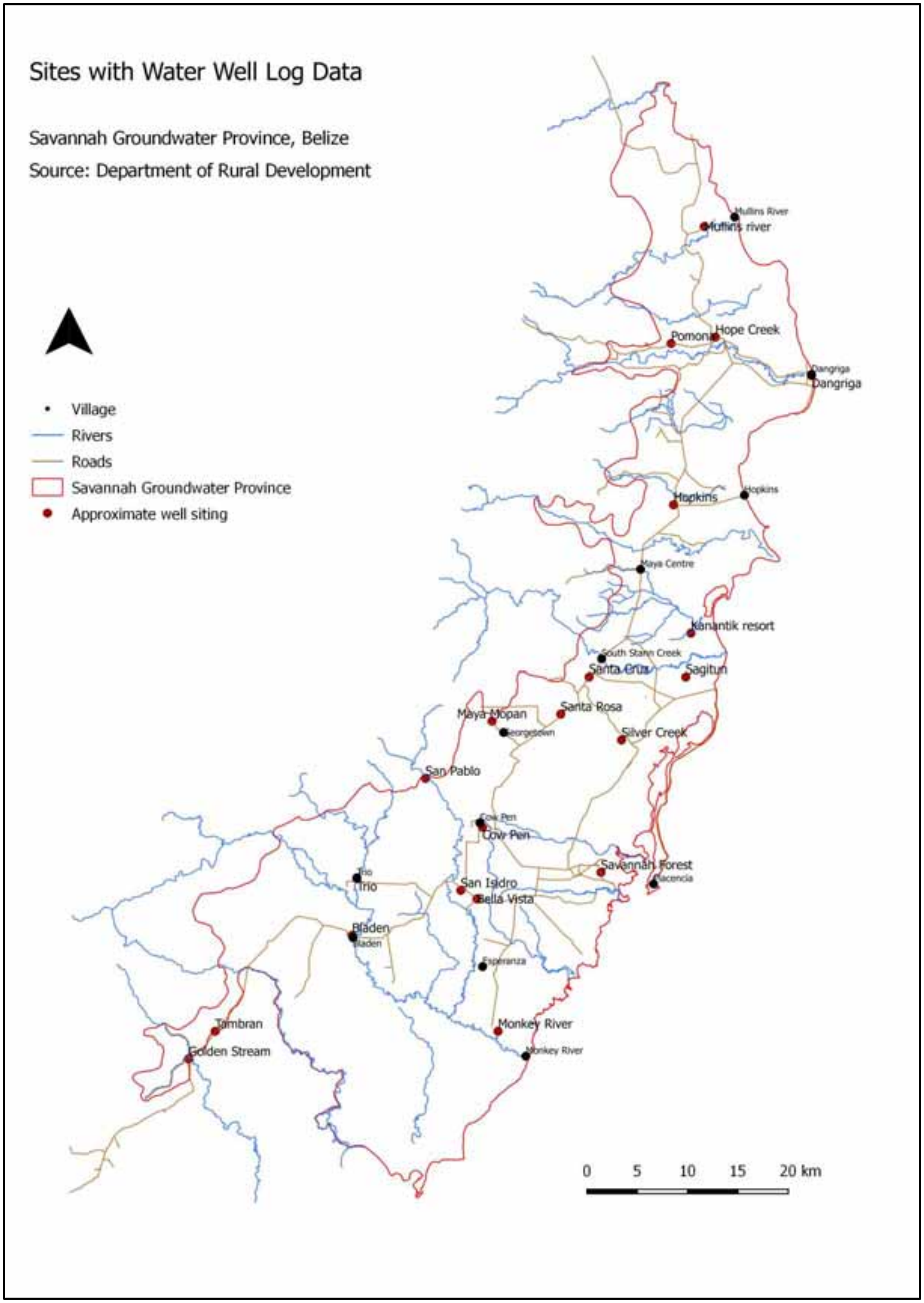
Map 8 Comparison of approaches to the Savannah Groundwater Province delineation.



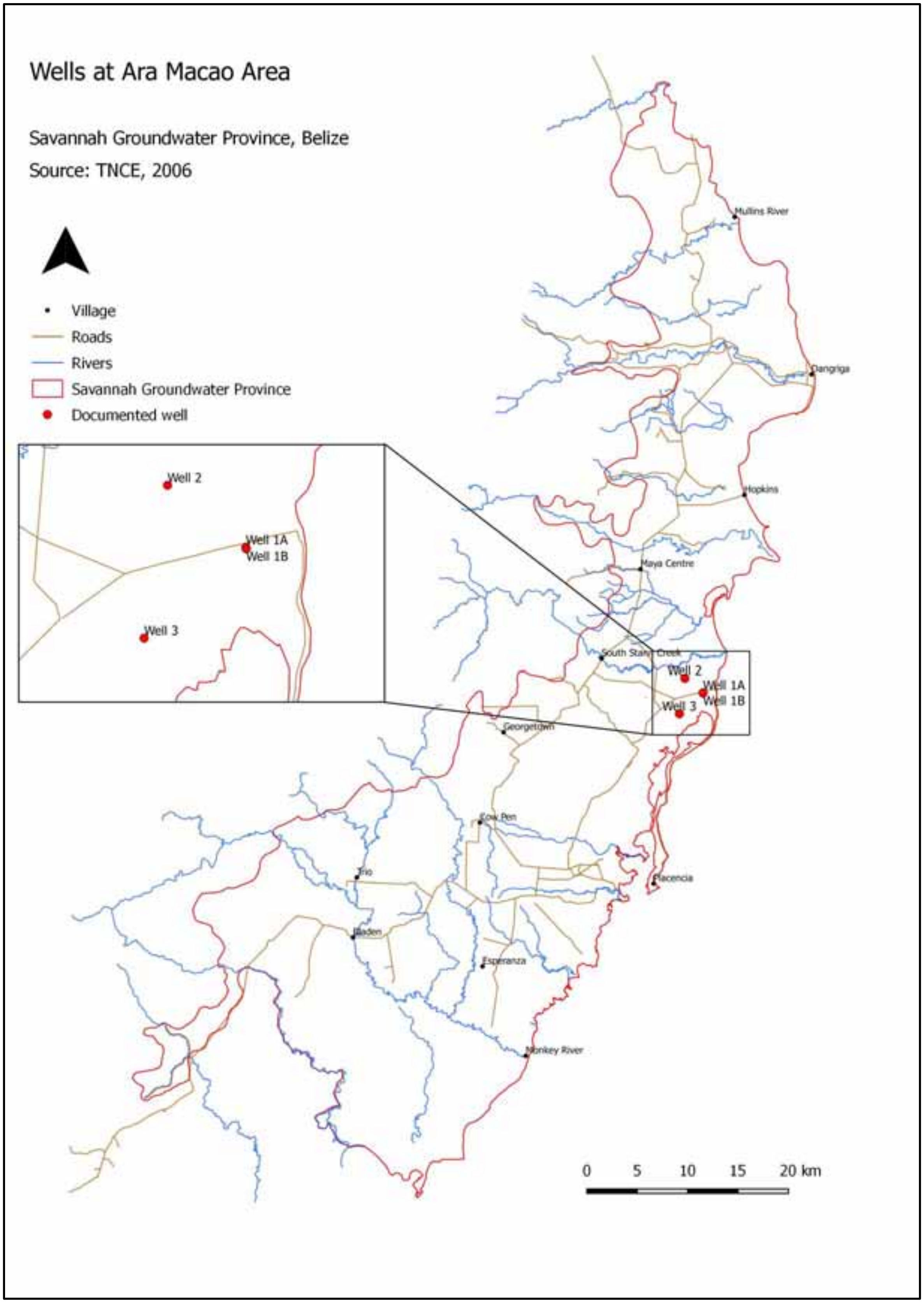
Map 9 Water sampling sites S1-S13 for detailed laboratory analysis at Bowen&Bowen, Ltd. laboratory.



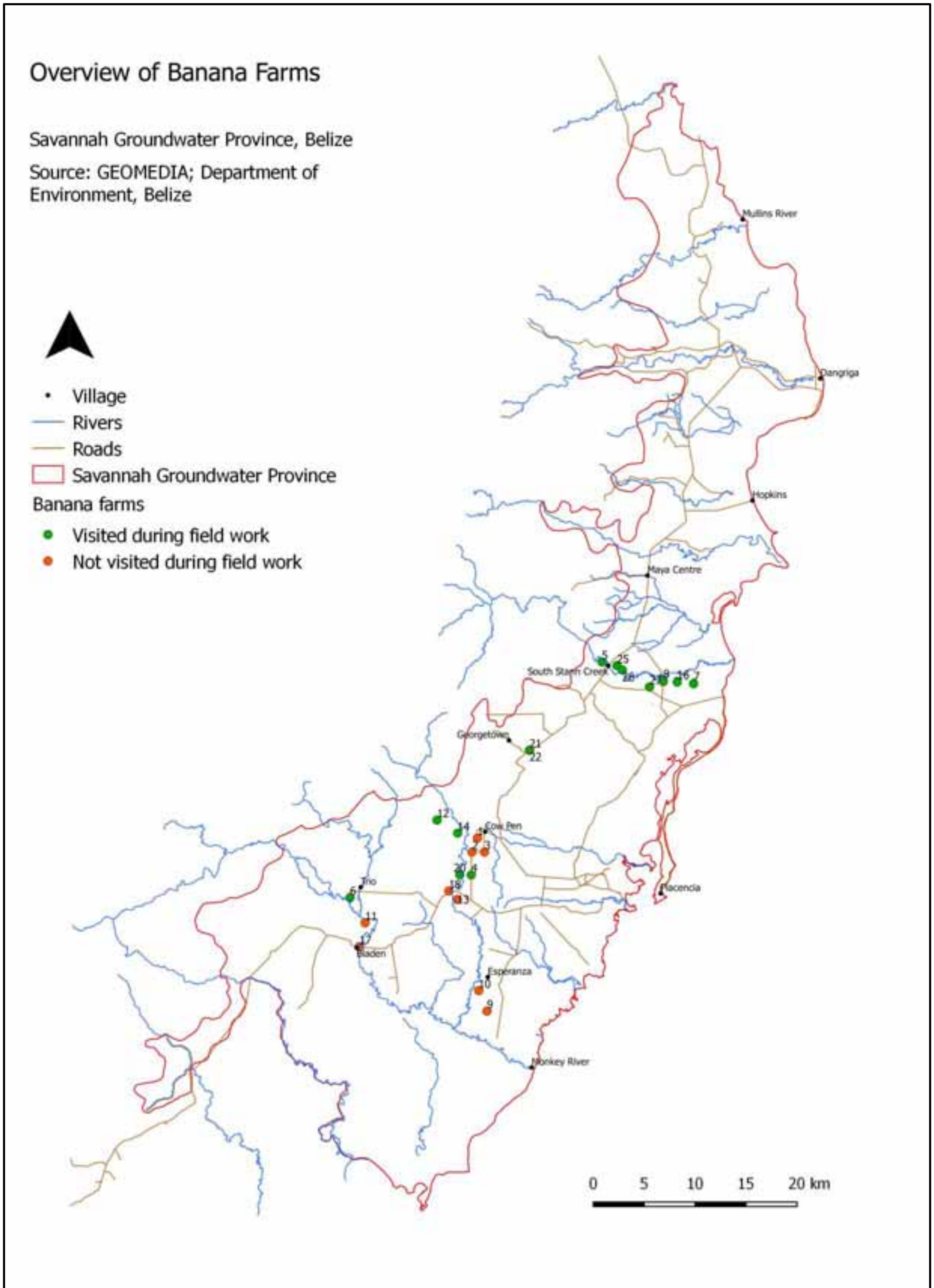
Map 10 Distribution of sites with water well log data, Department of Rural Development



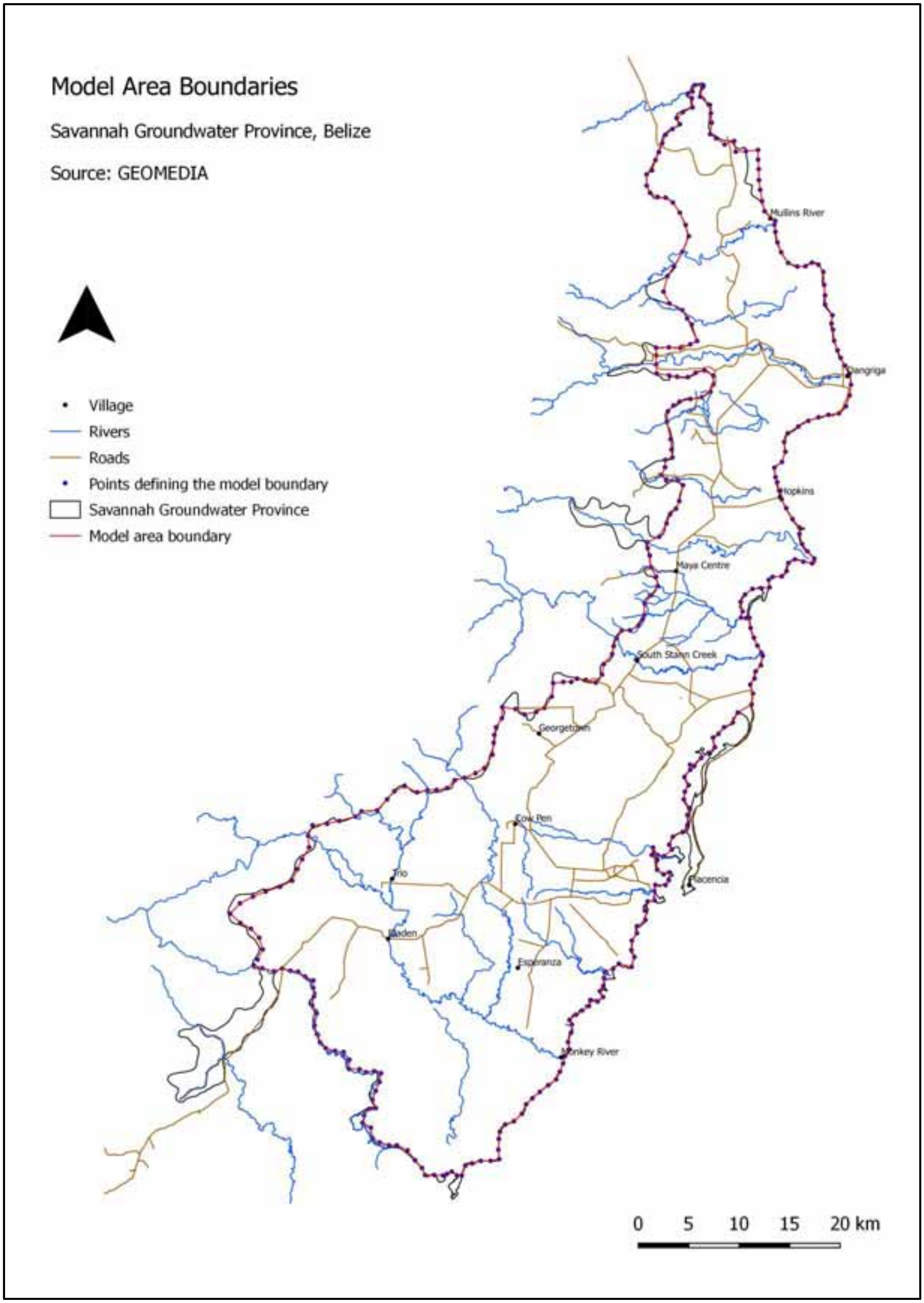
Map 11 Location of Ara Macao wells, TNCE, 2006.



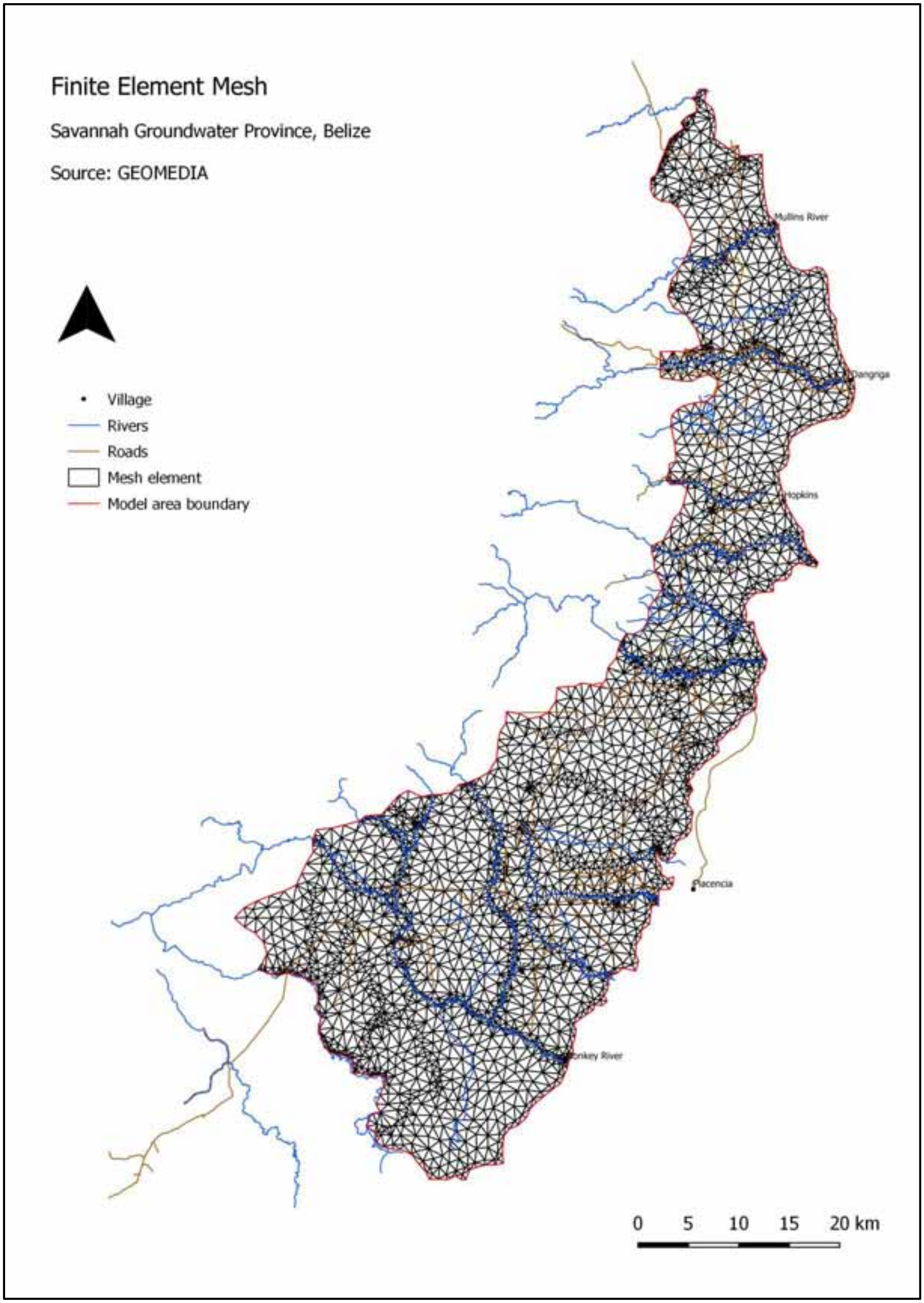
Map 12 Banana farms with identification of visited site during field work.



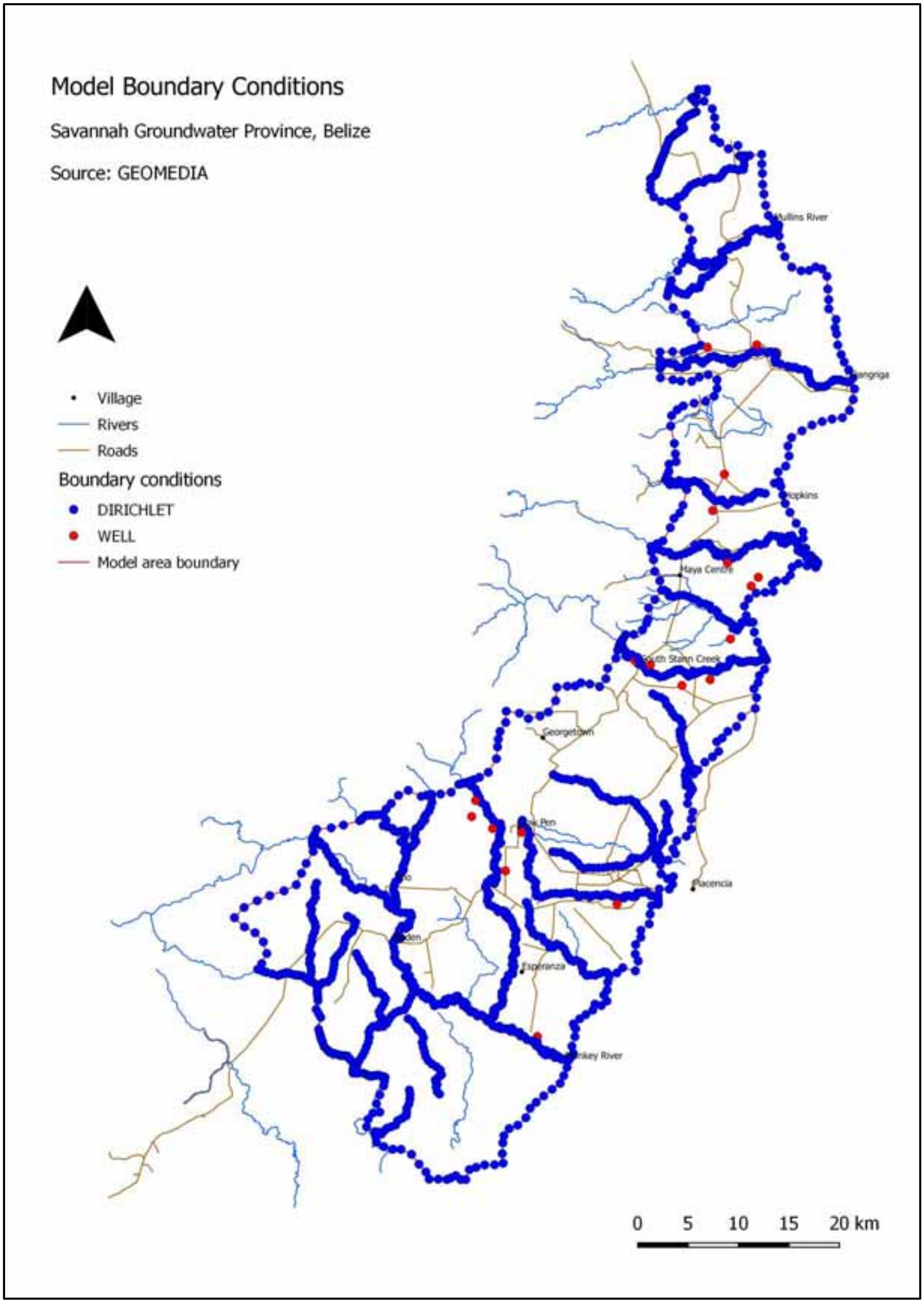
Map 13 Model area boundaries.



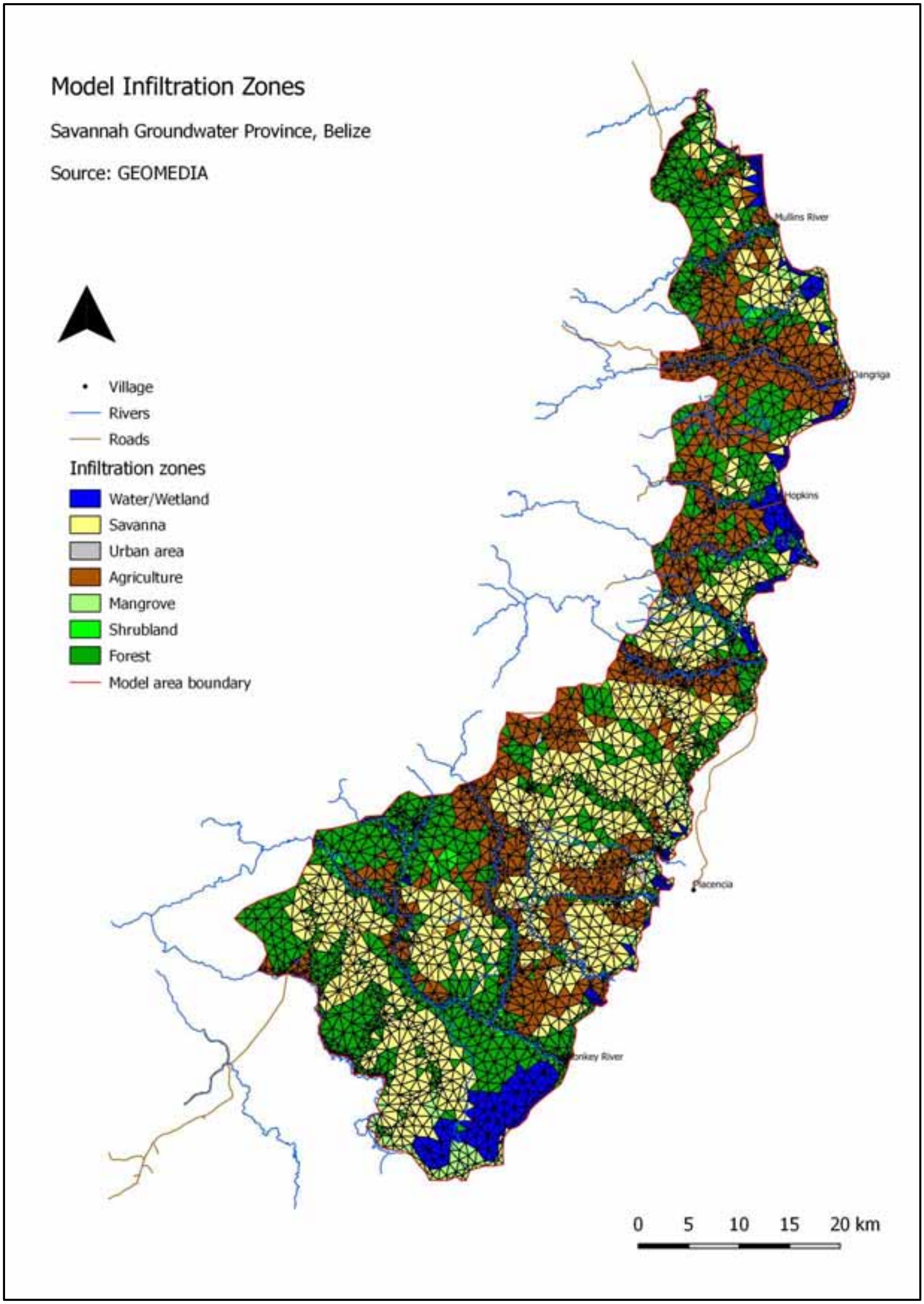
Map 14 Finite element mesh of model.



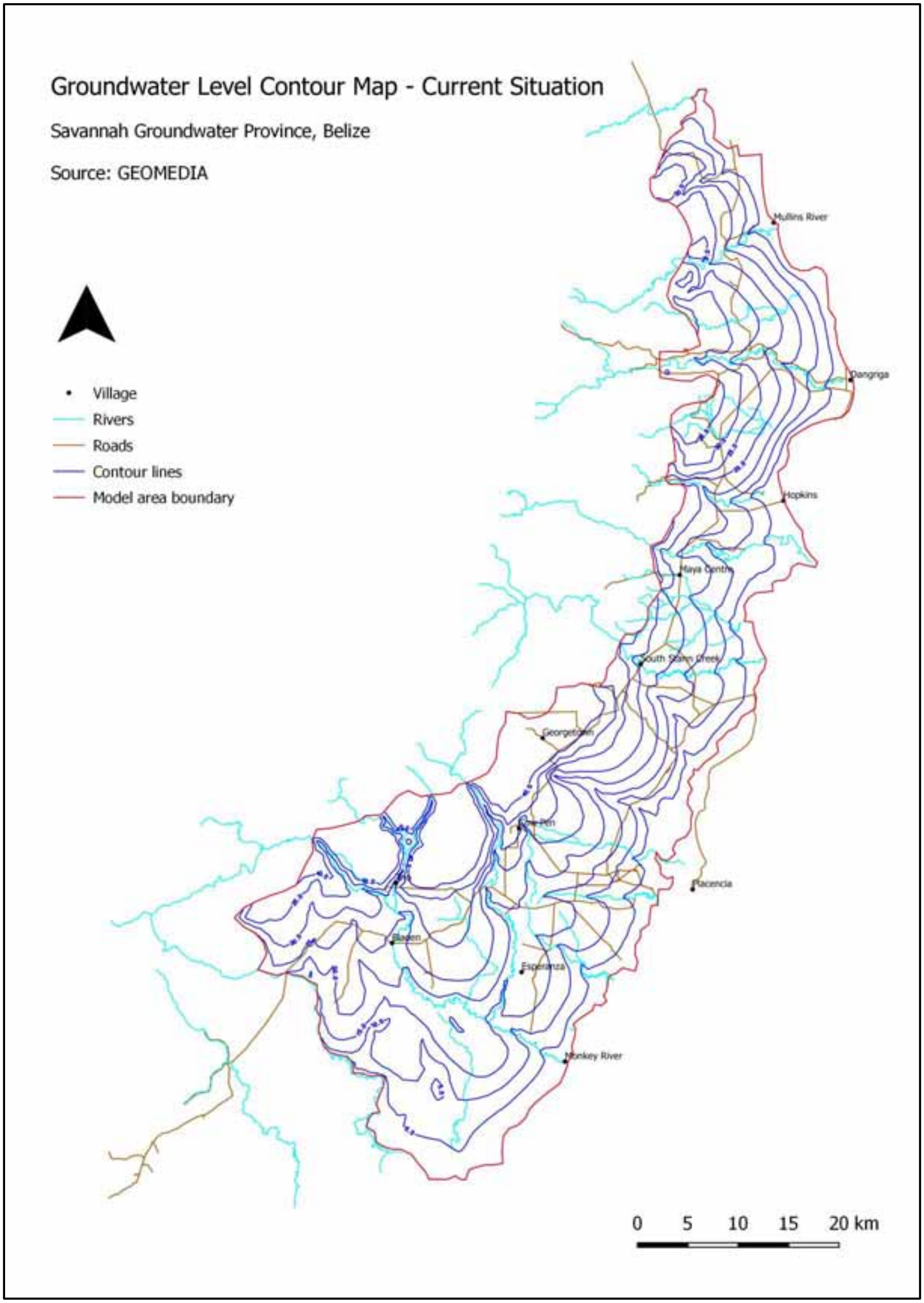
Map 15 Model boundary conditions.



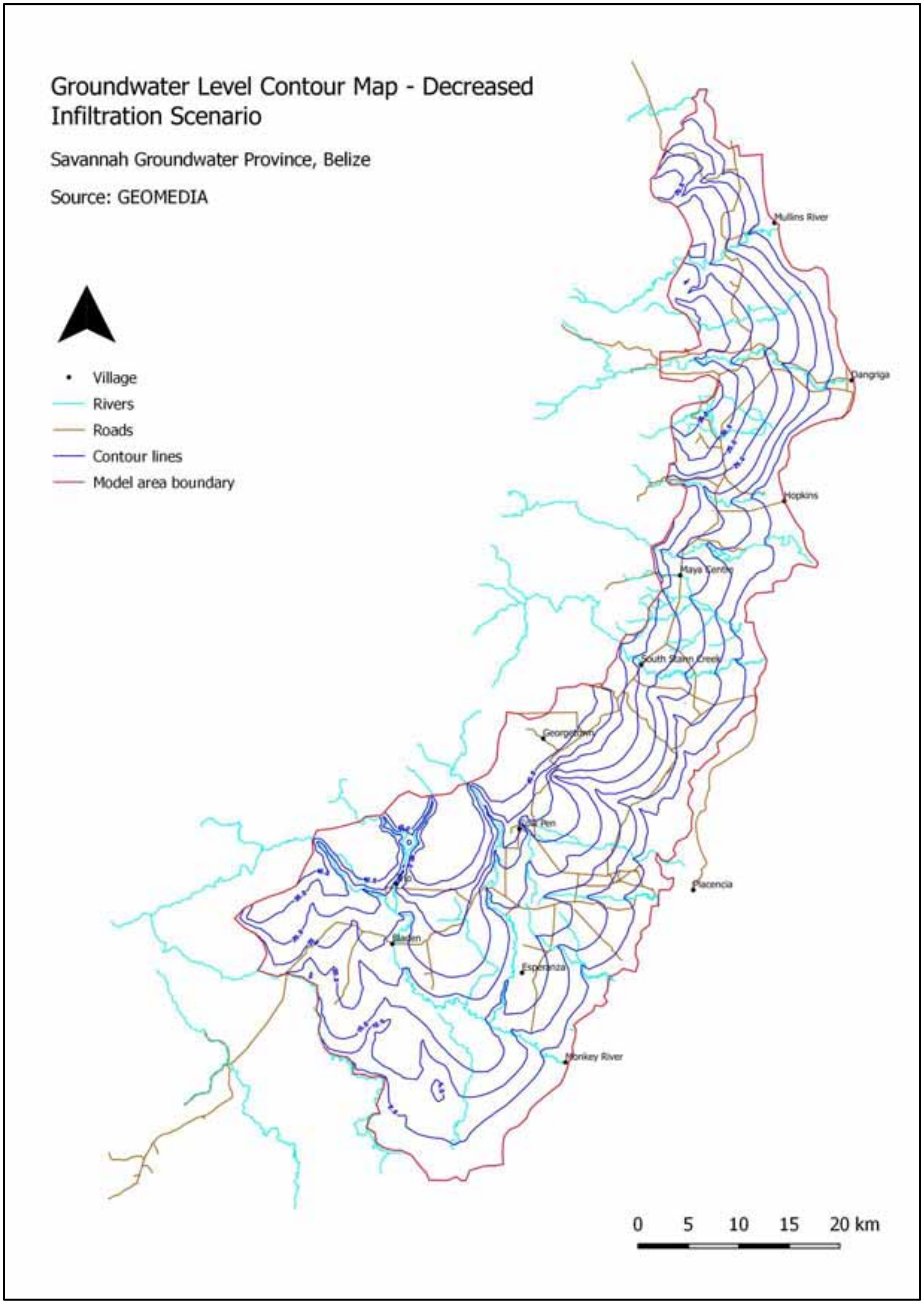
Map 16 Model infiltration zones based on different ecosystem characteristics.



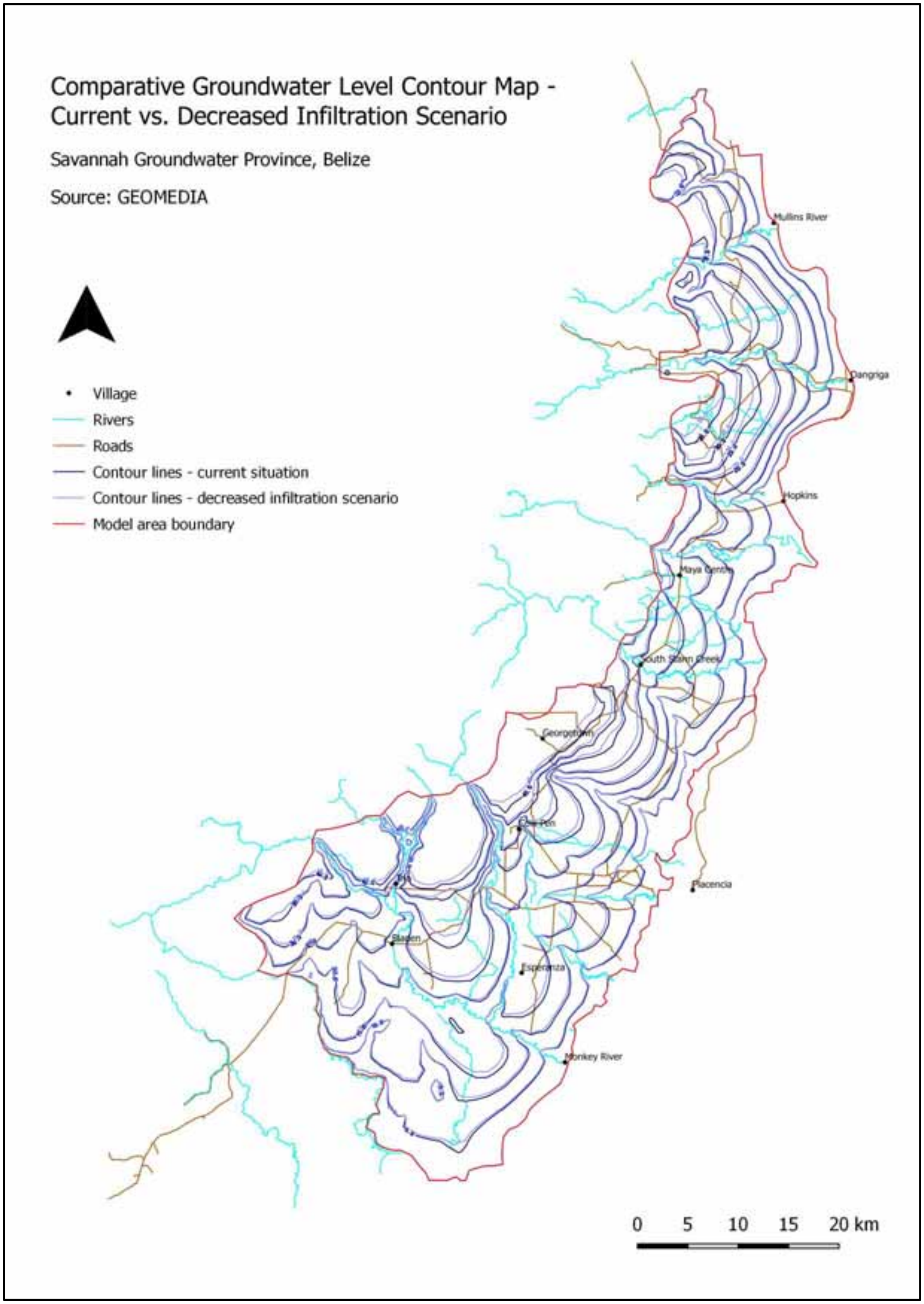
Map 17 Groundwater level contour map – current situation.



Map 18 Groundwater level contour map with decreased infiltration.



Map 19 Comparative groundwater level contour map.



Annex 3

Statistics of Existing Chemistry Data

Table 1 Statistics for Stann Creek District chemistry data, PUC

	pH	TDS	Iron	Fluoride	Chloride	Hardness	Nitrate	Sulphate	Depth	Yield
	-	ppm	ppm	ppm	ppm	ppm	ppm	ppm	m	L/min
Minimum	6.00	26.00	0.75	0.07	10.00	25.60	0.88	0.50	19.22	10.04
Maximum	8.20	26.00	2.60	0.40	17.00	356.00	1.10	10.00	61.00	150.07
Median	6.55	26.00	1.43	0.31	13.50	37.65	1.00	1.26	24.40	66.45
Mean	6.83	26.00	1.59	0.26	13.50	114.23	0.99	3.26	34.38	73.25
Standard deviation	0.84	0.00	0.76	0.14	3.17	139.78	0.09	3.93	17.78	59.87

Table 2 Statistics for Stann Creek District chemistry data, Ministry of Health.

	pH	Conductivity	TDS	Turbidity	Iron	Chloride	Hardness	Alkalinity	Nitrate	Phosphate	Sulphate
	-	uS/cm	ppm	ntu	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Minimum	5.18	29.90	14.60	0.25	0.01	1.00	3.00	2.00	0.60	0.06	1.00
Maximum	9.25	1380.00	689.00	230.00	3.50	406.00	284.00	216.00	5.50	0.08	3800.00
Median	6.70	84.60	41.50	1.82	0.11	10.45	28.50	24.00	1.50	0.07	3.24
Mean	6.76	198.22	98.02	9.99	0.37	31.09	57.13	49.90	1.75	0.07	304.50
Standard deviation	0.93	244.94	122.03	29.09	0.64	60.34	64.11	51.54	0.93	0.01	899.08

Table 3 Statistics for Toledo District chemistry data, Ministry of Health.

	pH	Conductivity	TDS	Turbidity	Iron	Chloride	Hardness	Alkalinity	Nitrate	Sulphate
	-	uS/cm	ppm	ntu	ppm	ppm	ppm	ppm	ppm	ppm
Minimum	5.20	68.40	34.00	0.42	0.02	1.00	25.00	63.90	1.10	1.00
Maximum	7.95	635.00	317.00	35.60	0.43	100.00	405.00	292.00	8.10	10.80
Median	7.40	459.50	229.00	1.44	0.04	6.00	172.95	152.90	1.40	3.00
Mean	7.21	419.94	209.60	4.84	0.09	16.22	195.28	186.57	2.37	3.16
Standard deviation	0.72	179.94	89.78	10.29	0.13	29.89	102.31	78.89	2.21	2.85

Table 4 Statistics for chemistry data from groundwater wells, Belize Aquaculture Ltd.

	pH	Conductivity	TDS	Turbidity	Iron	Chloride	Hardness	Alkalinity	Nitrate	Nitrite	Salinity	Sulphate	Total chlorine	Free chlorine
	-	uS/cm	ppm	ntu	ppm	ppm	ppm	ppm	ppm	ppm	ppt	ppm	ppm	ppm
Minimum	3.94	24.40	12.00	1.10	0.00	0.00	4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	7.63	3520.00	1780.00	17.80	1.48	1469.00	480.00	166.00	3.80	0.29	3.00	63.86	5.14	5.25
Median	5.89	87.40	42.00	3.70	0.06	5.65	32.00	12.00	0.60	0.00	0.00	3.62	0.00	0.00
Mean	5.89	385.90	182.49	5.02	0.19	56.80	80.88	18.44	1.00	0.01	0.17	8.80	0.07	0.07
Standard deviation	0.75	644.24	315.52	3.59	0.28	213.19	97.48	26.83	0.92	0.04	0.55	14.11	0.60	0.61

Table 5 Statistics for chemistry data from surface water, Belize Aquaculture Ltd.

	pH	Temperature	DO	Conductivity	Alkalinity	Nitrate	Nitrite	Sulphate
	-	°C	ppm	uS/cm	ppm	ppm	ppm	ppm
Minimum	6.73	23.90	5.44	178.50	0.00	0.00	0.00	1.00
Maximum	8.42	28.30	7.95	602.00	44.00	0.30	0.01	14.00
Median	7.07	26.00	6.45	375.00	17.00	0.20	0.00	6.00
Mean	7.25	26.12	6.56	380.50	16.55	0.15	0.00	6.36
Standard deviation	0.56	1.35	0.74	157.35	10.79	0.12	0.00	4.44

Table 6 Average values of chemistry data for BAL groundwater wells and BAL surface water sampling point, Belize Aquaculture Ltd.

Site	pH	Conductivity	TDS	Turbidity	Iron	Chloride	Hardness	Alkalinity	Nitrate	Nitrite	Salinity	Sulphate	Total chlorine	Free chlorine
	-	uS/cm	ppm	ntu	ppm	ppm	ppm	ppm	ppm	ppm	ppt	ppm	ppm	ppm
Well # 1	5.75	1282.93	601.87	4	0.34	227.19	185.4	13.53	0.35	0	0.6	32.06	0	0
Well # 2	5.78	447.39	206.8	3.69	0.07	29.73	76.47	25.13	0.97	0	0.2	6.64	0	0
Well # 3	5.79	39.84	19.15	4.06	0.05	9.62	50.23	28.15	0.42	0	0	1.16	0	0
Well # 4	6.12	45.34	21.19	9.05	0.38	4.21	42.38	16.81	0.71	0.01	0	2.88	0.32	0.33
Well # 5	6.05	92.64	42	4	0.06	3.76	46.07	10.33	2.45	0.03	0	2.43	0	0
Surface water	7.246	380.5						16.55	0.15	0		6.36		

Annex 4

Well Documentation – HGE-1

Document 1 Well Drilling Permit – Forest Department

FOREST DEPARTMENT

Ministry of Forestry, Fisheries and Sustainable Development
Forest Drive, Belmopan, Belize
Tel: (501) 822-1524 • Fax: (501) 822-1523
Email: secretary.fd@ffsd.gov.bz

Please Quote
Ref. No. CD/60/3/14(39)

Jason Fisher
GEOMEDIA Ltd.
Hornokrcska 707 714000 Parague 4
Czech Republic

June 16th, 2014

SCIENTIFIC COLLECTION/RESEARCH PERMIT
WILDLIFE PROTECTION ACT NO. 14/2000

Permission is hereby granted to the above-named and addresses to do **Research/Collection** in the country of Belize subject to the following conditions:

1. The permit is:
   a) Valid for **Jason Fisher.**
   b) Valid until **September 30th, 2014**

2. This permit provides research/collection to be done in: **Deep River Forest Reserve.**

3. The permit allows the holders to do research entitled: **Assessment of Groundwater Resources in the Southern Coastal Water Province of Belize Referred to as Savannah Groundwater Province.**

4. The objective of the research is: to support the Government of Belize, Ministry of Natural Resources and Agriculture in completing an assessment of Belize's ground water resources in the Savannah Groundwater Province in the face of increasing demand for water resources in growing urban, touristic and agricultural areas requiring access to safe, adequate and reliable water supplies.

5. This permit provides for the following: the drilling of two hydro geological well only.

6. The permit holder must supply the Forest Department with **both digital and hard copies of final reports at the end of the Project.**

7. This permit may be cancelled at anytime not withstanding condition 1(b) above at the discretion of the Minister of Forestry, Fisheries and Sustainable development.

9. The permit holder shall make provisions to accommodate Forest Department Staff on field trips as Convenient to both parties.

10. Research fee has been paid vide Treasury Receipt No 1158631 dated June 17th 2014

Wilber Sabido
Chief Forest Officer

Companions List

Dr. Michal Stibitz
Dr. Hana Jirakova
Vaclav F

Cc: CFO

Document 2 Well Drilling Report – HGE-1

Attention: GEOMEDIA Ltd. Date: August 16, 2014
From: Jason Fisher
Subject: Deep River Forest Reserve (Belize) Well Report

Location

The Deep River Forest Reserve is located in the district of Toledo, Belize south east of the Maya Mountains. It covers approximately 67291.5 Acres/ 27232 Hectares. The reserve in within the Savannah Groundwater Province and is a part of the Deep River watershed (Figure 1). The site is located approximately 150 m from the Deep River on a fluvial terrace.

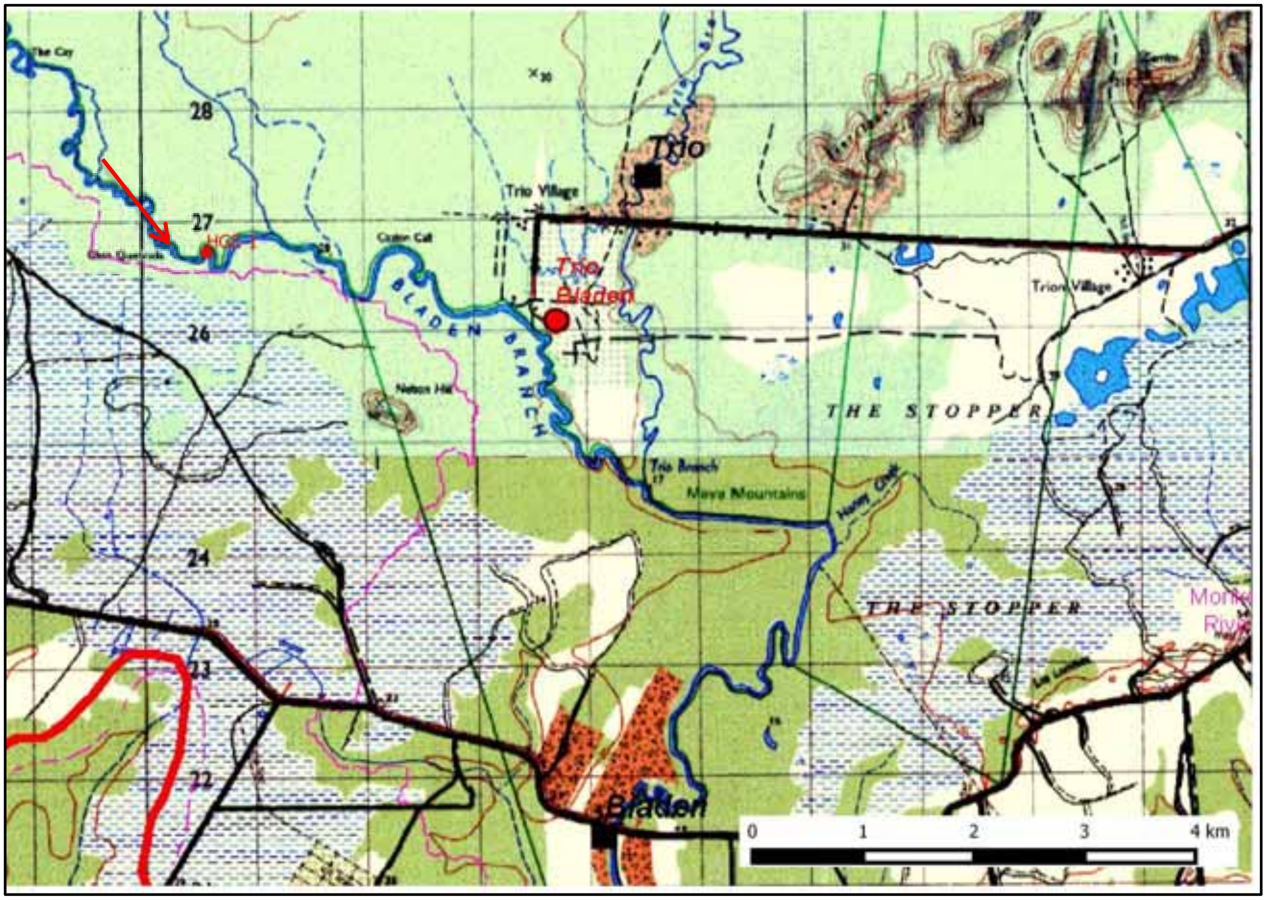


Figure 1: Location of HGE-1 Deep River Forest Reserve Well

Equipment and process

The Department of Rural Development was contracted to carry out the drilling for the Deep River Forest Reserve Well. The department utilizes a truck mounted 760 hp rig capable of drilling up to 400 ft. A rotary bit (9 inches ; 9 and ¾ inches) is utilized for soft material and a hammer bit (8 and 7/8th) for hard indurated rock. This unit is accompanied by a support truck unit which holds up to 1000 gallons of water used to supply the rig (Figure 2).

During drilling, 70 ft of soft clayey material was encountered creating the need for steel casing. Here, 4 black steel casings were utilized so that drilling could proceed and to prevent the collapse of the bore.

Well casings blanks and screens were utilized after the completion of the hole. Approximately 100 ft. of casing screens were utilized for the observed water bearing zone. Casing blanks were utilized for the remaining zones i.e. 160 ft (Figure 3, Figure 5).

After completion of the well bore it was then gravel packed and cemented (Figure 4).

Figure 2: A- Drill rig alongside Support truck; B- Drig rig set up to commence bore

Figure 3: A gravel packing of completed bore: B – completed HGE1 bore

Figure 4: A – PVC well casing blanks and screens utilized for HGE1: B- installation of PVC casings

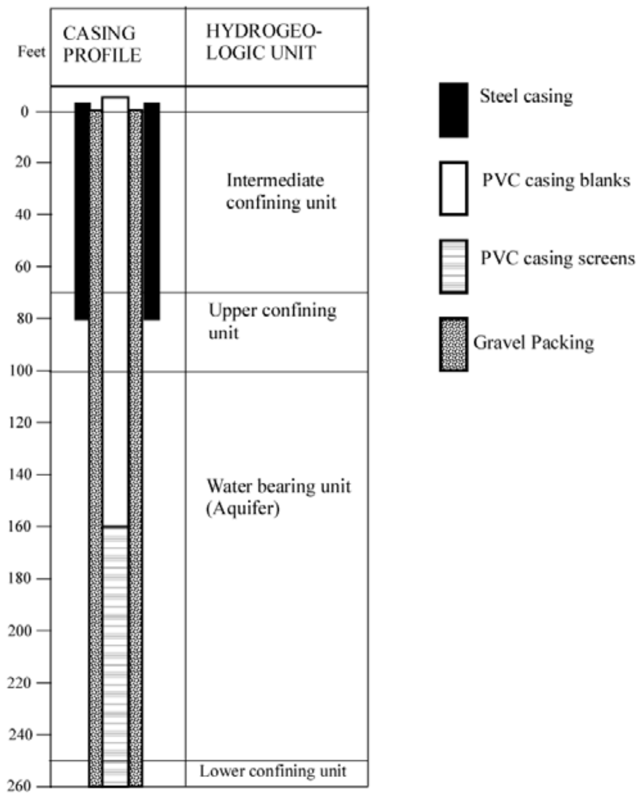


Figure 5: Well casing scheme

From the end of the bore casing is in the following order : 20 ft pvc blanks; 100 ft pvc casings: pvc blanks remainder of the hole.Casing-screens were at a depth of 160-260ft (Figure 5)

Well bore information and schedule

BORE INFORMATION	
Bore designation	HGE-1
Bore co-ordinates	16 320597 E 1826915 N
Total Depth	260ft/79m
DATE	**Activity**
July 15, 2014	Commence drilling of DR01 up to 120ft;
July 16, 2014	Payment of retrieval of steel casing, Spanish Lookout
July 17, 2014	Transportation of casing to DR01 site
July 18, 2014	Sample review and descriptions
July 19, 2014	Putting down and welding of steel casing
July 20, 2014	Resume and complete drilling at 260ft. Installing of casings (blanks and screens)
July 21, 2014	Gravel packing and cementing of the well
July 22- 24, 2014	Sample descriptions, photo-documentation and report writing.
August 13 -17,2014	Hydraulic pump testing

Geological Profile

Methods

In order to determine the geological profile, chippings were collected during drilling at every 10ft or wherever there was an obvious change in the lithology. The chippings were washed over a brass/stainless #230 sieve and then dried. They were identified using an Amscope binocular microscope coupled with other basic geological tools including hand lens and dilute HCI. The Wentworth grain size chart was used when necessary. Where carbonates were encountered they were described using either Folk's (1959) or the Dunham (1962) classification or a combination of both.

Geological Profile

A detailed geological log and a generalised stratigraphic and hydrogeologic section and has been produced for the HGE-1 well (Figures 13-14)

Throughout the bore 4 major units have been identified not including the top soil and the alluvium unit.

Calcarenite – Yellow brown sandy limestone with whole foraminifera and foraminifera fragments. This unit exhibits what appears to be oil staining at the depth of 120 ft. (Figure 6).

Figure 6: Calcarenite from HGE1

Mudstone – two mudstone units were identified namely a greenish gray calcerous unit and a dark gray calcareous unit. Both units show signs of foraminifera. The contrast of colours has to do with the amount of organic content within each unit. However the greenish gray colour may indicate the presence of iron coatings with partially reduced iron, also showing pyritization of some organic matter. These units act as 'confining layers' (Figures 7-8).

Figure 7: Greenish Gray calcareous mudstone unit identified in HGE1

Figure 8: Dark Gray calcareous mudstone unit

Conglomeratic limestone – the conglomeratic limestone unit was encountered up to four times with some slight variations. Generally the unit varies in colour and possesses micritic limestone and wackestone/packstone with volcaniclastic pebbles up to 1cm in length. Some broken pebbles are observed. Some units have a dark argillaceous lime mud with organic matter and that acts as a matrix with pebbles of lime clasts (Figure 9-11).

Figure 9: Conglomeratic limestone unit in HGE1 showing volcaniclastic pebbles

Figure 10: Conglomeratic unit with broken rounded pebbles and dark coloured lime mud

Figure 11: Conglomeratic limestone with rounded pebbles and wackestone/packstone

Wackestone/packstone – This unit is white and consists of non-sketelal grains including ooids, peloids and intraclasts, with sketelal grains namely foraminifera and fragments of mollusca. Some dissolution features are observed namely vugs (Figure 12).

Figure 12: Wackestone/packstone unit HGE1

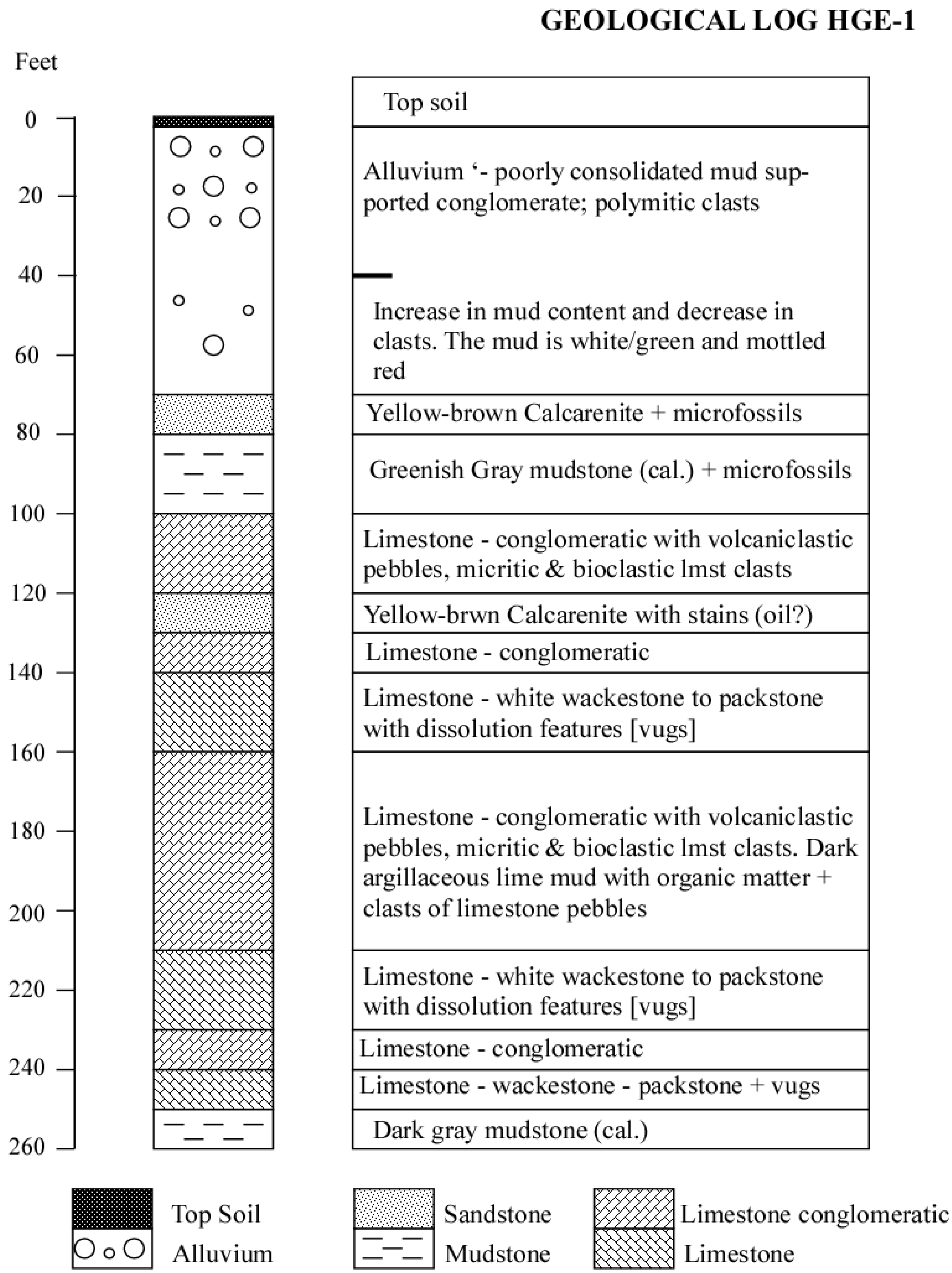


Figure 13: Detailed geological log of HGE1

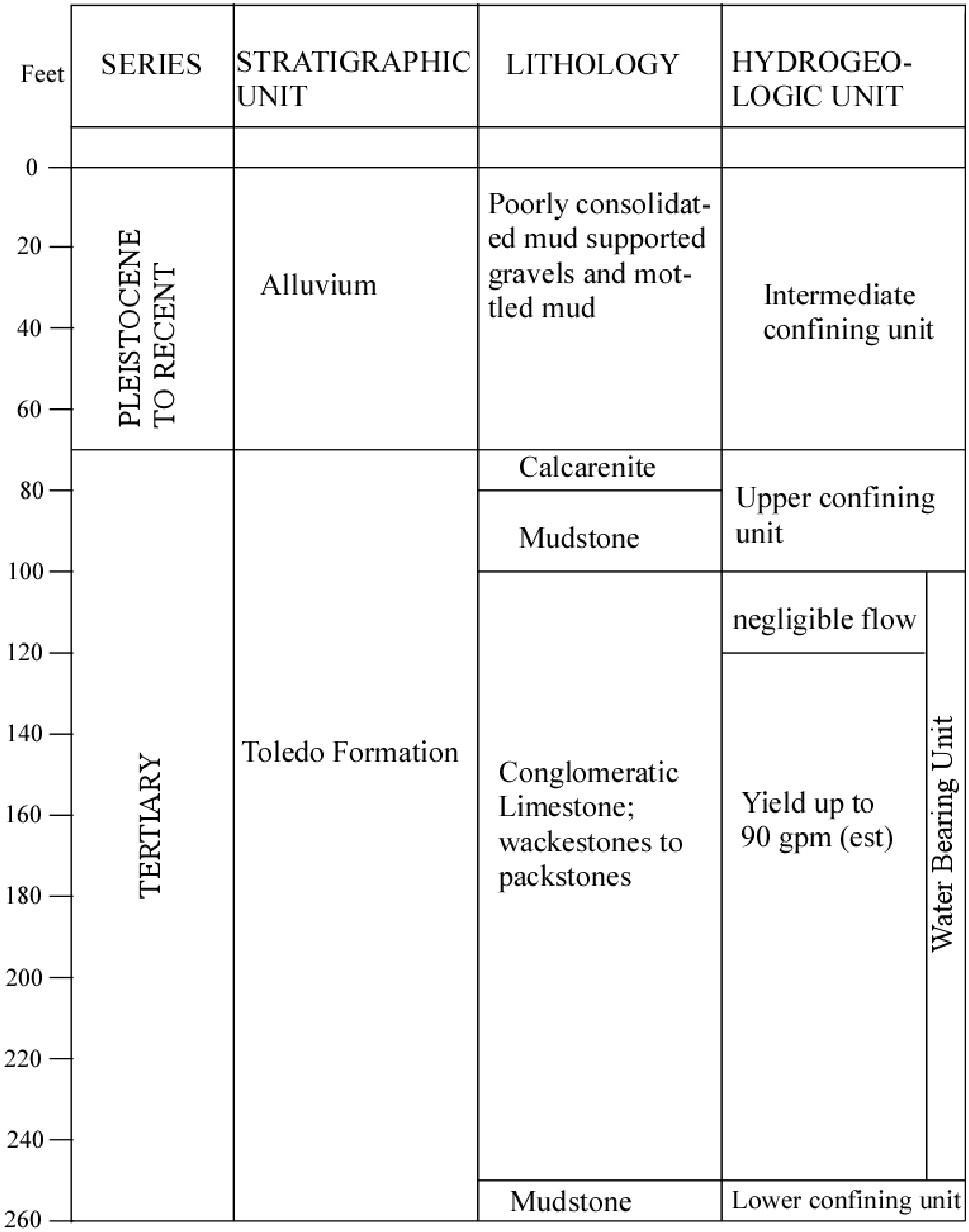


Figure 14: Generalised stratigraphic and hydrogeologic section of HGE1

Document 3 Well Hydraulic Testing Report – HGE-1

Attention: GEOMEDIA Ltd. Date: August 17, 2014
From: Jason Fisher
Subject: Deep River Forest Reserve (Belize) Well Report

Location

The Deep River Forest Reserve is located in the district of Toledo, Belize south east of the Maya Mountains. It covers approximately 67291.5 Acres/ 27232 Hectares. The reserve in within the Savannah Groundwater Province and is a part of the Deep River watershed. The site is located approximately 150 m from the Deep River on a fluvial terrace.

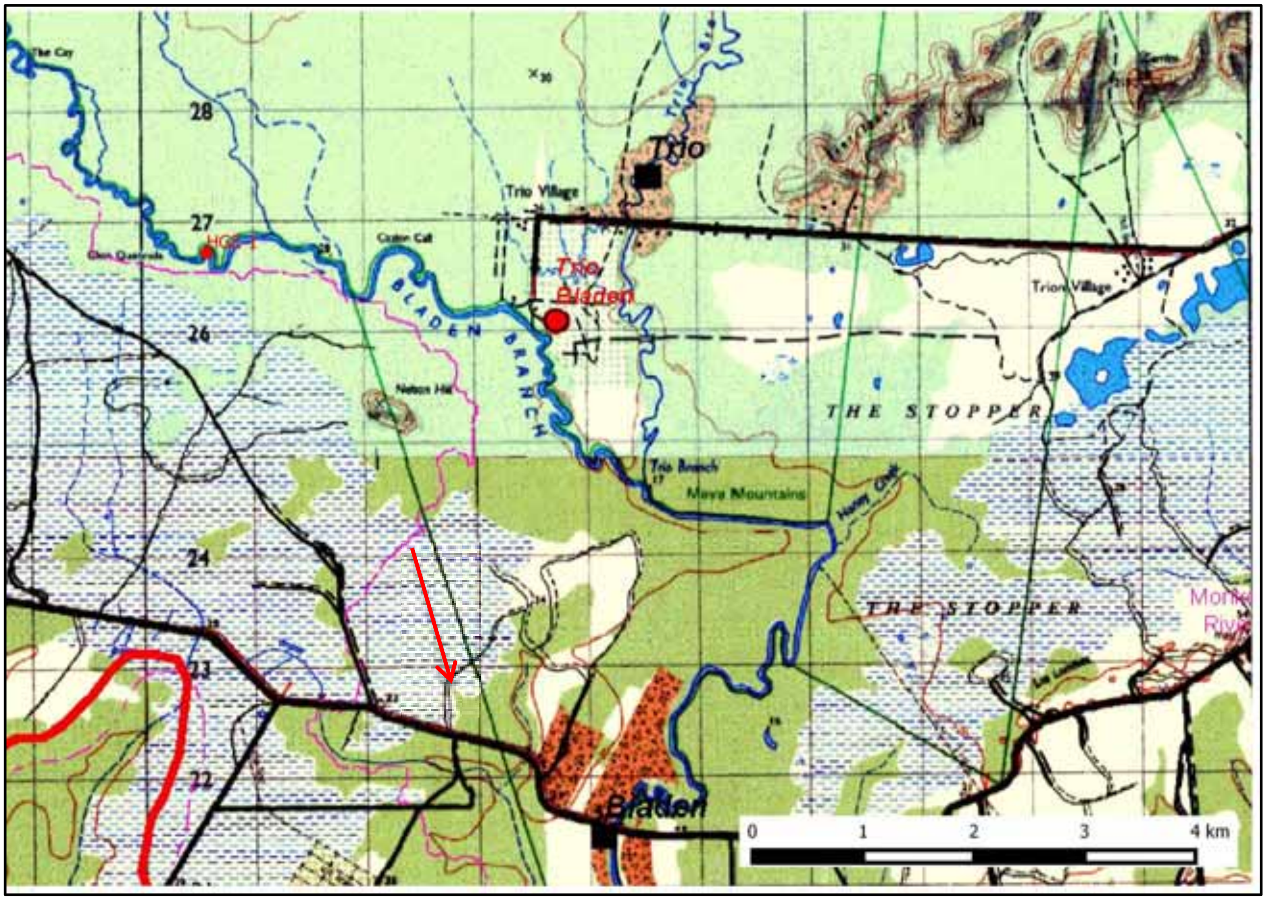


Figure 1: Location of HGE-1 Deep River Forest Reserve Well

Equipment and process

The Department of Rural Development was contracted to carry out the hydraulic pump testing for the HGE-1 well. A drill rig was used to install a 10hp submersible pump (Figure 3-4). The pump was powered by a diesel 400kw generator.

Figure 2: Submersible pump utilized for hydraulic testing of HGE-1

Figure 3: Rural Development crew setting up for hydraulic testing of HGE-1

Static water level was measured prior to the start of pumping and during the process in order to determine the rate of drawdown. Upon completion of hydraulic testing the time taken to return to the starting water level was observed (rate of recovery).

Flow rate (gallons per minute) was observed at different intervals throughout the test namely one minute intervals; 10 minute intervals; 30 minute intervals and hourly intervals. This was done using a flow meter (Figure 5).

Figure 4: Flow meter utilized during hydrualic testing of HGE1

Hydraulic Testing and schedule

BORE INFORMATION	
Bore designation	HGE-1
Bore co-ordinates	16 320597 E 1826915 N
Total Depth	260ft/79m
DATE	**Activity**
August 13, 2014	Commence constant rate hydraulic testing
August 14, 2014	constant rate hydraulic testing
August 15, 2014	constant rate hydraulic testing
August 16, 2014	constant rate hydraulic testing completion and recovery

Hydraulic Test Results :

START August 13,2014
END August 16, 2014

water level at start 38ft
rate of recovery following 72 hour pumping : 6 minutes

TIME	FLOW RATE (gpm)	GROUNDWATER TABEL LEVEL below surface(ft)	NOTES
12:20 odp.	140,00	57	
12:25 odp.	139,01	68	
12:30 odp.	134,00	80	reading taking every minute
12:31 odp.	124,24	80	
12:32 odp.	121,89	80	
12:33 odp.	119,55	80	
12:34 odp.	118,43	80	
12:35 odp.	120,04	80	
12:36 odp.	119,55	80	
12:37 odp.	120,09	80	
12:38 odp.	119,92	80	
12:39 odp.	120,04	80	
12:40 odp.	119,43	80	
12:41 odp.	119,92	80	
12:42 odp.	119,55	80	
12:43 odp.	119,80	80	
12:44 odp.	119,09	80	
12:45 odp.	120,04	80	
12:46 odp.	119,92	80	
12:47 odp.	120,28	80	
12:48 odp.	120,04	80	
12:49 odp.	120,16	80	
12:50 odp.	119,22	80	
12:51 odp.	119,31	80	
12:52 odp.	120,04	80	
12:53 odp.	119,32	80	
12:54 odp.	120,04	80	
12:55 odp.	119,55	80	
12:56 odp.	119,55	80	
12:57 odp.	119,92	80	
12:58 odp.	120,04	80	
12:59 odp.	119,92	80	
1:00 odp.	119,31	80	reading taking every 10 minutes

1:10 odp.	119,56	80	
1:20 odp.	119,43	80	
1:30 odp.	119,18	80	
1:40 odp.	118,58	80	
1:50 odp.	119,43	80	
2:00 odp.	106,78	80	
2:10 odp.	118,70	80	
2:20 odp.	119,06	80	
2:30 odp.	118,84	80	
2:40 odp.	118,94	80	
2:50 odp.	118,34	80	
3:00 odp.	118,70	80	
3:10 odp.	119,06	80	
3:20 odp.	118,94	80	
3:30 odp.	118,09	80	
3:40 odp.	118,22	80	
3:50 odp.	106,06	80	
4:00 odp.	118,07	80	reading taken every 30 mins
4:30 odp.	117,72	80	
5:00 odp.	117,97	80	
5:30 odp.	117,74	80	
6:00 odp.	117,04	80	
6:30 odp.	117,72	80	
7:00 odp.	118,70	80	
7:30 odp.	118,58	80	
8:00 odp.	118,70	80	
8:30 odp.	119,84	80	
9:00 odp.	118,34	80	
9:30 odp.	118,32	80	
10:00 odp.	119,58	80	reading taken every hour
11:00 odp.	119,55	80	
12:00 dop.	118,46	80	August 14, 2014; 12 hour mark
1:00 dop.	118,22	80	
2:00 dop.	118,46	80	
3:00 dop.	118,54	80	
4:00 dop.	118,34	80	
5:00 dop.	118,42	80	
6:00 dop.	118,10	80	
7:00 dop.	119,06	80	
8:00 dop.	119,55	80	
9:00 dop.	120,28	80	
10:00 dop.	120,77	80	
11:00 dop.	120,16	80	

12:00 odp.	120,52	80	
1:00 odp.	121,01	80	24 Hour Mark
2:00 odp.	121,26	80	
3:00 odp.	122,34	80	
4:00 odp.	122,10	80	
5:00 odp.	122,35	80	
6:00 odp.	122,72	80	
7:00 odp.	123,23	80	
8:00 odp.	122,22	80	
9:00 odp.	123,20	80	
10:00 odp.	122,19	80	
11:00 odp.	123,38	80	
12:00 dop.	122,54	80	
1:00 dop.	122,23	80	August 15,2014; 36 hour mark
2:00 dop.	121,62	80	
3:00 dop.	123,82	80	HGE-1 water sample collected
4:00 dop.	122,92	80	
5:00 dop.	122,92	80	
6:00 dop.	123,31	80	
7:00 dop.	121,90	80	
8:00 dop.	123,56	80	
9:00 dop.	122,92	80	
10:00 dop.	123,56	80	
11:00 dop.	122,91	80	
12:00 odp.	124,05	80	
1:00 odp.	123,56	80	48 hour mark
2:00 odp.	124,96	80	
3:00 odp.	124,91	80	
4:00 odp.	123,54	80	
5:00 odp.	123,81	80	
6:00 odp.	124,78	80	
7:00 odp.	123,93	80	
8:00 odp.	123,93	80	
9:00 odp.	123,45	80	
10:00 odp.	123,90	80	
11:00 odp.	123,44	80	
12:00 dop.	124,03	80	
1:00 dop.	123,56	80	August 16,2014; 60 hour mark
2:00 dop.	123,68	80	
3:00 dop.	123,09	80	
4:00 dop.	122,84	80	
5:00 dop.	122,96	80	
6:00 dop.	123,44	80	

7:00 dop.	124,48	80	
8:00 dop.	124,18	80	
9:00 dop.	123,93	80	
10:00 dop.	124,54	80	
11:00 dop.	124,54	80	
12:00 odp.	123,44	80	
12:20 odp.	123,93	80	72 hour mark

Annex 5

Proposed Operation Guidelines
-
Exploration and Monitoring Well

Annex 5: Proposed operation guidelines – exploration and monitoring well

Project: Enhancing Belize's Resilience to Adapt to the Effects of Climate Change – Assessment of Groundwater Resources in the Southern Coastal Water Province of Belize Referred to as Savannah Groundwater Province (referred to as the Project)

Guidelines for maintenance and operation of the HGE-1 well

1. In the framework of the abovementioned Project, GEOMEDIA Ltd. has completed a groundwater exploration and monitoring well HGE-1 in Deep River Forest Reserve, approx. 4.5 km from Trio Village on July 21, 2014.

2. The drilling was executed upon receipt of permit by the Forest Department, issued on June 17, 2014 (enclosure 2). The total well depth is 85 m (279 feet). The bore was completed on July 27, 2014 by PVC casing to the height of 0.63 m (25 inches) above land surface and appropriately secured by bore cap (photo in enclosure 3).

3. The reliable well yield of HGE-1 according to hydraulic tests completed by GEOMEDIA on August 17, 2014 exceeds 6 liters per second (95 gpm). This is well above the current water supply demand in the area.

4. The Forest Department (Ministry of Forestry, Fisheries and Sustainable Development), the Department of Rural Development (Ministry of Labour, Local Government and Rural Development) and the Chairman of Trio Village have been informed about the well location and execution of drilling works as well as hydraulic testing.

5. The HGE-1 well shall be the first monitoring well for the Savannah Province under government authority. NIWRA shall bear the authority and responsibilities for maitaining the well and coordinate the monitoring program among agencies of GOB.

6. The collected information is to be forwarded to the representative of GEOMEDIA in Belize for validation and further processed to national water well database. The adequate access to the well site is to be maintained by Deep River Forest Reserve.

7. The primary purpose of the well is to provide scientific data serving regional groundwater management. Under circumstances, the well may be temporarily used by the Trio Village or by the Deep River Forest Reserve to improve local water supply in the area. Such a use shall be a matter of technical approval by GEOMEDIA.

List of enclosures:
Enclosure 1: Topographic situation of the HGE-1 well
Enclosure 2: Permit by the Forest Department, Ministry of Forestry, Fisheries and Sustainable Development
Enclosure 3: HGE-1 well site upon the well completion

Enclosure 1: Topographic situation of the HGE-1 well

Enclosure 2: Permit by the Forest Department, Ministry of Forestry, Fisheries and Sustainable Development

FOREST DEPARTMENT

Ministry of Forestry, Fisheries and Sustainable Development
Forest Drive, Belmopan, Belize
Tel: (501) 822-1524 • Fax: (501) 822-1523
Email: secretary.fd@ffsd.gov.bz

Please Quote
Ref. No. CD/60/3/14(39)

Jason Fisher
GEOMEDIA Ltd.
Hornokrcska 707 714000 Parague 4
Czech Republic

June 16th, 2014

SCIENTIFIC COLLECTION/RESEARCH PERMIT
WILDLIFE PROTECTION ACT NO. 14/2000

Permission is hereby granted to the above-named and addresses to do **Research/Collection** in the country of Belize subject to the following conditions:

1. The permit is:
   a) Valid for **Jason Fisher**.
   b) Valid until **September 30th, 2014**.

2. This permit provides research/collection to be done in: **Deep River Forest Reserve.**

3. The permit allows the holders to do research entitled: **Assessment of Groundwater Resources in the Southern Coastal Water Province of Belize Referred to as Savannah Groundwater Province.**

4. The objective of the research is: to support the Government of Belize, Ministry of Natural Resources and Agriculture in completing an assessment of Belize's ground water resources in the Savannah Groundwater Province in the face of increasing demand for water resources in growing urban, touristic and agricultural areas requiring access to safe, adequate and reliable water supplies.

5. This permit provides for the following: the drilling of two hydro geological well only.

6. The permit holder must supply the Forest Department with **both digital and hard copies of final reports at the end of the Project.**

7. This permit may be cancelled at anytime not withstanding condition 1(b) above at the discretion of the Minister of Forestry, Fisheries and Sustainable development.

9. The permit holder shall make provisions to accommodate Forest Department Staff on field trips as Convenient to both parties.

10. Research fee has been paid vide Treasury Receipt No 1158631 dated June 17th 2014

Chief Forest Officer

Wilber Sabido
Chief Forest Officer

Cc: CFO
[illegible]

Companions List

Dr. Michal Stibitz
Dr. Hana Jirakova
Vaclav F
[illegible]

Enclosure 3: HGE-1 well site upon the well completion

Annex 6

Proposed Operation Guidelines
-
Water Management Database

Annex 6: Proposed operation guidelines – Water Management Database

Project: Enhancing Belize's Resilience to Adapt to the Effects of Climate Change – Assessment of Groundwater Resources in the Southern Coastal Water Province of Belize Referred to as Savannah Groundwater Province (referred to as the Project)

Guidelines for maintenance and operation of the Water Management Database – Savannah Province

1. In the framework of the abovementioned Project, GEOMEDIA Ltd. has completed a Water Management Database (*referred to as the Database*), integrating multitude of data from the fields of geology, hydrogeology and hydrochemistry.

2. The purpose of the Database is to provide information for integrated and coordinated regional water management by governmental, public and private organizations. Further purpose of the Database is to provide data for scientific and research purposes.

3. The original source data records were provided by a number of agencies and departments of GOB (enclosure 1). Further data were acquired in the field by GEOMEDIA in the framework of the abovementioned project.

4. The original source data are processed and validated by qualified personnel of GEOMEDIA. The processed data are stored in the Well Management Database using Microsoft Office Excel package.

5. The data are retrieved to be validated by environmental and geo-scientific statistical methods, and provide temporal and spatial information related to groundwater quantity and quality in the Savannah Province.

6. The Database is housed by NIWRA with several agencies such as Health, Rural Development, WASA and few others acting as nodes for data input.

7. GEOMEDIA shall provide adequate training for responsible personnel of involved agencies.

8. The Database shall be further maintained and developed by GEOMEDIA. GEOMEDIA shall provide yearly updates of the Database to UNDP, GOB and other partner organizations (enclosure 1) once yearly by April 1 of the following year.

9. The partner organizations listed in the enclosure 1 shall provide the relevant data collected by them in raw format, such as drilling, hydraulic testing or laboratory protocols during a calendar year by February 1 of the following year.

List of enclosures:
Enclosure 1: Overview of Well Management Database partner organizations - Authorities, Agencies and other organizations providing exchanging data with the Database

Enclosure 1: Overview of Well Management Database partner organizations - Authorities, Agencies and other organizations providing exchanging data with the Database

Authorities, Agencies and other organizations	**Provided Data**
National Meteorological Service, Hydrology Unit	• Continuous record of precipitation • Continuous record of temperatures • Information on evaporation and transpiration • Data on stage levels in Monkey and Sittee Rivers, discharges / flow rates
Public Health Bureau, Ministry of Health	• Chemical analysis of groundwater including date of sampling, well identification • Chemical analysis of surface water including date of sampling, identification of sampling sites
Geology and Petroleum Department, Ministry of Energy, Science & Technology and Public Utilities	• Well log profiles including complete record of measurements (resistivity, temperature, lithology etc.) for petroleum wells Monkey River – 1 / Susan -1 MR (S-1) • Documentation report for wells Monkey River-1 and Susan -1 • Well logs of San-Juan wells • Belize spatial data for GIS processing
Department of the Environment, Ministry of Forestry, Fisheries and Sustainable Development	• Environmental Impact Assessment Studies relevant for the Savannah Groundwater Province
Department of Rural Development, Ministry of Labour, Local Government and Rural Development	• Water well logs of Stan Creek and Toledo districts
Public Utilities Commission	• Daily precipitation, temperatures • Available chemical analyses • Report: Aquifer and pumping tests for Ara Macao wells near Riversdale, Stann Creek District • Report: The Savannah Groundwater Province Threats and Challenges
Belize Water Service Ltd.	• Available chemical analyses for 2 wells • Well yield information
Ministry of Agriculture and Fisheries	• An Irrigation Policy and Strategy for Belize • Agricultural Production Statistics for 2012
Banana farms	• Chemical analyses of irrigation water from 19 banana farms
Belize Aquaculture Ltd.	• Chemical analyses for 5 wells (time series)

Annex 7

Proposed Operation Guidelines
-
Groundwater Model Savannah Province

Annex 7: Proposed operation guidelines – Regional Groundwater Simulation Model

Project: Enhancing Belize's Resilience to Adapt to the Effects of Climate Change – Assessment of Groundwater Resources in the Southern Coastal Water Province of Belize Referred to as Savannah Groundwater Province (referred to as the Project)

Guidelines for maintenance and operation of the Regional Groundwater Simulation Model – Savannah Province

1. In the framework of the abovementioned Project, GEOMEDIA Ltd. has elaborated the Regional Groundwater Simulation Model (*referred to as the Model*), based on the data integrated in the Water Management Database.

2. The purpose of the Model is to provide information for integrated and coordinated regional water management by governmental, public and private organizations. The Model was developed and calibrated by GEOMEDIA, using an internationally acknowledged software package FEFLOW (see Final Report by GEOMEDIA, August 2014).

3. The Model enables to test groundwater management scenarios, reflecting projects that are planned in the model domain and their groundwater extraction requirements.

4. The projects shall be subject to testing by the Model based on recommendation of GOB.

5. The Model shall be further maintained and developed by GEOMEDIA. GEOMEDIA shall provide ad hoc updates for individual projects submitted for assessment as well as yearly updates of the Model to UNDP and GOB at least once yearly by April 1 of the following year.