Groundwater Exploration and Assessment in the Republic of Costa Rica

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Restricted-File Federal Interagency Report

Photograph by Wayne R. Belcher, U.S. Geological Survey

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We would also like to give a special acknowledgement and thanks to the Water Directorate staff and the members of the Technical Working Group for their enthusiasm and contributions in this work.

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)

Datum

Horizontal coordinate information is referenced to the World Geodetic System (WGS84) projected in the Lambert Costa Rica North and Lambert Costa Rica South System.

Vertical coordinate information is referenced to the WGS84 Earth Gravitational Model (EGM 96) geoid for the Shuttle Radar Topographic Mission data.

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations

3-D	three-dimensional
AU	Aguacate unit
BASE	Basement unit
ET	evapotranspiration
ETg	groundwater evapotranspiration
HGU	hydrogeologic unit
HFM	hydrogeologic framework model
RTI	Radar Technology International
SED	sedimentary unit
SED-L	lower sedimentary unit
SED-U	upper sedimentary unit
SENARA	El Servicio Nacional de Aguas Subterráneas, Riego y Avenamiento
USGS	U.S. Geological Survey
VA-B	Bagaces Volcanic Aquifer
VA-L	Liberia Volcanic Aquifer
VOL	volcanic unit
VOL-L	volcanic lava unit
QSED	Quaternary sediment unit
WATEX	Groundwater Exploration System (remote sensing tool)
WGS84	World Geodetic System 1984

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Introduction

In 2015, the Republic of Costa Rica entered into an agreement with the U.S. Geological Survey (USGS) to assess the water resources of Costa Rica and to build capacity for further water resource investigations by Costa Rican geoscientists.

The study area covers 51,260 square kilometers (km^2)—the entire land area of the Republic of Costa Rica. The study consisted of four components:

- Component A–Remote Sensing Tool (WATEX)
- Component B–Hydrogeologic Assessment
- Component C–Optimization Assessment of Groundwater Development and Use, and
- Component D–Capacity Building and Technology Transfer

The remote sensing tool (WATEX), hydrogeologic assessment, and optimization assessment of groundwater development and use components are documented in the appendices. These documents are not USGS products, but rather products from collaborators. These products have been reviewed by the Technical Working Group that is composed of water professionals from several agencies and academia in Costa Rica. Additional review was completed by USGS project personnel.

Objectives and Scope

The partnership program with the USGS and Republic of Costa Rica has four components – remote sensing, hydrogeologic assessment, optimization assessment, and capacity building.

Component A–Remote Sensing Tool (WATEX)

The remote sensing tool (WATEX) is a proprietary algorithm that combines remotely sensed data collected by various satellites and ancillary data such as climatological, geologic, geomorphologic, hydrologic and hydrogeologic, and seismic and geophysical information, where available, to reveal areas of greater potential for productive groundwater supply. It is a cost-effective methodology that provides a rapid evaluation of groundwater resources for the purpose of enhancing resiliency to climate change and contributing to long-term planning and development. Analysis of the study results

(1) revealed productive aquifers suitable for multiple uses,

(2) contributed to long-term planning for agricultural and economic growth and development, and

(3) identified locations suitable for groundwater recharge that could be appropriate for the construction of micro-dams and irrigation projects.

The WATEX algorithm is used to assess potential additional groundwater sources and equip local water professionals with knowledge derived mostly from remotely sensed data. If developed and managed wisely, these additional water resources could improve livelihood, promote economic growth, and enhance resiliency to climate change.

Component B–Hydrogeologic Assessment

Although WATEX has proven to be effective in locating subsurface features that store groundwater, it cannot address issues such as long-term productivity and sustainability, and water quality; it cannot define deep aquifers buried under thick sedimentary deposits without using reflection seismic data to inform the remote sensing interpretation. Such characterization of groundwater resources requires the use of a ground-based hydrogeologic assessment. Preliminary regional-scale three-dimensional (3-D) models of the hydrogeology, potentiometric maps, and water budgets make up the hydrogeologic assessment.

Component C–Optimization Assessment of Groundwater Development and Use

Component C builds on the results of the remote sensing tool (WATEX) and hydrogeologic assessment. An optimization analysis of the sustainable water-use patterns of two priority areas were identified by the Technical Working Group. This optimization analysis examines the performance associated with various measures that maximize societal benefits of groundwater development and use with minimal negative impact to water availability and sustainability.

Component D–Capacity Building and Technology Transfer

Component D focused on formally training Costa Rican water professionals in groundwater field techniques and WATEX applications for water resources. The nature and subject of this training was determined in close consultation with the relevant Costa Rican agencies and conducted throughout the project.

Description of Study Area

Costa Rica is in Central America, situated between Nicaragua to the north and Panama to the south (Figure 1). The eastern coast is bordered by the Caribbean Sea and the western coast by the Pacific Ocean. The country has a surface of 51,370 km² and is divided into seven governing provinces.

Figure 1. Map showing location of Costa Rica (Central Intelligence Agency, 1987).

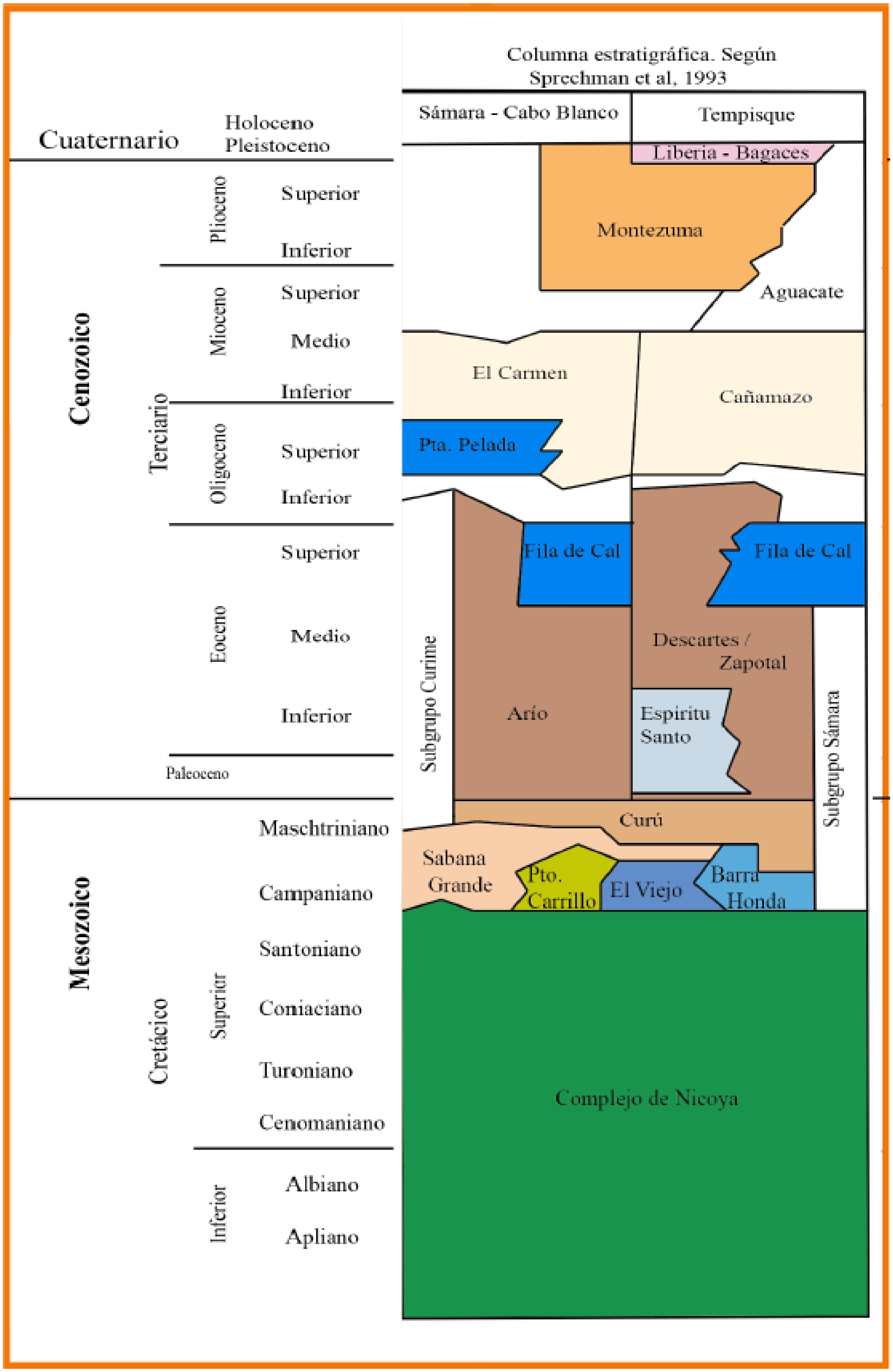
The country contains three main mountain ranges:

- The Guanacaste range in the north, which is composed of large volcanoes such as Rincon de la Vieja, Miravalles Tenorio, and Arenal
- The Central Volcanic Range, which includes the Poas, Barba, Turrialba, and Irazu volcanoes
- The Talamanca Range in the south, with the highest point of Costa Rica—the Cerro Chirripo, which rises to an altitude of 3,820 meters (m)

Geologic Setting (summarized from Radar Technology International [RTI], 2019)

The geologic history of Costa Rica starts from the deep-sea floor Pacific Ocean sediments, which were deposited approximately 65 million years ago and then compressed by the subduction of the Cocos Plate and uplifted over an elongated submarine volcanic ridge. This ridge emerged from the sea almost 5 million years ago as the Cordillera of Costa Rica. Since then, several phases of uplift activated by the subduction of the Cocos Plate have led to the progressive uplift of the mountain ranges. This uplift has separated the Guanacaste block (which contains the Tempisque watershed) in the north from the Talamanca block in the south, by the pull-apart zone of the Central Valley and the Tortuguero–Sarapiqui watershed. The uplift was accompanied by accelerated erosion that stripped most of the hydrologically important geologic units from marine and continental depositional environments in the central region of the country.

Stratigraphic columns for the Tempisque and Tortuguero–Sarapiqui watersheds are presented in Figure 2 and Figure 3.

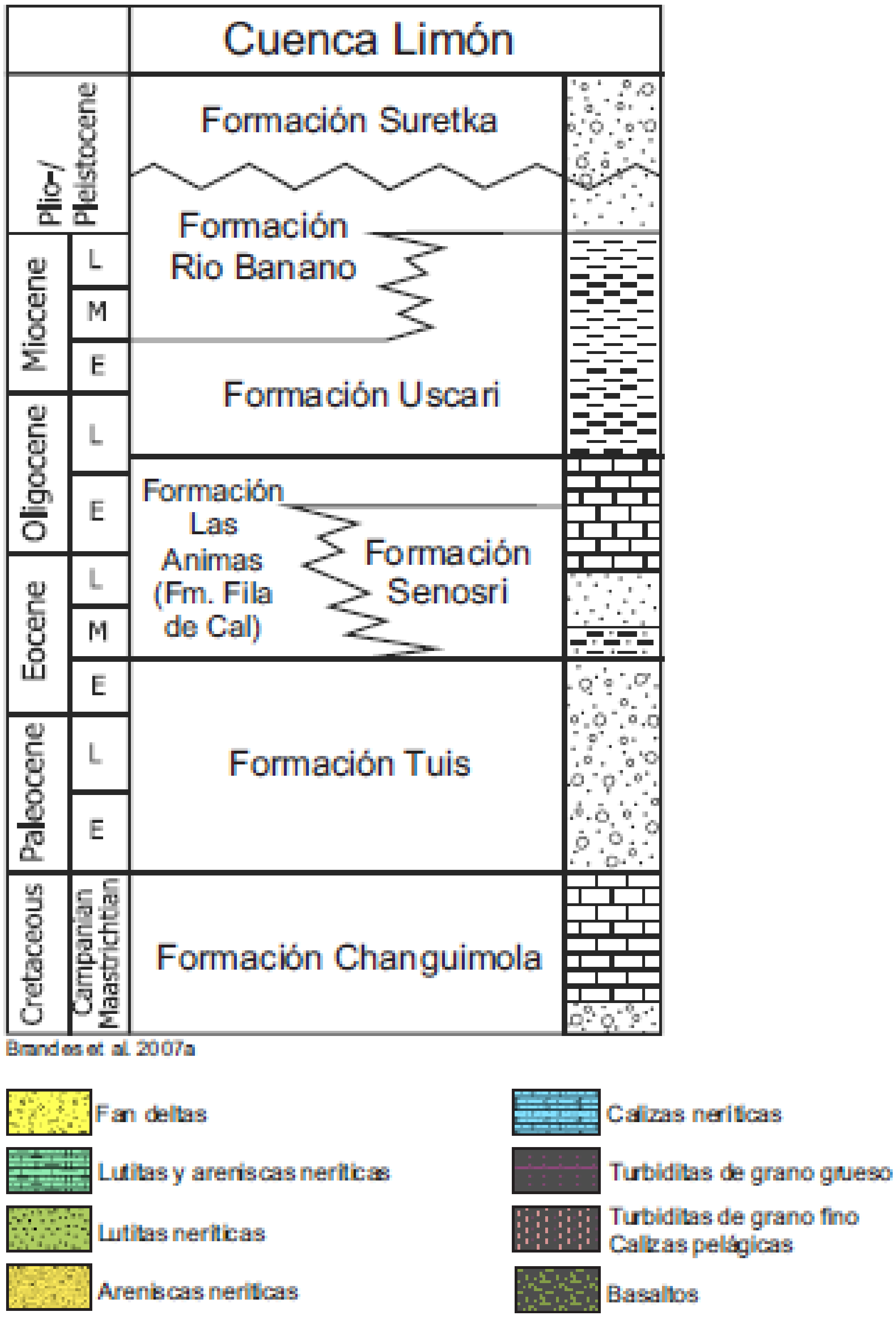


Columna estratigráfica. Según Sprechman et al, 1993
Cuaternario
Holoceno
Pleistoceno
Cenozoico
Terciario
Plioceno
Superior
Inferior
Mioceno
Superior
Medio
Inferior
Oligoceno
Superior
Inferior
Eoceno
Superior
Medio
Inferior
Paleoceno
Mesozoico
Cretácico
Superior
Maschtriniano
Campaniano
Santoniano
Coniaciano
Turoniano
Cenomaniano
Inferior
Albiano
Apliano
Sámara - Cabo Blanco
Tempisque
Liberia - Bagaces
Montezuma
Aguacate
El Carmen
Cañamazo
Pta. Pelada
Fila de Cal
Fila de Cal
Descartes / Zapotal
Subgrupo Curime
Arío
Espiritu Santo
Subgrupo Sámara
Curú
Sabana Grande
Pto. Carrillo
El Viejo
Barra Honda
Complejo de Nicoya

Formaciones	Litología	Ambiente de depositación
Fm. Bagaces	Ignimbritas, lavas y epiclastos subordinados	Volcánico
Fm. Liberia	Ignimbritas formadas por acumulaciones de cenizas pomáceas.	Continental, seco y fluvio-lacustre.
Fm. Montezuma	Areniscas, lutitas y conglomerados litorales y sublitorales del Plio-Pleistoceno	Litofacies de origen marino y continental (posible regresion)
Fm. El Carmen	Sedimento marinos someros carbonatados	Ambiente marino-somero
Fm. Punta Pelada	Calizas someras	Ambiente marino-somero neritico
Miembro Zapotal (Fm. Descartes)	Secuencia alternancia de calcilutitas, calcarenitas, tobas.	Secuencia turbidítica distal.
Fila de Cal	Calizas de plataforma del Eoceno Superior y Oligoceno	Rampas y plataformas carbonatadas
Espíritu Santo	Calizas con macroforaminíferos y algas rojas, intercaladas con tobitas de grano fino.	Por sedimentación turbidítica monótona, interrumpido por flujos de gravedad.
Fm. Arío	Calcilutitas y areniscas carbonatadas de plataforma	Rampas y plataformas carbonatadas
Fm. Curú	Areniscas y lutitas turbiditicas, menor proporción bechas y conglomerados	Sedimento terrígeno depositado por gravedad, por depósitos turbidíticos.
Fm. Barra Honda	Calizas de plataforma pobremente estratificadas	Ambiente de mar somero que se formaron extensos arrecifes.
Fm. El Viejo	Calizas y areniscas carbonatadas de plataforma	Ambiente marino somero, arrecifal
Fm. Sabana Grande	Areniscas y lutitas calacareas principalmente, con presencia tambien de secuencias turbiditicas	Ambiente marino pelágico y hemipelágico
Fm. Puerto Carrillo	Brechas basalticas y areniscas finas calcareas y calizas	Brechas de escarpes submarinos profundos e insulares
Complejo de Nicoya	Basaltos toleíticos en forma de coladas masivas y en almohadillas	Vulcanismo submarino y Ofiolitas

Figure 2. Stratigraphic column and descriptions for the Tempisque watershed (Jorge Luis Blanco, 2019, written commun.).

Columnas Litoestratigráficas



Formación	Edad	Descripción	Espesor (m)	Ambiente
Limón	Plioceno-Reciente	En la parte inferior floatstones con tafocenosis y fragmentos de corales y en la parte superior limos intercalados con areniscas cuarzosas.	100	Sedimentos marinos someros- arrecife de coral
Rio Banano	Mioceno Sup-Pleistoceno	Arenas volcaniclásticas ligeramente calcáreas interestratificadas con facies de frente deltaico.	1 700	Depósito continental – volcaniclástico (Delta)
Suretka	Plio-Pleistoceno	Conglomeradas que gradan lateralmente a limonitas calcáreas, lutitas y calizas arrecifales.	2 000	Continental-Fluviatil
Doán (Aguacate)	Plio-Pleistoceno	Aglomerado de origen lahárico, tobas, ignimbritas y flujos de lava	2 800	Volcánico-continental
Guayacán	Plioceno Inferior	Diques y sills hipoabisales y basaltos alcalinos	700	Fuente magmática diferenciada
Uscari	Mioceno Medio	Sedimentos siliciclásticos (lodos)	800	Delta progradante de plataforma.
Senosri	Eoceno Superior-Mioceno Inferior	Calizas alodápicas y depósitos de flujos masivos carbonatados (calcilutitas).	2 400	Rampa carbonatada, alto nivel del mar y calma tectónica
Punta Pelada	Oligoceno Superior	Calizas	250	Rampa Carbonatada
Barbilla (Fila de Cal)	Oligoceno Inferior	Calizas	250	Rampa Carbonatada
Animas (Fila de Cal)	Eoceno Superior	Caliza periplataforma intercaladas con tobas	150	Plataforma carbonatada insular
Tuis	Paleoceno-Eoceno Medio	Serie volcaniclástica y turbiditas marinas.	3 000	Proveniente arco volcánico insular
Changuinola	Cretácico Superior	Calizas pelágicas, su litología principal son calcilutitas pelágicas y lodolitas calcáreas.	1 280	Marino profundo (Talud)

Figure 3. Stratigraphic column and descriptions of sedimentary deposits and rocks in the Tortuguero–Sarapiqui watershed (Jorge Luis Blanco, 2019, written commun.).

Priority Areas

The Technical Working Group for the project met with RTI and USGS staff to select five priority areas for more detailed studies. The USGS team evaluated the five potential areas and selected two as the priority areas to receive further study: the Tempisque watershed and the Tortuguero–Sarapiqui watershed. A third priority area (San Carlos watershed) was set aside for use by the Costa Rican water professionals to apply the methodologies from this project after completion and in consultation with the USGS (Figure 4). Analysis of the San Carlos watershed is not presented in this report.

Figure 4. Map showing locations of selected priority areas (Tempisque watershed shaded in yellow, San Carlos watershed shaded in green, and Tortuguero–Sarapiqui watershed shaded in purple).

The Technical Working Group listed many justifications for the selection of the two priority areas:

(1) Tempisque watershed (about 5,500 km^2 in area):

- Complex hydrogeology
- Water-stressed area that is a good candidate for optimization analysis to assess best uses for scarce resource

- Demonstration of the study methods in the tectonically compressed northern area
- Possible water-bearing zones on the eastern margin of the watershed
- Good infrastructure such as wells, roads, and pipelines
- Vulnerable to climate-change effects because of the aridity of the watershed
- Original study area for the project (which was later expanded to the entire area of Costa Rica)
- Local economic dependent on tourism (an important industry in Costa Rica)

(2) Tortuguero–Sarapiqui watershed (about 9,050 km^2):

- Good candidate (less hydrogeologically complex than the Tempisque watershed) for illustrating the concepts and procedures of conceptualizing a hydrogeologic system
- An example of the aquifer systems in the central “pull-apart” geomorphic region
- High potential for undeveloped groundwater resources in the thick relatively high-permeability and (or) high-porosity delta deposits

Methods

Component A–Remote Sensing Tool (WATEX)

For Component A, the remote sensing methodology follows these general steps:

(1) Identify, acquire, process, and interpret remotely sensed data from several satellites, including Landsat, orbital radar, and Shuttle Radar Topographic Mission to delineate areas of interest. Each site and subsite were classified for potential groundwater resources.

(2) Acquire ancillary data, including precipitation, topographic maps, and geologic, seismic, geomorphologic and hydrogeologic information to interpret the remotely sensed data and hydrogeologic interpretations.

(3) Calibrate and validate the interpretation of the remotely sensed data by collecting field data.

Component B–Hydrogeologic Conceptualization

Many of the features identified by the remote sensing tool (WATEX) are as interpreted to be buried stream channels and (or) faults containing groundwater. Long-term sustainability may depend on whether these features act as sources for regional aquifers; as conduits for higher-altitude recharge; as collectors of local precipitation; or as some combination of these factors.

The hydrogeologic conceptual model development for the Tempisque and Tortuguero–Sarapiqui watersheds included:

(1) three-dimensional (3-D) volumetric models showing hydrogeologic unit thicknesses and extents,

(2) estimates of aquifer storage from the volumetric models,

(3) potentiometric maps showing regional groundwater flow directions, and

(4) estimated groundwater budgets based on measurable or estimated groundwater recharges and discharges.

The construction of the 3-D hydrogeologic framework model involves five stages (Figure 5):

(1) Lumping geologic units into units of similar hydraulic character, known as hydrogeologic units (HGUs).

(2) A digital elevation model was combined with geologic maps to provide a series of points locating the outcropping surfaces of HGUs.

(3) Cross sections and borehole logs were oriented in 3-D space to define locations of HGUs in the subsurface.

(4) Surface and subsurface data from map, borehole, and cross sections were interpolated using gridding algorithms to define surfaces representing the tops of HGUs.

(5) Using stratigraphic principles, 3-D hydrogeologic framework models (HFMs) were constructed for the two priority areas in a geologic modeling software package. These HFMs represent the stratigraphic and structural relations by stacking hydrogeologic units in a stratigraphic order.

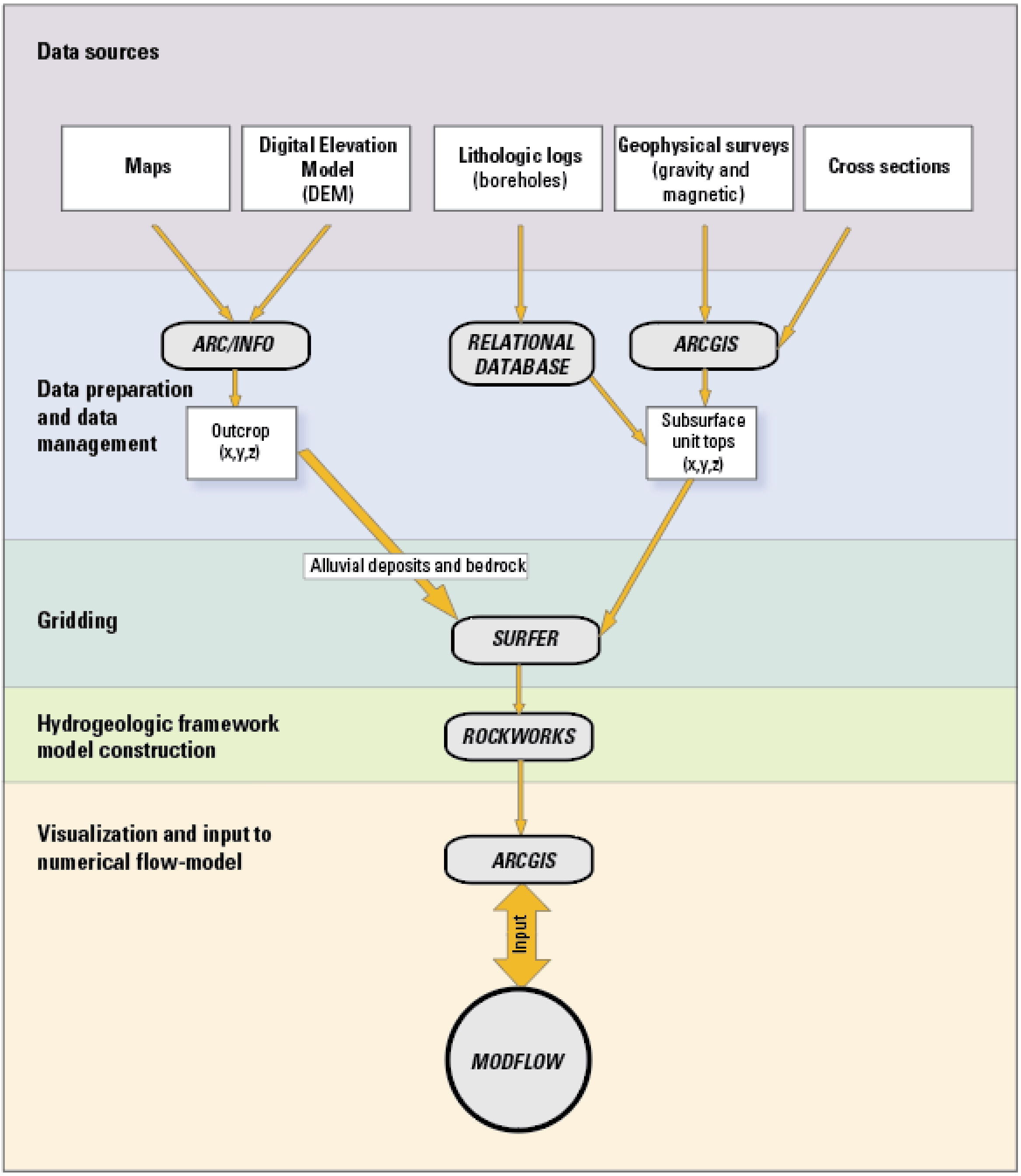


Figure 5. Flowchart to produce a hydrogeologic framework model.

Data from maps, geologic cross sections, well lithologies, springs discharge databases, and pumping databases were used in the hydrogeologic assessment (Table 1). The following data presented in Table 1 were used in the hydrogeologic assessment. The hydrogeologic spatial data (map, wells, and cross sections) used in constructing the HFMs are presented in Table 2 and Table 3 and in Figure 6. These data were gridded by using the Surfer gridding software (using the nearest neighbor algorithm with the parameters presented in Table 4. An iterative process of varying the gridding search radius was used to produce the most realistic geologic surfaces.

Table 1. Data used in the hydrogeologic assessment.

[Abbreviations: IMN, Instituto Meteorlogico Nacional; MINAE, Ministerio de Ambiente y Energia; UCR, University of Costa Rica; UNM, University of New Mexico]

Data type	Source	Use
Geologic map	UCR-MINAE, 2007 1:400,000-scale	hydrogeologic framework model
Cross sections	RTI 2018	hydrogeologic framework model
Wells–water levels	MINAE database	potentiometric surface maps
Wells-lithologies	MINAE database	hydrogeologic framework model
Permitted springs	Departamento Desarrollo Hidrico 2019	potentiometric surface water budget
Unpermitted springs	Departamento Desarrollo Hidrico 2019	potentiometric surface water budget
Precipitation map	IMN 2005 1: 1,500,000-scale	water budget
Evapotranspiration	NMSU 2019	water budget

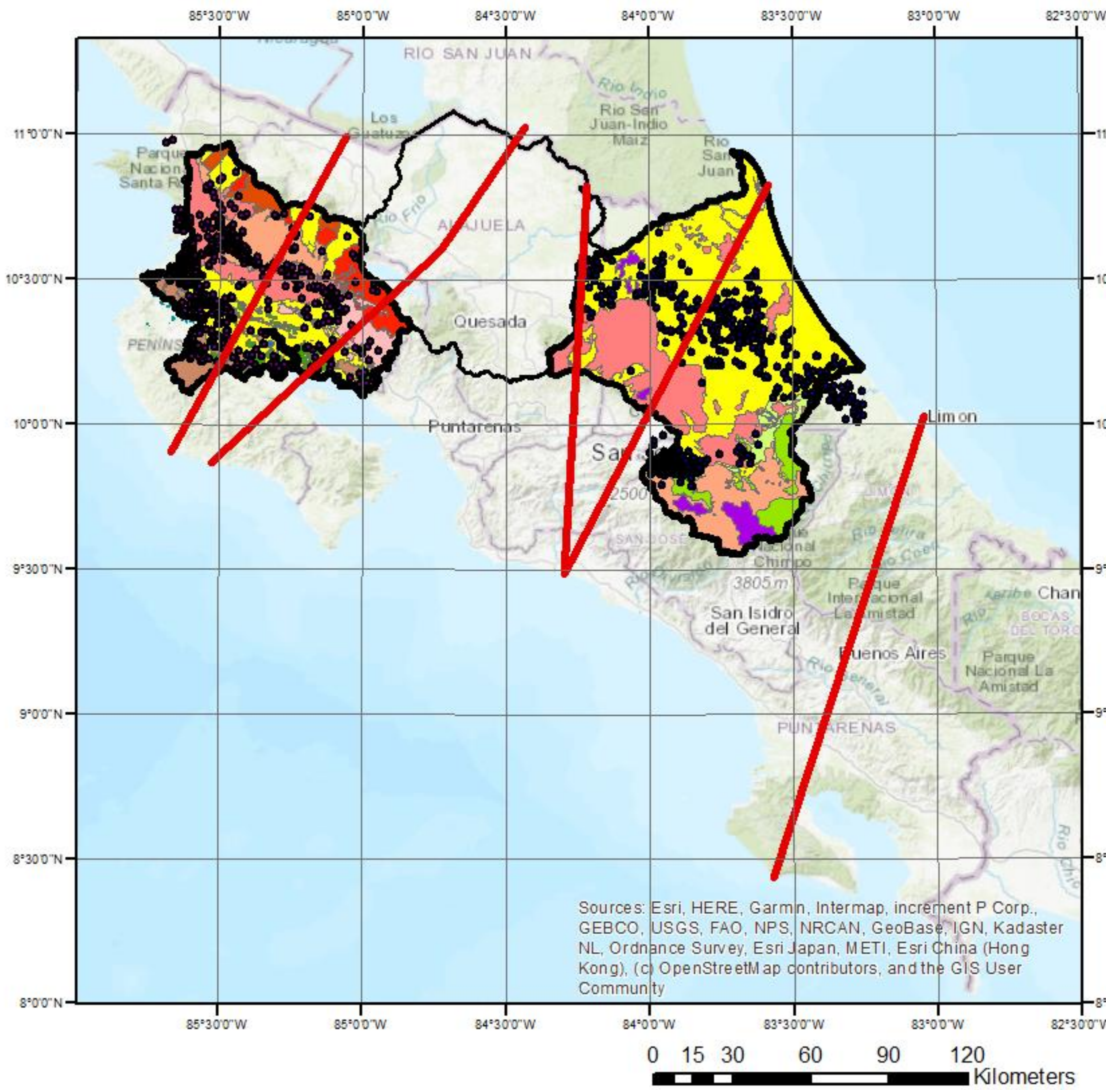


Figure 6. Map showing the location of hydrogeologic maps (colored polygons; see Figure 15 and Figure 16 for explanation of hydrogeologic units depicted on map), borehole (colored dots), and cross section (red lines) data used in construction of hydrogeologic framework models.

Table 2. Data used in constructing hydrogeologic unit grids for the Tempisque watershed.

Hydrogeologic Unit	Map data	Well data	Cross-section data
Quaternary sediments (QSED)	X	X	
Liberia aquifer (VA-L)	X	X	
Bagaces aquifer (VA-B)	X	X	
Sedimentary unit (SED)	X	X	
Basement (BASE)	X	X	
Lava flows (VOL-L)	X	X	
Aguacate unit (AU)	X	X	
Monteverde volcanics (VOL)	X	X	

Table 3. Data used in constructing hydrogeologic unit grids for the Tortuguero–Sarapiqui watershed.

Hydrogeologic Unit	Map data	Well data	Cross-section data
Quaternary sediments (QSED)	X	X	
Lava flows (VOL-L)	X	X	
Aguacate unit (AU)	X	X	
Sedimentary unit (SED)	X	X	
Basement (BASE)	X	X	X
Intrusive (INT)	X	X	

Table 4. Gridding parameters for hydrogeologic top-surface grids.

[Abbreviations: m, meters]

Priority area	Lower left coordinates (Lambert Costa Rica North, m)	Upper right coordinates (Lambert Costa Rica North, m)	Grid spacing (m)
Tempisque watershed	342000, 231000	446000, 329000	1,000
Tortuguero–Sarapiqui watershed	498000, 170000	618000, 325000	1,000

Component C–Optimization Assessment of Groundwater Development and Use

A detailed optimization analysis of groundwater development and use was performed on the Tempisque and Tortuguero–Sarapiqui watersheds. The analysis is based on an empirical farm income optimization model, and the results are used to inform policy debates dealing with the effectiveness of various patterns of crop irrigation and other water uses in the regions drawing upon the aquifers defined by the remote sensing tool (WATEX) and the hydrogeologic assessment. The analysis made a "with-versus-without additional water" comparison that reflected agricultural benefits from converting from the exclusively rainfed agriculture to an agriculture supplemented by the much more reliably supplied and lesser-cost groundwater in the region.

Using the newly identified sources of groundwater growers could invest in state-of-the-art irrigation infrastructure to reduce surface-water applications. The importance of access to an affordable water-conserving irrigation infrastructure, in order to reduce surface-water withdrawals, takes on more importance in the face of growing shortages in surface-water supplies. The principle behind this assessment is, for existing agricultural land use, to evaluate the benefits of installing an irrigation infrastructure (at a cost) by using a more reliable water supply, changing to greater value crops and drought resistant crops, growing multiple crops per year, or changing to livestock grazing or other uses of water resources.

Component D–Capacity Building and Technology Transfer

The capacity building and technology transfer consisted of a series of formal classes and field exercises to train the Costa Rican water professionals on remote sensing, use of the Groundwater Exploration Navigation System (GENS), building 3-D hydrogeologic framework models, and the use of the optimization modeling.

Results of Component A–Remote Sensing Tool (WATEX)

The results of this study indicated that the most important geologic formations for water resources of Costa Rica are the remaining Miocene-Pliocene marine sediments (15 to 5 million years old) and the Holocene- to Neogene-aged fractured volcanic rocks (5 million years to present). These marine sediments and volcanic rocks have enhanced permeability from fracturing in the pull-apart zone, which was observed in the Central Valley and in the Tortuguero–Sarapiqui watershed. The structural control of this pull-apart zone, which has an area of about 10,000 km^2, tends to allow greater amounts of recharge in the zone through open fractures.

Costa Rica can be divided into three tectonic regimes (Figure 7):

- The Northern Zone, which is characterized by compression, consists of a chain of andesitic stratovolcanoes trending northwest, parallel to the Meso Atlantic Trough and hosting two main arc basins (Tempisque forearc basin and the San Carlos back-arc basin)
- The Pull-apart Zone, where the Tarcoles shear corridor, in combination with the Hess Escarpment, creates a transtensional set of fractures in the Central Valley of Costa Rica
- The Southern Zone, where a compressive zone is created by the combined effect of the Trans-Isthmic corridor and the subduction of the Cocos ridge

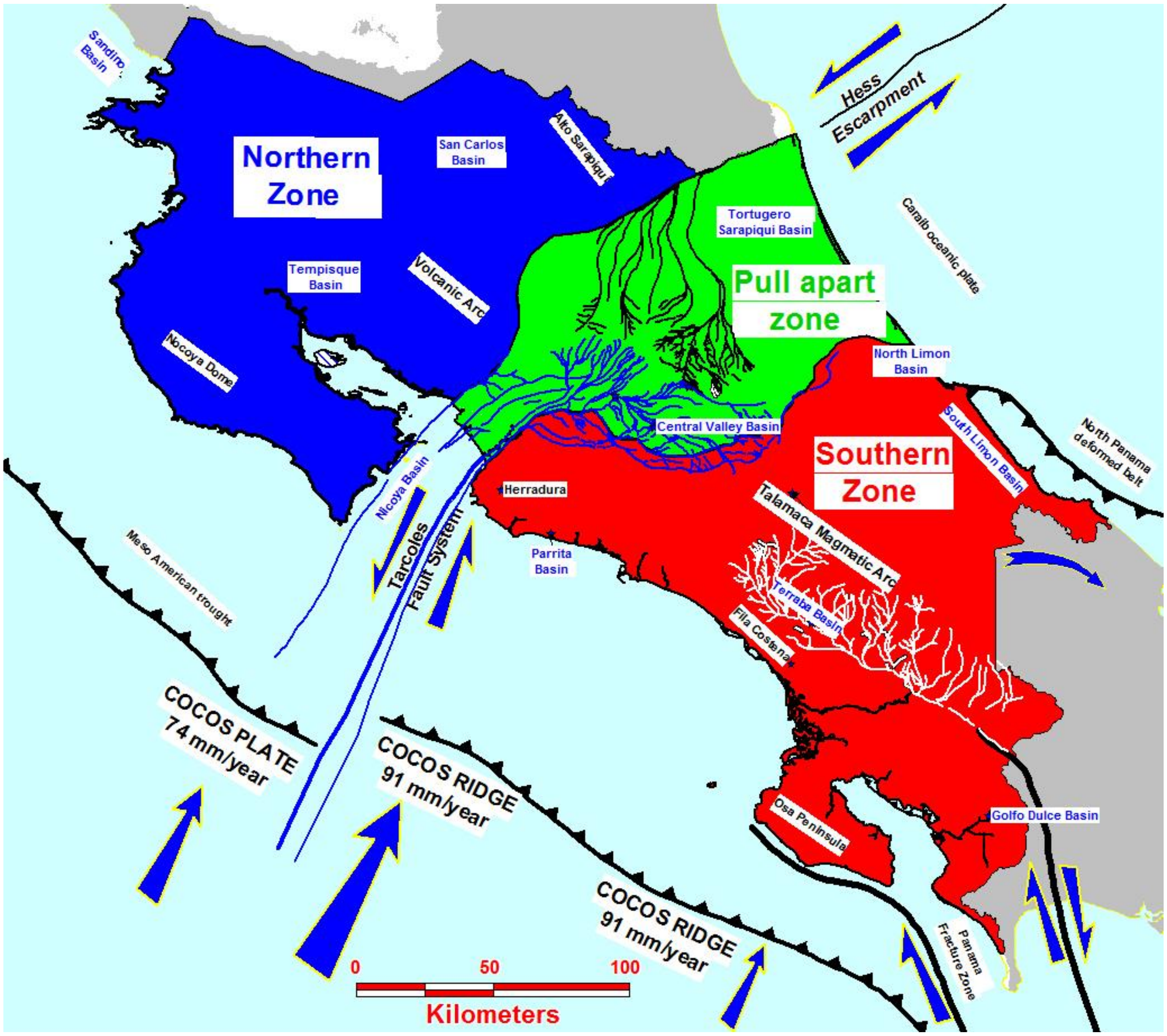


Figure 7. Map showing the tectonic regimes identified in Costa Rica.

Rainforest areas over 900 m in altitude are important areas for recharge to aquifers because of orographic effects and the retention of water by vegetation allowing more infiltration and less runoff. The groundwater recharge areas will not be sustained if the rainforest health is not maintained and impermeable surfaces are permitted to cover these permeable fractured land-surface areas.

The potential recharge areas in the central pull-apart zone are 55 percent of the total surface of Costa Rica. Flowing springs are present in many areas below 900 m in elevation (at the Pacific coast in the fractured Aguacate Formation on the Pacific side; the Colima formation tunnels of Puente Mulas and the

Los Chorros springs in the Central Valley area; and the Turrialba, Tucurrique, and Guapiles springs on the Caribbean side) and suggest recharge from the adjacent rainforest areas above 900 m. In this favorable structural context, a new promising area has been detected in the Tortuguero–Sarapiqui watershed, where potential aquifers in deltaic formations on the southern side of the Hess Escarpment have been identified (Figure 7).

The Talamanca Range represents 39.74 percent of the total potential recharge area and likely recharges nearby aquifers in the El General Valley, on the Pacific side, and to the North and South Limon Basins on the Caribbean side (Figure 7).

In Costa Rica, there are many aquifers that frequently receive a greater volume of recharge than the aquifer storage capacity, and artificial recharge of permeable units might offer a complementary solution, especially in the Guanacaste province which remains the most vulnerable to droughts and floods. The groundwater storage capacity of the Nicoya basement rock is very limited because of its low permeability. Alluvial aquifers near the coast are threatened by salinization, and deep aquifers are most likely non-existent on the western side of the Tempisque watershed. The growing tourism industry of the Guanacaste province will require that freshwater be transported by pipelines or created by desalinization plants. At the time of this investigation, the excess water from Arenal Lake was being used to deliver freshwater with a pipeline to the Guanacaste coastal area.

The resulting groundwater potential occurrence maps for aquifers at 0–30 meters in depth, 30–150 meters in depth, and greater than 150 meters in depth of the Tempisque watershed are presented in Figure 9, Figure 10, and Figure 11, and in Figure 12, Figure 13, and Figure 14 for the Tortuguero–Sarapiqui watershed. These maps are intended to site new water-supply wells.

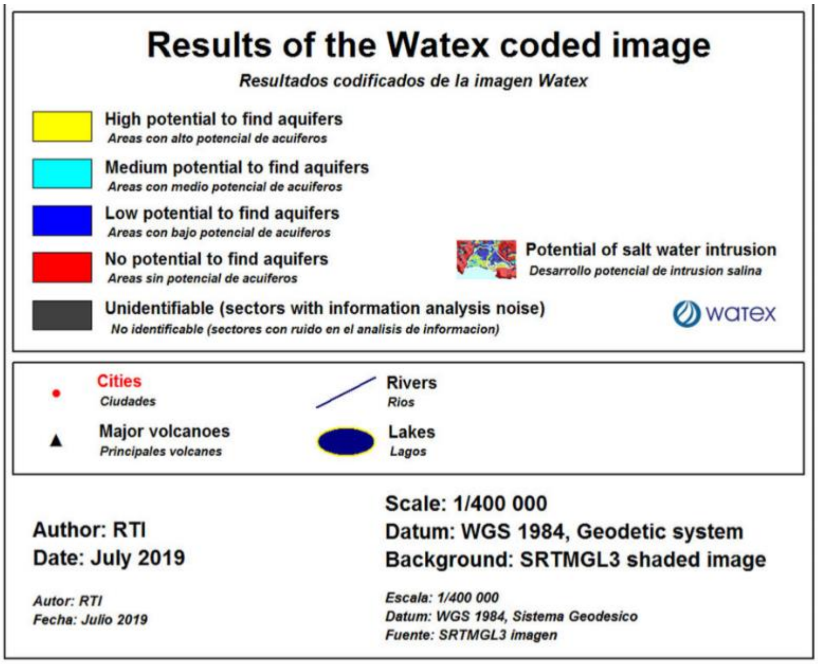


Figure 8. Explanation for Figure 9 to Figure 14.

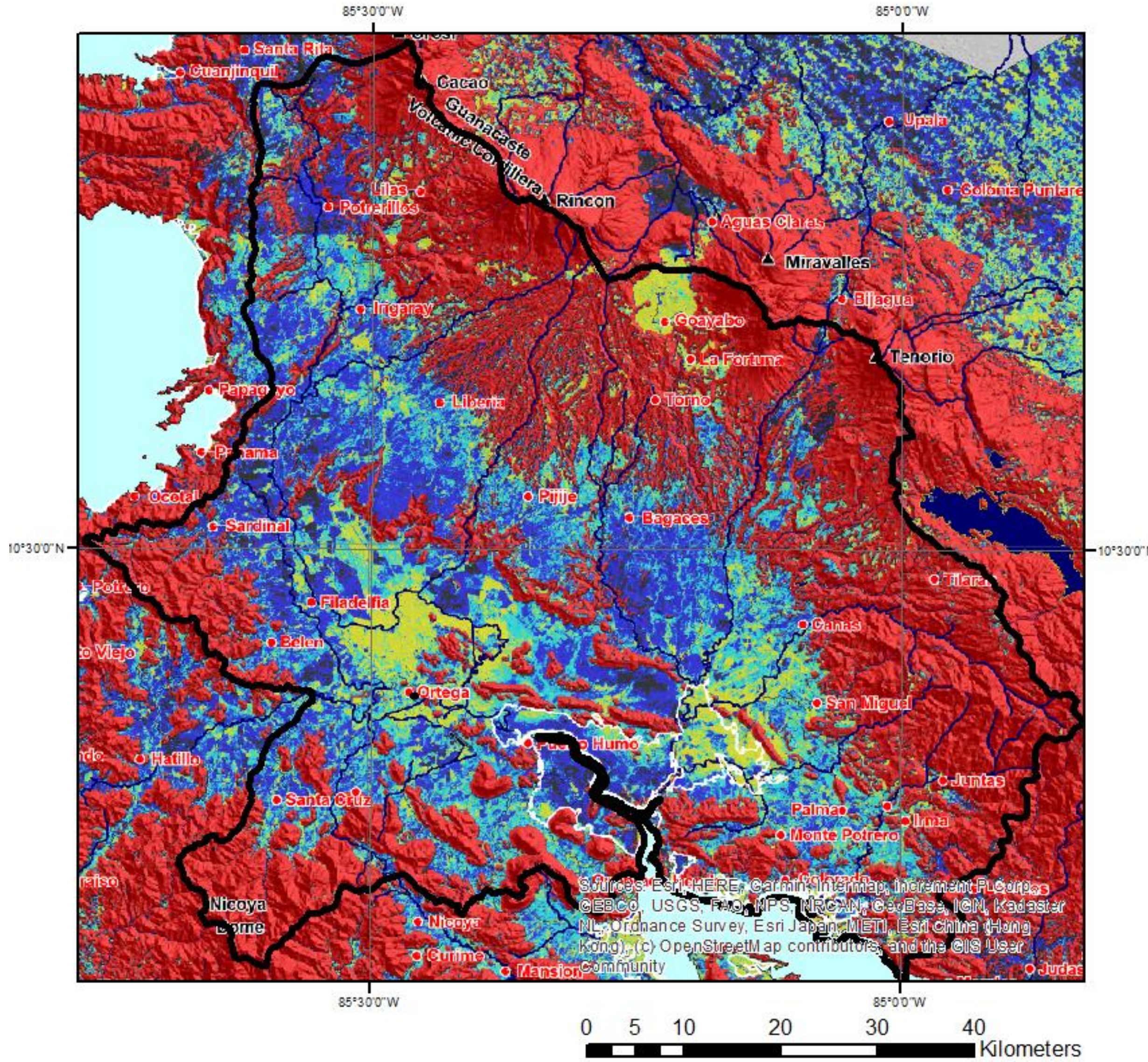


Figure 9. Map showing groundwater potential map for aquifers 0–30 meters in depth in the Tempisque watershed.

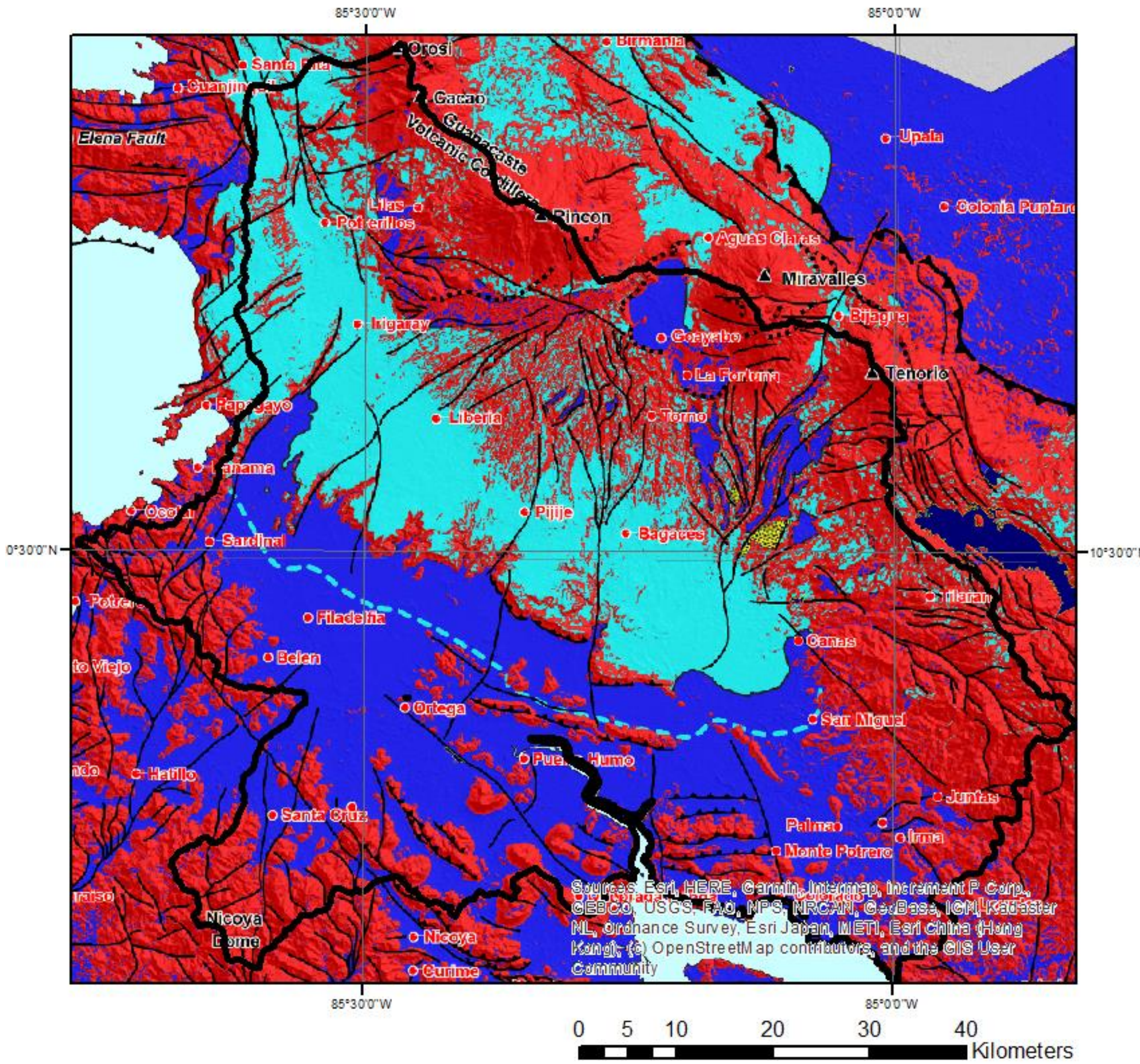


Figure 10. Map showing groundwater potential map for aquifers 30–150 meters in depth in the Tempisque watershed.

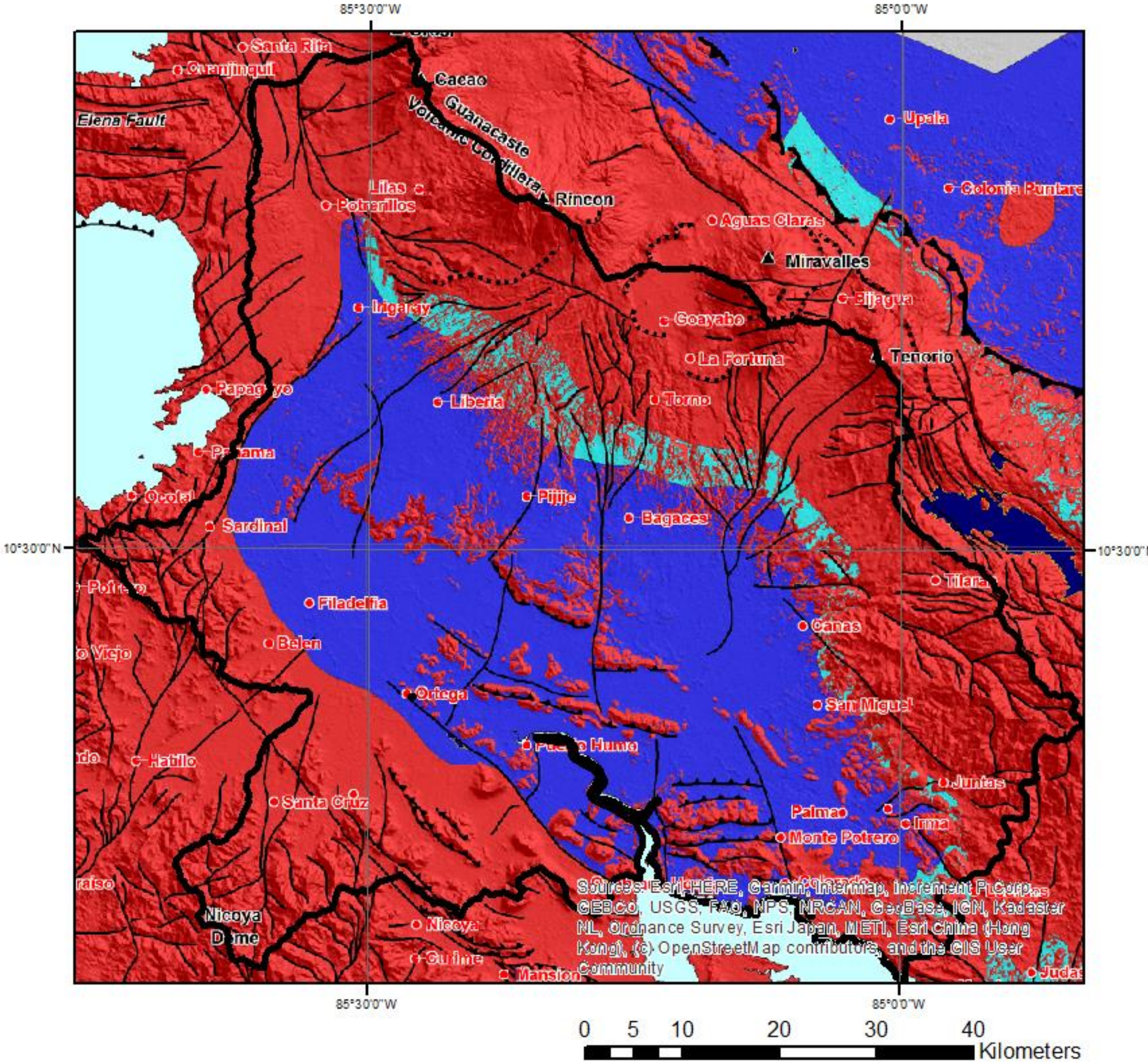


Figure 11. Map showing groundwater potential map for aquifers greater than 150 meters in depth in the Tempisque watershed.

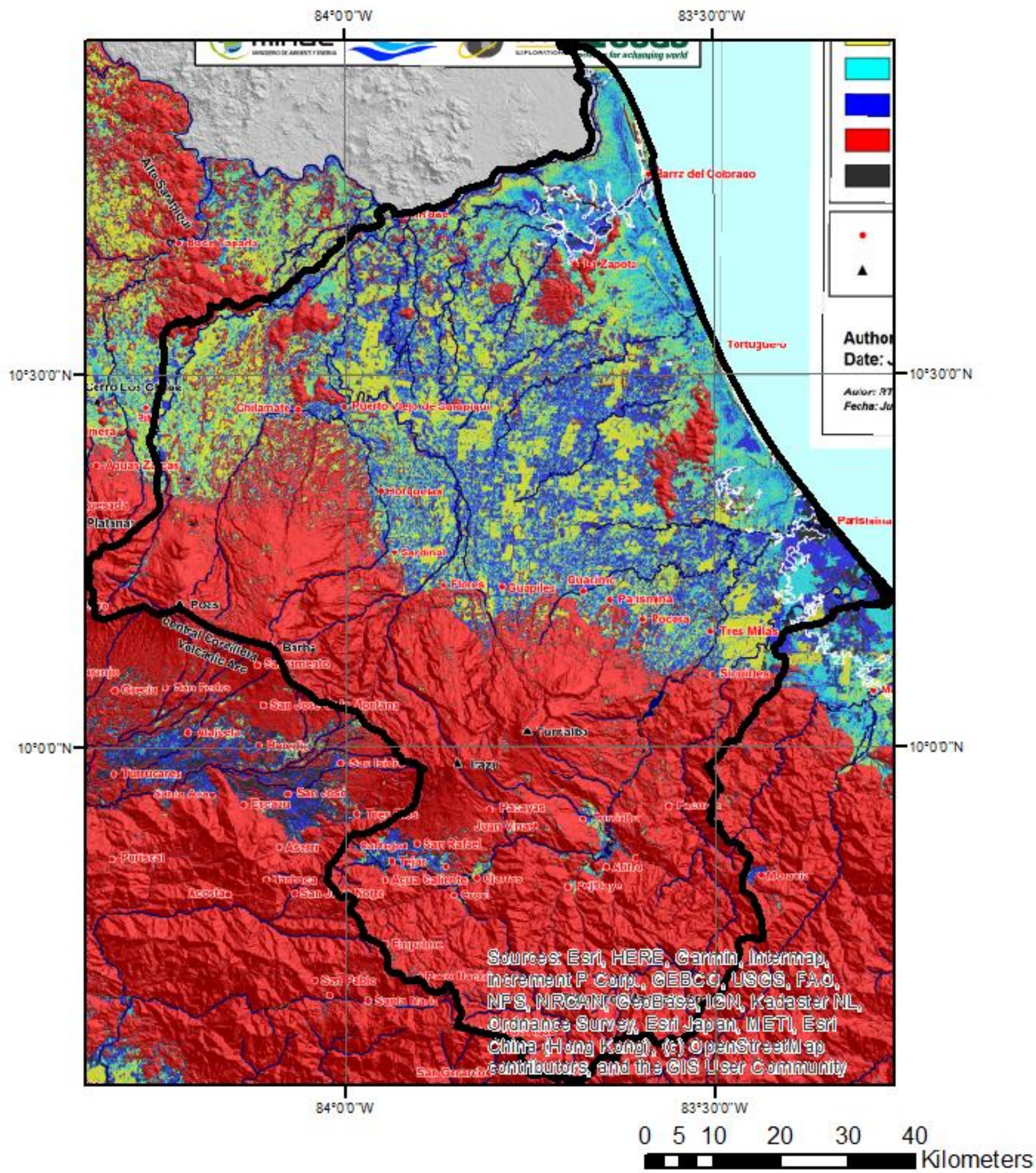


Figure 12. Map showing groundwater potential map for aquifers 0–30 meters in depth in the Tortuguero–Sarapiqui watershed.

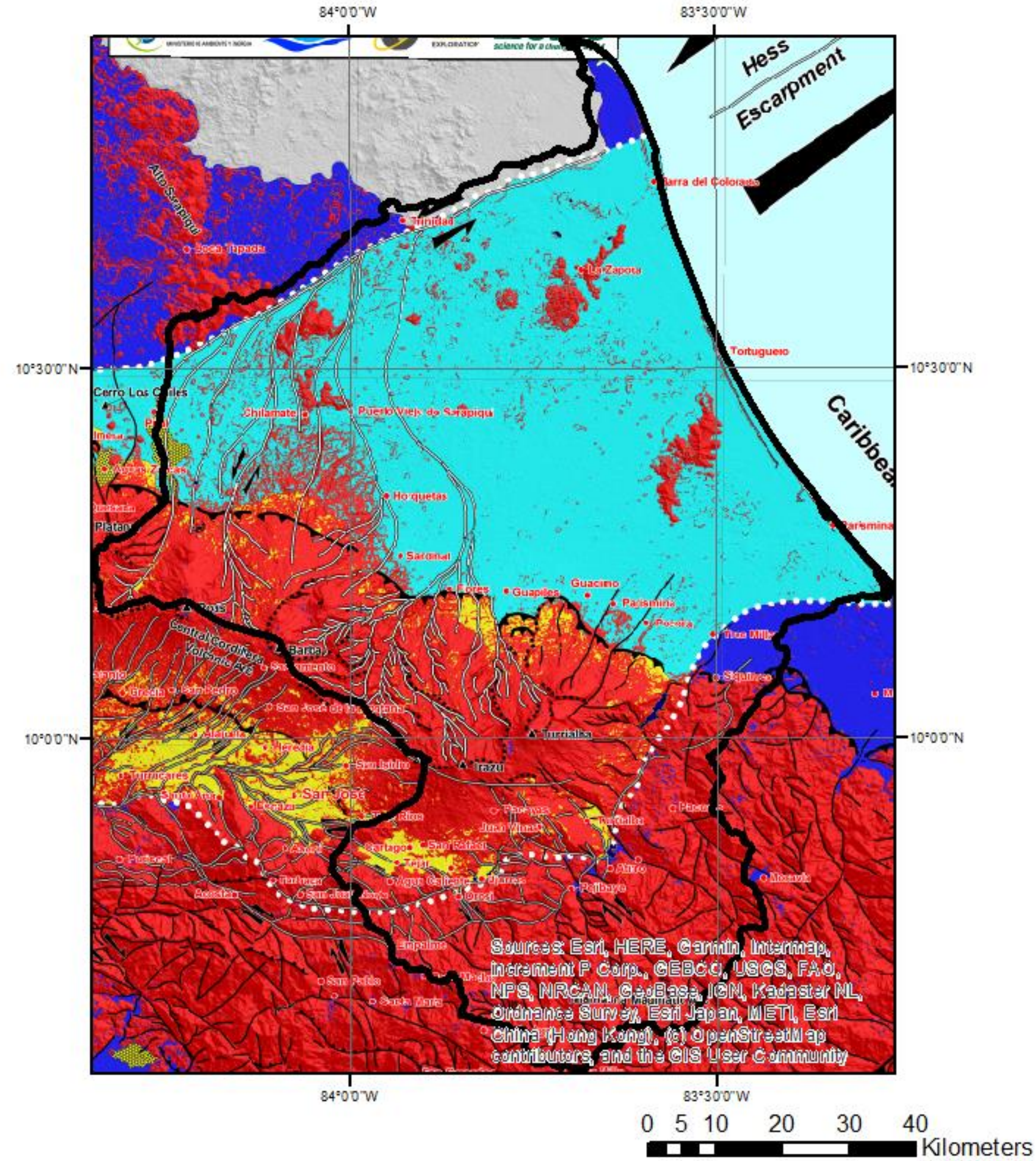


Figure 13. Map showing groundwater potential map for aquifers 30–150 meters in depth in the Tortuguero–Sarapiqui watershed.

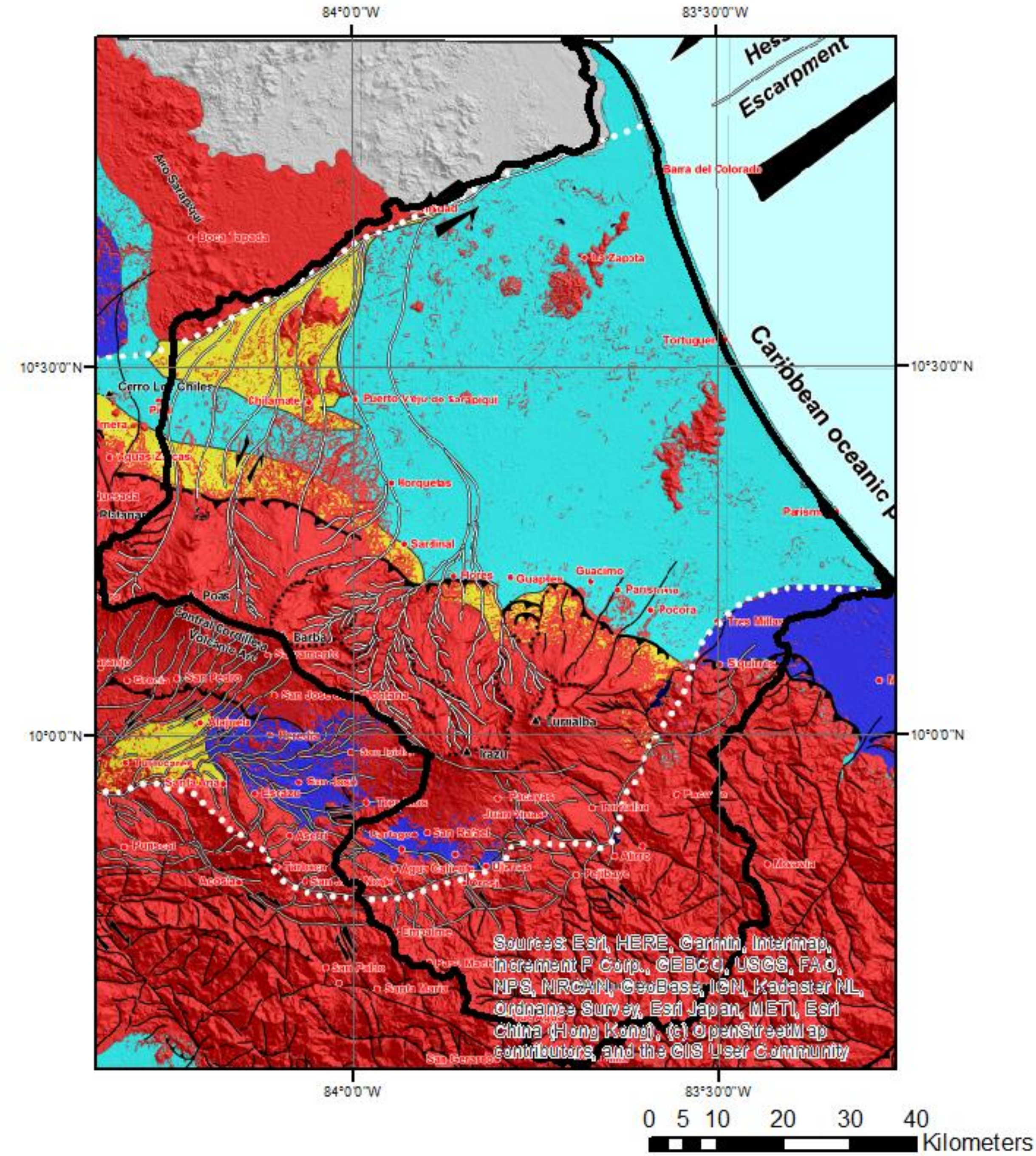


Figure 14. Map showing groundwater potential map for aquifers greater 150 meters in depth in the Tortuguero–Sarapiqui watershed.

Results of Component B–Hydrogeologic Assessment

The hydrogeologic assessment consists of three products:

- hydrogeologic interpretation including the construction of a 3-D hydrogeologic framework model
- potentiometric maps
- water budgets

All three of these products are based on limited data and should be considered preliminary results.

Hydrogeologic Units

The rocks and deposits forming the hydrogeologic framework for a groundwater flow system are termed hydrogeologic units (HGUs). An HGU has considerable lateral extent and has reasonably distinct hydrologic properties because of its physical (geological and structural) characteristics. The identification, acquisition, and conversion of suitable data, and proper processing and analysis procedures for these data, are critical for successful characterization and conceptualization. The Technical Working Group, comprised of geoscientists from the Costa Rica government and academia, worked together to select these HGUs based on the geology of the priority areas. Table 5 and Table 6 present the HGUs for the Tempisque and Tortuguero–Sarapiqui watersheds.

Table 5. Hydrogeologic Units for the Tempisque watershed.

Geologic Units	Lithology	Hydrogeologic Unit Name	Hydrogeologic Unit Designation
Depositos aluviales recientes	Quaternary sediments	Quaternary sediments	**QSED**
Terrazas del Plio-Peistoceno	River terrace deposits	Quaternary sediments	**QSED**
Unidad de Debris Flow y Avalanche	Debris flows and avalanches	Quaternary sediments	**QSED**
Diatomitas y lutitas fluvio-lacustres	Fluvio-lacustrine deposits	Quaternary sediments	**QSED**
Vulcanismo del Pleistoceno (0,6-0,2 Ma)	Volcanics flows	Volcanic flows	**VOL-L**
Vulcanismo del Pleistoceno (1,1-0,6 Ma)	Volcanic flows	Volcanic Flows	**VOL_L**
Fm. Liberia	Tuff	Volcanic Aquifer Liberia	**VA_L**

Fm. Bagaces	Ignimbrites	Volcanic Aquifer Bagaces	**VA_B**
Canas Dulces	Ignimbrites	Volcanic Aquifer Bagaces	**VA_B**
Fm. Montezuma	Sandstone/shales/conglomerates	Montezuma unit	**MU**
Fm. Monteverde	Volcanics	Volcanic unit	**VOL**
Fm. Grifo Alto	Volcanics	Aguacate unit	**AU**
Fm. Descartes	Calcareous sandstones and shales	Upper Sedimentary-rock unit	**USU**
Fm. Barra Honda	Limestones	Upper limestone unit	**TURB_U**
Fm. Curu	Turbidites	Upper turbidite unit	**TURB_U**
Fm. Piedras Blancas	Turbidites	Upper turbidite unit	**TURB_U**
Barbudal	Calcareous shale/sandstones	Middle sedimentary-rock unit	**MSU**
Fm. El Viejo	Limestone	Lower limestone unit	**LLU**
Fm. Namb¡	Turbidites	Lower turbidite unit	**TURB_L**
Fm. Sabana Grande	Calcareous shale/sandstones	Lower sedimentary-rock unit	**LSU**
Complejo de Nicoya (Radiolaritas)	Nicoya Complex (metamorphic)	Basement	**BASE**
Complejo de Nicoya (basaltos)	Nicoya Complex (metamorphic)	Basement	**BASE**
Gabros y doleritas	Nicoya Complex (metamorphic)	Basement	**BASE**
Complejo de Nicoya (Intrusivos gabroides)	Nicoya Complex (metamorphic)	Basement	**BASE**
Complejo de Nicoya (Picritas Komatit ├¡cas)	Nicoya Complex (metamorphic)	Basement	**BASE**

Table 6. Hydrogeologic units for the Tortuguero–Sarapiqui watershed.

Geologic Units	**Lithology**	**HGU Name**	**HGU Abbreviation**
Depositos aluviales recientes	Unconsolidated sediment	Quaternary sediments	**QSED**
Unidad de Debris Flow y Avalanche	Debris flows and avalanches	Quaternary sediments	**QSED**
Tortuguero	Volcanic flows	Volcanic flows	**VOL-L**
Vulcanismo del Pleistoceno (Platanar)	Volcanic flows	Volcanic flows	**VOL-L**
Vulcanismo Pleistoceno (0.3-0.2 Ma)	Volcanic flows	Volcanic flows	**VOL-L**
Vulcanismo del Pleistoceno (0.6-0.2 Ma)	Volcanic flows	Volcanic flows	**VOL-L**
Vulcanismo del Pleistoceno (1.1-0.6 Ma)	Volcanic flows	Volcanic flows	**VOL-L**
Fm. Guayacín	Volcanic flows	Volcanic flows	**VOL-L**
Fm. Tiribi	Volcanic tuff	Volcanic	**VOL-L**
Monteverde Volcanics	Volcanics	Volcanic	**VOL**
Fm. Suretka	Conglomerate breccia	Sedimentary-rock unit	**SED**
Fm. Queb. Chocolate	Sedimentary	Sedimentary-rock unit	**SED**
Rio Banano Fm.	Sedimentary	Sedimentary-rock unit	**SED**
Fm. Uscari	Sandstone shale conglomerate	Sedimentary-rock unit	**SED**

Grupo Aguacate	Sed	Aguacate unit	AU
Fm. Grifo Alto	Aguacate	Aguacate unit	AU
Fm. La Cruz	Aguacate	Aguacate unit	AU
Fm. Coris	Sedimentary and sandstone	Sedimentary-rock unit	**SED**
Mb. Roca Carballo	Sediments	Sedimentary-rock unit	**SED**
Fm. San Miguel	Volcanic	Volcanic	**VOL**
Fm. Pena Negra	Calareous limestone	Limestone unit	**LU**
Fm. Pacacua	Sedimentary	Sedimentary-rock unit	**SED**
Fm. Sensori	Limestones	Limestone unit	**LU**
Fm. Fila de Cal	Limestones	Limestone unit	**LU**
Fm. Curre	Turbidites	Turbidite unit	**TURB**
Fm. Tuis	Volcaniclastics and turbidites	Turbidite unit	**TURB**
Talamanca	Intrusive	Intrusive	INT
Mb. Tapant¡	Intrusive	Intrusive	INT
Fm. Sarapiqu¡	Intrusive	Intrusive	INT
Intrusivos del Plioceno	Intrusive	Intrusive	INT
Nicoya Complex	Serpentinites	Basement	**BASE**

The geologic units of the 1:400,000-scale national geologic map (Denyer and Alvarado, 2007) were reclassified as HGUs for the Tempisque and Tortuguero priority areas. These maps are presented in Figure 15 and Figure 16. It should be noted that the HGUs depicted on the maps are further simplification of those in Table 5 and Table 6.

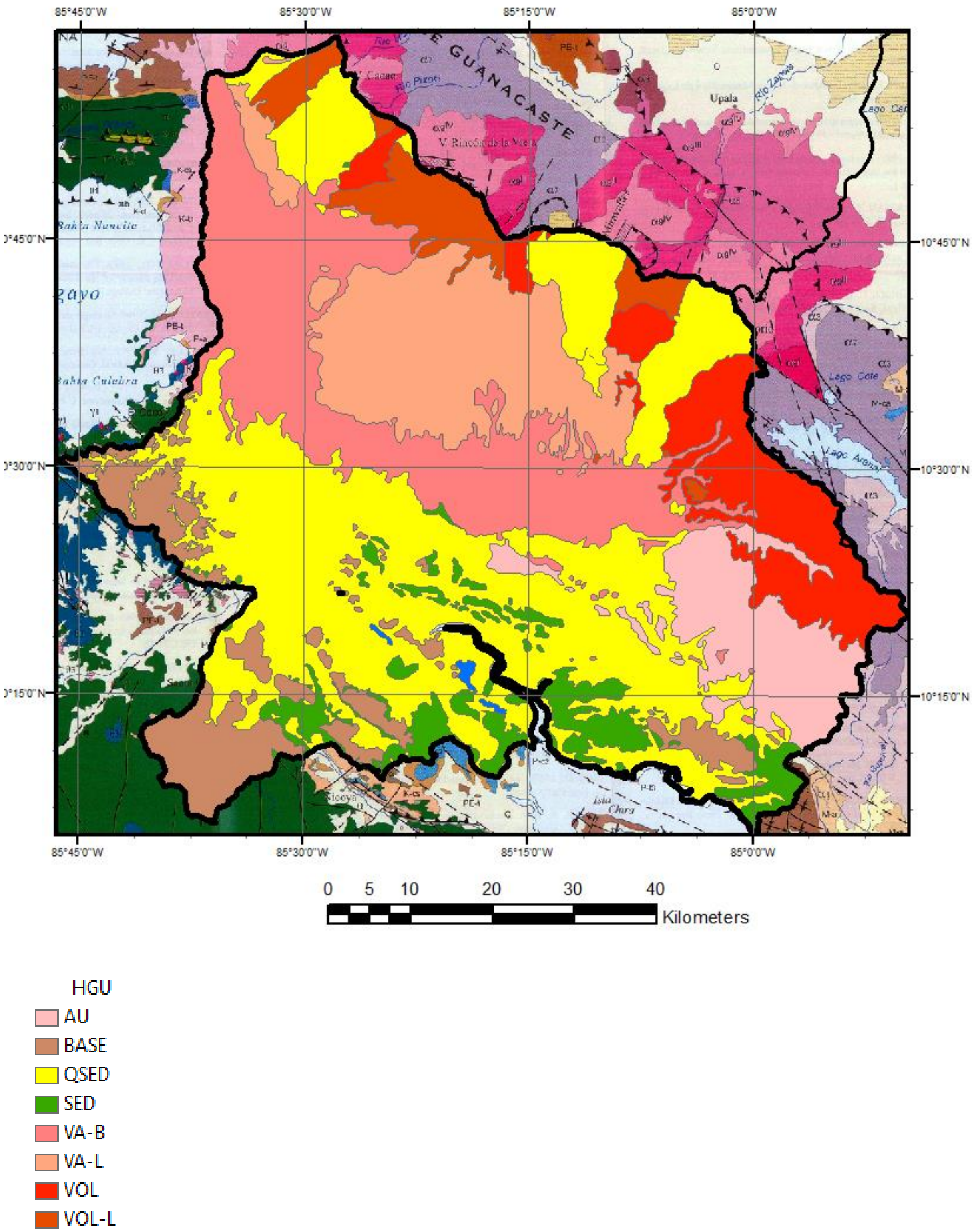


Figure 15. Map showing the hydrogeology of the Tempisque watershed.

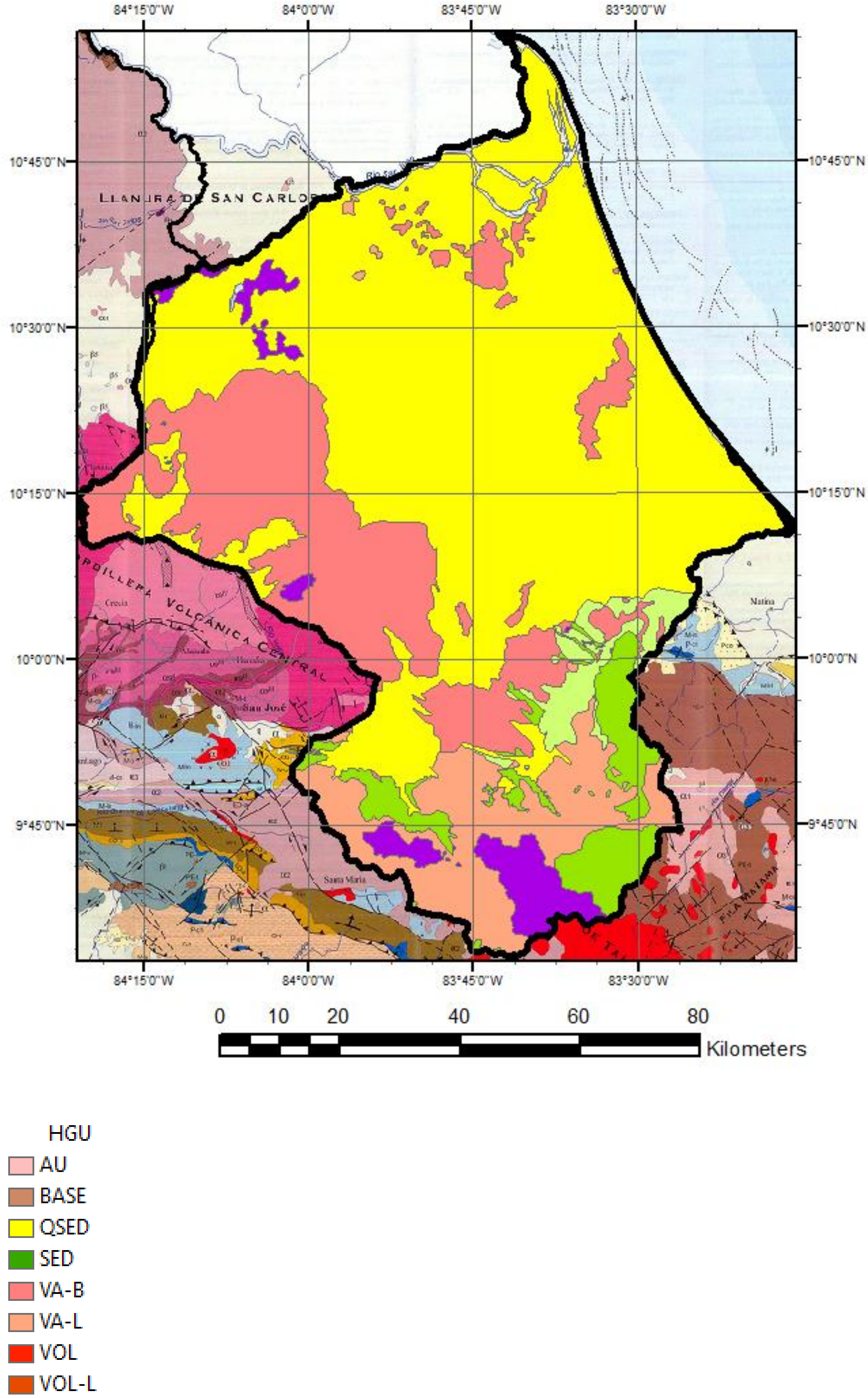


Figure 16. Map showing the hydrogeology of the Tortuguero–Sarapiqui watershed.

Hydrogeologic Framework Model

A 3-D hydrogeologic framework model (HFM) is a computer-based geometric model of the hydrogeology of the study area(s) constructed from geospatially registered surface and subsurface geologic data. It serves as an integrative platform to model subsurface geology, defining the physical geometry (altitude, thickness, and extent) and material properties of the surface and subsurface materials and structures through which groundwater flows, for all locations in the volume of interest (at a scale appropriate for the investigation).

Data from maps, wells, and cross sections (Figure 6) were compiled to create a data set of the top horizon of each HGU. These data were gridded using gridding software and the resulting grids were “stacked” in a geologic modeling program to produce an HFM. Most HFM software is not designed to handle time-stratigraphic emplacement of intrusions (unit 6 in Figure 17), these features need to be inserted into an HFM out of their correct time sequence (unit 1 in Figure 17). Therefore, intrusions, no matter what age, are represented as the lowest (“oldest”) deposition surface.

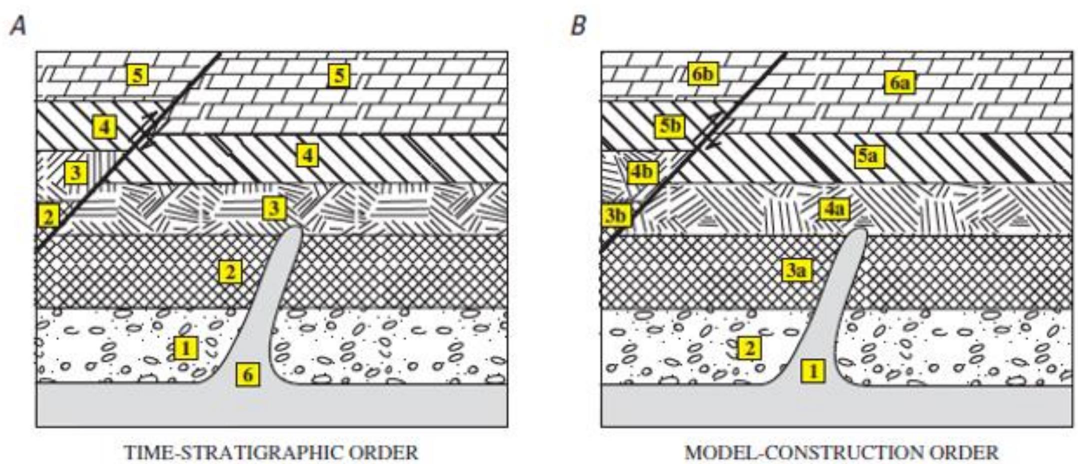


Figure 17. Diagrams showing *A*, time-stratigraphic; and *B*, model-construction order of geologic events (after Faunt and others, 2010).

The stacking order of the HGUs in the Tempisque and Tortuguero–Sarapiqui watersheds are presented in Figure 18 and Figure 19, respectively. Several HGUs depicted in Table 5 and Table 6 were combined to simplify the construction of the HFMs based on stratigraphy, lithology, and geometry.

Order	Formation	Pattern
1.0	QSED	
2.0	VA-L	
3.0	VA-B	
4.0	SED	
5.0	BASE	
6.0	VOL-L	
7.0	AU	
8.0	VOL	

Figure 18. Stacking order of HGUs used in the construction of the Tempisque watershed hydrogeologic framework model.

Order	Formation	Pattern
1.0	QSED	
2.0	VOL-L	
3.0	AU	
4.0	SED	
5.0	BASE	
6.0	INT	

Figure 19. Stacking order of hydrogeologic units used in the construction of the Tortuguero–Sarapiqui watershed hydrogeologic framework model.

Three-Dimensional Volumetric Models

Two HFMs were produced of the two priority areas (Tempisque and Tortuguero–Sarapiqui watersheds) and are presented in Figure 20 and Figure 21. These HFMs represent a volumetric model of the simplified hydrogeology of the Tempisque and Tortuguero–Sarapiqui watersheds.

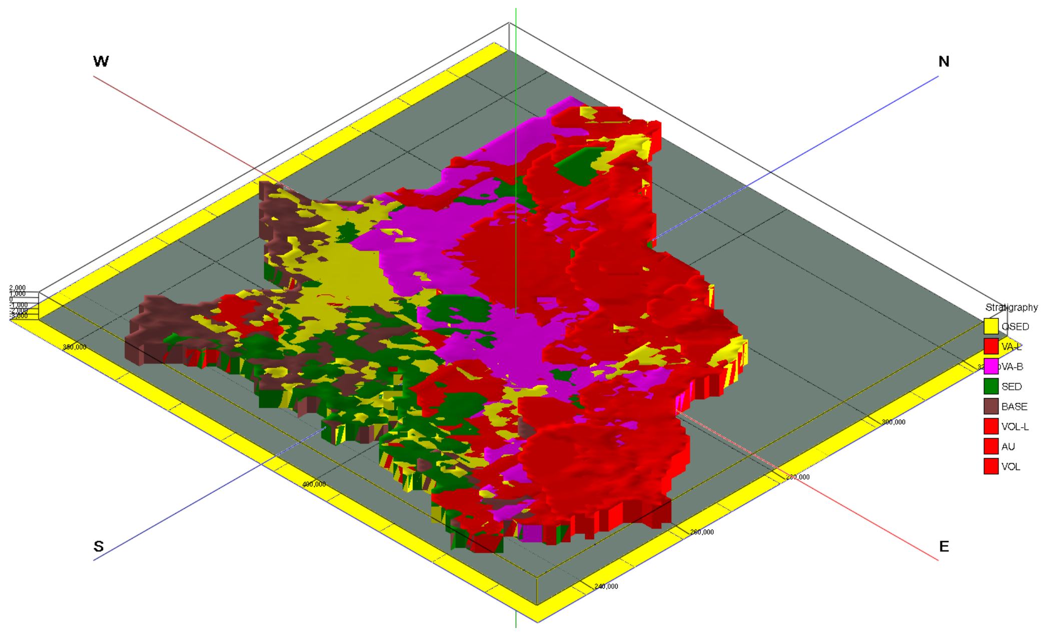


Figure 20. Isometric view of hydrogeologic framework model of the Tempisque watershed. View is to the northwest with no vertical exaggeration. Scale is variable from the isometric view.

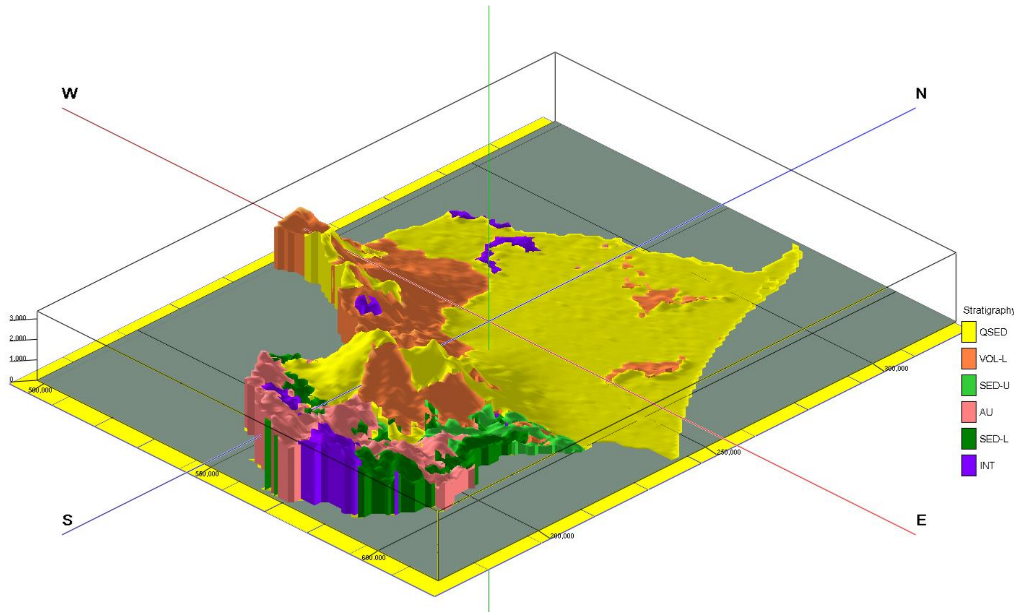


Figure 21. Isometric view of the hydrogeologic framework model of the Tortuguero–Sarapiqui watershed. View is to the northwest with a vertical exaggeration of 5. Scale is variable from the isometric view.

Estimation of Water Stored in Likely Aquifers

Using the HFM, water volumes stored in the most productive likely aquifers were calculated. For the Tempisque watershed, these were the alluvium, Bagaces, and Liberia aquifers. For the Tortuguero–Sarapiqui watershed, the alluvium and Aguacate aquifers were likely the most productive. Table 7 presents the calculated volumes of these aquifers and using specific yield values for the Tempisque region (SENARA, 2013), an estimate of the stored volume of groundwater in these aquifers was estimated. Examining ranges of specific yield reported in Anderson and Woessner (1992, p. 43), the volume of water stored in the identified aquifers in the Tempisque and Tortuguero–Sarapiqui watersheds could vary from 2 percent to almost 50 percent of the estimated aquifer volume.

Table 7. Estimates of water stored in selected aquifers in the Tempisque and Tortuguero–Sarapiqui watersheds.

Aquifers	Volume from hydrogeologic framework model cubic meters (m^3)	Specific yield (dimensionless)	[6]Volume of stored water (m^3)
Tempisque watershed			
Alluvium (QSED)	7.94E+12	[1]0.18	1.43E+12
Liberia (VA-L)	2.67E+12	[2]0.15	4.01E+11
Bagaces (VA-B)	8.61E+12	[3]0.15	1.29E+12
Tortuguero–Sarapiqui watershed			
Alluvium (QSED)	2.43E+13	[4]0.18	4.37E+12
Aguacate (AU)	1.54E+13	[5]0.15	2.31E+12

Notes:

[1]Tempisque Alluvium specific yield from SENARA and others (2013).
[2]Tempisque Bagaces specific yield from SENARA and others (2013).
[3]Liberia specific yield assumed to be same as Bagaces.
[4]Tortuguero Alluvium specific yield assumed to be same as Alluvium in Tempisque.
[5]Tortuguero Aguacate specific yield assumed to be same as Bagaces.
[6]Volumes of water, due to ranges in specific yield for the alluvium and volcanic-rock aquifers, may vary from 2 percent of the aquifer to almost 50 percent of the aquifer (Anderson and Woessner, 1992, p. 43).

Potentiometric Surface Maps

Estimated regional potentiometric surfaces were constructed to represent the top surface of the regional groundwater system in each priority area. Domenico and Schwartz (1990, p. 255–259) suggest that a regional potentiometric surface in intensely fractured, mountainous regions (such as Costa Rica) can be interpreted as a series of semi-continuous, free surfaces connected between basins by steep hydraulic gradients. The resulting water-level configuration is, therefore, interpreted as a relatively flat surface in the lowland areas connected by zones of steep hydraulic gradients in mountain blocks of comparatively low-permeability volcanic and intrusive rocks. The water-level contours are not intended to represent the water table within a specific aquifer, but rather a unified surface from which to generalize the regional occurrence and movement of groundwater across HGUs.

For the purposes of this study, the groundwater system is assumed to be in hydraulic equilibrium with no consideration for water levels affected by pumping. The water levels used to produce this map are likely a mixture of confined and unconfined water levels, especially in the bedrock units. Thus, the resulting maps represent a synthesis of potentiometric surfaces distributed across the HGUs of the priority areas.

The idealized regional potentiometric surfaces were constructed by using the locations and altitudes of regional springs, groundwater levels from wells and boreholes, surface-water features, recharge and discharge areas, the regional hydrogeology, and topography using GIS, automated interpolation techniques, and manual editing to incorporate “soft” data and tacit knowledge (D’Agnese and others, 1998). The maps were constructed by using the control-point data without consideration for either the depth of well penetration or the geologic formations (or HGUs) penetrated by the wells. The estimated idealized potentiometric surface maps developed for the Tempisque and Tortuguero–Sarapiqui watersheds do not distinguish wells screened in the alluvium from wells screened in bedrock. Figure 22 and Figure 23 present the potentiometric maps for the Tempisque and Tortuguero–Sarapiqui watersheds. In general, the groundwater in each of the regions flows from the highland areas to surface water and base levels (the oceans).

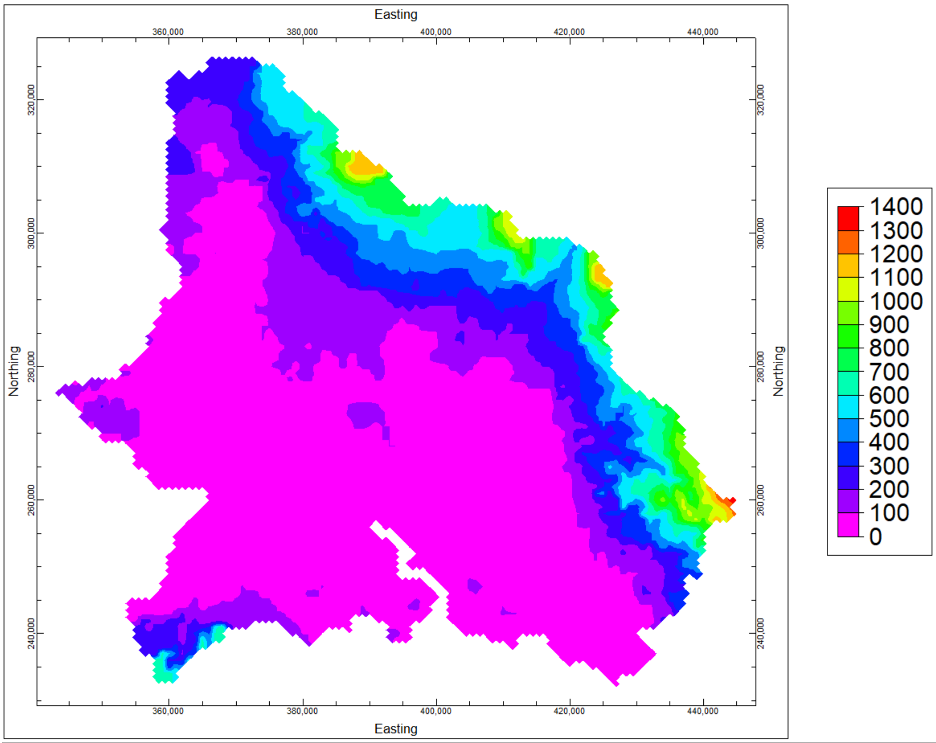


Figure 22. Map showing potentiometric surface of the Tempisque watershed (units in meters above sea level).

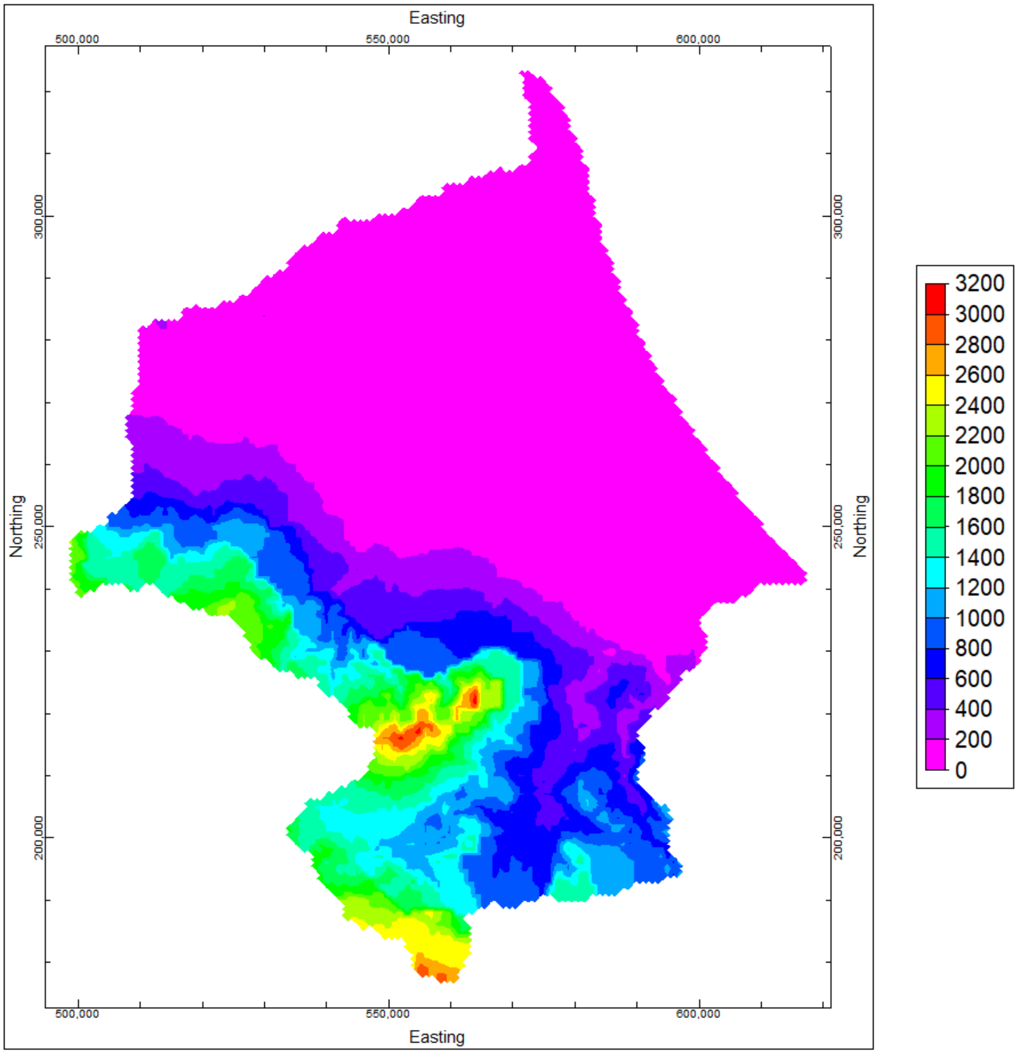


Figure 23. Map showing potentiometric surface of the Tortuguero–Sarapiqui watershed (units in meters above sea level).

Water Budget

A water budget was developed to evaluate the balance between the flow into and out of the groundwater flow system for all of Costa Rica and the two priority areas. The primary components of the water budget are:

(1) Recharge

a. net infiltration of precipitation (direct infiltration and from streams)

b. interbasin flow (unlikely)

(2) Discharge

a. groundwater evapotranspiration (ET_g)

b. spring flow

c. to rivers (gaining reaches)

d. well withdrawals

e. interbasin flow (unlikely).

Table 8, Table 9, and 0 present the water budgets for the entire country, the Tempisque watershed, and the Tortuguero–Sarapiqui watershed, respectively.

Table 8. Water budget for Costa Rica.

[Abbreviations: liters per year, l/yr]

Water budget component	Volumetric flow (l/yr)	Source/notes
RECHARGE/INFLOW		
Net infiltration/recharge	3.90E+13	Annual Average Precipitation Map 2005 (average for 2004) Institute of Meteorology; assumed 25% of precipitation is recharge based on comparative analysis of Schosinky (2007) results in SENARA and others (2013)
Interbasin flow	0.00E+00	Assumed to be 0
Total	**3.90E+13**	
DISCHARGE/OUTFLOW		
Evapotranspiration	5.84829E+13	University of New Mexico with Hargraeves and Samani (1985) with IMN data. Average ET = 1,500 mm/yr.
Permitted springs	3.4375E+11	Dirección de Agua database
Unpermitted springs	3.4375E+11	Assumed to be same as permitted springs overall
Permitted pumping	6.35E+11	MINAE database
Unpermitted pumping	2.54E+11	MINAE database; assumed to be 20-40 percent of legal pumping; used 40% for conservatism
Interbasin flow	0.00E+00	Assume 0
River flow		Incomplete data
Total	**6.01E+13**	
Difference	**-2.11E+13**	

Table 9. Water budget for the Tempisque watershed.

[Abbreviations: l/yr, liters per year]

Water Budget Component	**Volumetric flow (l/yr)**	**Data Source**
RECHARGE/INFLOW		
Net infiltration/recharge	2.61E+12	Annual Average Precipitation Map 2005 (average for 2004) Institute of Meteorology; assumed 25% of precipitation is recharge based on comparative analysis of Schosinky (2007) results in SENARA and others (2013)
Interbasin flow	0.00E+00	Assumed 0
Total	**2.61E+12**	
DISCHARGE/OUTFLOW		
Evapotranspiration	8.09E+12	University of New Mexico with Hargraeves and Samani (1985) with IMN data. Average ET = 1470 mm/yr.
Permitted springs	2.07E+10	Dirección de Agua database
Unpermitted springs	2.07E+10	Assumed to be same as permitted springs overall
Permitted pumping	1.63E+11	MINAE database
Unpermitted pumping	6.51E+10	MINAE database; assumed to be 20–40 percent of legal pumping; assumed 40% for conservatism
Interbasin flow	0.00E+00	Assumed 0
River flow	4.16E+11	Difference in upstream and downstream gages–assume groundwater fed
Total	**8.36E+12**	
Difference	-5.74E+12	

Table 10. Water budget for the Tortuguero–Sarapiqui watershed.

[Abbreviations: l/yr, liters per year]

Water budget component	Volumetric flow (l/yr)	Data source
RECHARGE/INFLOW		
Recharge	7.76E+12	Annual Average Precipitation Map 2005 (average for 2004) Institute of Meteorology; assumed 25% of precipitation is recharge based on comparative analysis of Schosinky (2007) results in SENARA and others (2013)
Interbasin flow	0.00E+00	Assumed 0
Total (IN)	**7.76E+12**	
DISCHARGE/OUTFLOW		
Evapotranspiration	1.10E+13	University of New Mexico with Hargraeves and Samani (1985) with IMN data. Average ET = 1164 mm/yr.
Permitted springs	5.34E+10	Dirección de Agua database
Unpermitted springs	5.34E+10	Assumed to be same as permitted springs overall
Permitted pumping	3.63E+10	MINAE database
Unpermitted pumping	1.09E+10	MINAE database; assumed to be 20-30 % of legal pumping; assumed 30% for conservatism
Interbasin flow	0.00E+00	Assumed none
Total (OUT)	**1.12E+13**	
Difference	-3.40E+12	More discharge than recharge

Discussion

The uncertainty in the water budgets is limited by the estimated values and uncertainties of the components that make up the overall water budget. Healy and others (2007) state, "[w]ater budgets provide a means for evaluating availability and sustainability of a water supply. A water budget simply states that the rate of change in water stored in an area is balanced by the rate at which water flows into and out of an area." The water budgets presented in this report are preliminary and national and regional in scale from uncertain data and, thus, are not balanced. It is difficult, given the nature of most of the data (such as precipitation, spring flow, presumed permitted pumping, assumed nonpermitted pumping), to assign quantitative values of uncertainty. The spring flow does not account for the possibility of evaporation or re-infiltration of flow into permeable units. The estimates of evapotranspiration (ET) are total ET values that are based on rates using assumed vegetation types and growing season using the Hargreaves and Samani (1985) method. The actual groundwater ET (ET_g) is likely less than the total ET. In one study at the La Selva Biological Station in Costa Rica, ET_g was approximately 75 percent of total ET (Cadol and others, 2012), but it is unclear how applicable this value is at regional and national scales. Recharge is assumed to be a fixed 25 percent of precipitation of the annual average from 2004. This percentage was chosen after comparing the results from the Schosinsky (2007) method of estimating recharge from SENARA and others (2013) with the total 2004 volume of precipitation over the SENARA and others (2013) study area. A more sophisticated method of estimating recharge, along with measurements of ET within the watersheds using in-place instrumentation or remotely sensed data (or a combination of both) could provide more accurate estimates, which could improve the overall water budget. The discharge of the non-permitted wells is based on an assumed percentage of the total discharge of the permitted wells, per guidance from the Technical Working Group. Flow of non-permitted springs is assumed to be equal to that of permitted springs but is essentially unknown. All water budget components, such as recharge, are limited by the inherent uncertainties in these estimates, which are described in the literature from which they were obtained.

As mentioned previously, it is not possible at this time to calculate quantitative estimates of uncertainty for the water budget components. The water budgets presented in Table 8, Table 9, and Table 10 suggest that evapotranspiration is greater than recharge by very significant amounts. These numbers could be improved by further work to improve recharge estimates and to assess the fraction of evapotranspiration provided by groundwater. Based on past experience in the United States (Belcher and Sweetkind, 2010), recharge estimates are likely to possess the greatest uncertainty within the water budget. Permitted pumping is based on the total volume allowed and not the actual pumping volumes. Non-permitted pumping is assumed to be a percentage of the permitted pumping and would have the same uncertainty.

Results of Component C–Optimization Assessment of Groundwater Development and Use

Groundwater use has continually increased in highly valued sectors in northern Costa Rica, particularly residential domestic use and tourism in the Tempisque watershed and pineapple agriculture expansion in the Tortuguero–Sarapiqui watershed. Recent stress on groundwater supplies in the Tempisque and Tortuguero–Sarapiqui watersheds threaten the sustainability of these aquifers. However, protecting aquifers by limiting groundwater use can be an economically expensive proposition because water uses that rely on groundwater supply can produce considerable value, value that could be lost if protective measures limiting withdrawals are enacted. This study presents an approach to address the economic consequence of reducing groundwater withdrawals to protect aquifers versus groundwater development and use by constructing and applying an aquifer protection optimization model for the Tempisque and Tortuguero regions in the northern part of the Republic of Costa Rica.

For this assessment, a numerical model was developed using the General Algebraic System (GAMS) software. The model optimizes pumping locations and schedules to maximize discounted net present value of benefits summed over four water-using sectors during 2014–2017.

The optimization exercise was conducted for three water-using sectors: agriculture, urban users that consist of domestic and tourism, and commercial uses. The geographic scope is two regions for each of the two provinces (aquifers), including Liberia and Caimital-Nicoya for the Tempisque watershed and the Carmen and Siquirres regions for the Tortuguero–Sarapiqui watersheds.

Optimization Scenarios

The analysis is conducted to assess consequences for each of the four potential aquifer management scenarios that could have been enacted for those years. The four scenarios are listed here:

Scenario 1 No aquifer protection was secured beyond that achieved from the existing level of pumping observed for the years 2014–2017.

Scenario 2 Aquifers were returned to observed 2014 pumping volumes over 3 years by reducing historical pumping among periods and economic sectors to minimize economic losses from the pumping restrictions. This scenario is a pure economic optimization run. It sets a lower bound on the cost of aquifer protection, but does not specify any policy, plan, or program that could guarantee that targeted reduction in pumping.

Scenario 3 Reduction of permitted pumping by all users in an amount enough to promote aquifer sustainability defined in Scenario 2. The scenario required pumping reductions among sectors to be proportional to each sectors historical pumping volumes. For example, if overall pumping must fall by a certain percentage to secure sustainability, all groundwater-dependent sectors would have their permitted pumping allowances reduced by an equal percentage. The reduced permitted pumping would require monitoring and enforcement to assure that overall pumping is reduced sufficiently to protect sustainability in both priority areas. Reductions in permitted pumping, without monitoring and enforcement, provide little assurance of securing actual pumping reductions. Weak monitoring and enforcement could be expected to result in increased unpermitted pumping.

Scenario 4 This scenario implements the same overall volume of permitted pumping reductions needed to secure aquifer sustainability as for the Scenario 3. However, for this scenario, pumping permits would be allowed to be traded among all permittees and the Government of Costa Rica in the same aquifer. This reduced permitted pumping also would require monitoring and enforcement to protect the aquifers. Allowing permit trading would tend to move shortages out of low-valued uses and limit increased shortages in high-valued uses, such as domestic, tourism, and commercial.

Results of Optimization Modeling

Results for each of the four scenarios are summarized here:

Scenario 1 With actual historical withdrawals from the aquifers (no new pumping alterations), discounted net present (2017) value of benefits over the 4-year period is 644,000,000 U.S. dollars. Of that total amount, benefits are distributed as 10 percent for agriculture in the Tempisque watershed; 3 percent to agriculture in the Tortuguero–Sarapiqui watershed; 40 percent to urban users in the Tempisque watershed; 20 percent to urban users in the Tortuguero–Sarapiqui watershed; 12 percent to commercial users in the Tempisque watershed; and 15 percent to commercial users in the Tortuguero–Sarapiqui watershed. On a per-unit volume basis, the value of water is much greater for urban (domestic and tourism) and commercial use than for irrigated agriculture.

Scenario 2 Reductions in pumping under this scenario (aquifer protection) could have been achieved during the 2014–2017 period if total pumping in the Tempisque watershed had been restricted to 83 percent of observed 2014–2017 pumping volumes and pumping in the Tortuguero–Sarapiqui watershed had been restricted to 71 percent of (2017) pumping volumes. Discounted net present 2017 value of benefits during the 4-year period was 620,354,000 U.S. dollars; a reduction of 23,647,000 U.S. dollars of benefits that was achieved. This loss was about 3.7 percent of base total historical value during 2014–2017.

Scenario 3 Reduction in all permitted pumping for all uses by a sufficient amount to promote aquifer sustainability defined in the Scenario 2, would also result in both aquifers reaching a potentiometric surface level by 2017, which is equal to 2014 observed levels. This scenario could be implemented by way of sharing required pumping reductions among sectors in proportion to their historic pumping volumes.

This scenario could produce a total benefit in discounted net present (2017) value terms equal to 603,625 U.S. dollars, a reduction of 40,375,000 dollars in benefits. This loss is about 6.3 percent of base total historical pumping volumes, which is nearly twice as much as an efficient allocation of pumping reductions.

This scenario would also reduce total pumping to 83 percent of observed volumes in the Tempisque watershed and to 71 percent of observed volumes in the Tortuguero–Sarapiqui watershed. However, the allocation among sectors of the pumping reductions would be inefficient. This inefficiency could happen because lesser valued uses (agriculture) are reduced in the same proportion as greater valued uses (domestic, tourism, and commercial).

Scenario 4 For this scenario, pumping reductions were the same as for Scenario 3, but the same overall number of pumping permits could be traded among all permittees in the same aquifer. Such trading allows water to move to its greatest valued uses, for which agricultural users would lease, rent, or trade permitted groundwater withdrawals to urban utilities, tourist locations, and commercial users. The farmers would receive cash or in-kind payment, and the buyers would receive water to continue the operation of their high-valued enterprise.

This scenario would produce an estimated total benefit in discounted net present (2017) value terms equal to 620,625 U.S. dollars, a reduction of 23,647,000 U.S. dollars compared to base historical pumping volumes, a loss of about 3.7 percent compared to base observed pumping volumes. This loss is the same as for Scenario 2 listed earlier.

As was the case in Scenarios 2 and 3; Scenario 4 could also reduce total pumping to 83 percent of observed volumes in the Tempisque watershed and to 71 percent of observed volumes in the Tortuguero–Sarapiqui watershed. However, for this scenario, the allocation among sectors of the pumping reductions would be efficient. This efficiency could happen because lesser valued uses (agriculture) are reduced in a much greater proportion than are greater valued uses (urban and commercial).

Discussion

The results of the optimization analysis suggested that sustainable adjustments to an aquifer's water balance can take place in both the Tempisque and Tortuguero–Sarapiqui watersheds. This study has attempted to increase the extent of reliable aquifer pumping scenario choices these two priority areas could experience in order to support and inform debates over sustainable aquifer planning. Establishing pumping permits that are tradeable would reduce the losses from sustainable pumping by about half compared to a proportional sharing of shortages that would also sustain the aquifers. Tradeable permits that reduce pumping to about 83 percent of historical pumping volumes in the Tempisque watershed and about 71 percent in the Tortuguero–Sarapiqui watershed can be achieved with only about a 3.7 percent reduction in long term benefits from groundwater use.

Results of Component D–Capacity Building

Any long-term effort to independently assess, develop, and manage the water resources of the Republic of Costa Rica requires a community of well-trained Costa Rican hydrologic scientists, engineers, and technicians. Program technology transfer occurred by training and performing practical exercises with active professionals, field technicians, and university water professionals. Capacity building and technology transfer was an essential part of this work, to train Costa Rican water professionals and establish ongoing relationships with the USGS. Component D focused on providing formal training in groundwater field techniques and remote sensing applications for water resources. The nature and subject of this training was determined in close consultation with the relevant Costa Rican agencies and was conducted over the period of the study. Manuals developed as part of the Capacity Building can be found in appendices 1, 2, and 3.

Summary and Conclusions

This report presents the project methods and results achieved through the technical components of the project: remote sensing tool (WATEX), hydrogeologic assessment, and optimization assessment for groundwater development and use. More detail of these components can be found in the appendices. This was a national-scale study; it is anticipated that this national study will lead Costa Rican geoscientists to complete similar site-specific studies using these methods with more focused and detailed field work on specific areas.

Component A, the remote sensing tool (WATEX) results suggested that the principal hydrogeological assets of Costa Rica are based on fractured Miocene–Pliocene marine sedimentary rocks (15 to 5 million years old) and on the Holocene- to Neogene-aged fractured volcanic rocks (5 million years to present). All these aquifers have enhanced permeability from fracturing in the pull-apart zone, as observed in the Central Valley and Tortuguero–Sarapiqui watershed. The structural control of this pull-apart zone, which has an area of about 10,000 square kilometers (km^2), tends to allow greater amounts of recharge in the zone through open fractures. Maps showing groundwater potential for aquifers at 0–30 meters (m) deep, 30–150 m deep, and greater than 150 m deep were produced; these maps can be used to guide the development of groundwater resources in Costa Rica. For example, these maps were used to select two priority areas (Tempisque and Tortuguero–Sarapiqui watershed) to focus the work of Component B, Hydrogeologic Assessment, and Component C, Optimization Assessment for Groundwater Development and Use.

For each of the priority areas, Component B, Hydrogeologic Assessment, produced a hydrogeologic map of hydrogeologic units, hydrogeologic framework model, potentiometric map of regional water levels, and a water budget. The hydrogeologic framework model (HFM) was used to assess the volume of water stored in selected aquifers. The potentiometric maps presented flow directions from highland recharge areas to lowland areas and the oceans. Water budgets suggested that the aquifers in Costa Rica were being over-pumped, which called out the need for scientific optimization studies to inform policy debates about groundwater development and use.

Component C, Optimization Assessment for Groundwater Development and Use, analyzed four scenarios: no action, Scenario 1; reduction of pumping to 2014 levels, Scenario 2; shared reduction to return to sustainable levels, Scenario 3; and reduction in pumping through permit trading, Scenario 4. The results of the optimization analysis of these scenarios suggested that sustainable adjustments to an aquifer's water balance can occur in both the Tempisque and Tortuguero–Sarapiqui watersheds. The optimization assessment has attempted to increase the extent of reliable aquifer management choices in the two priority areas to support and inform debates over sustainable aquifer planning. It is worth noting here that in future site-specific studies, hydrogeologic assessment would be used to determine the sustainable amount of groundwater withdrawal, and optimization analysis would be used to determine allocation of groundwater in order to maximize the economic benefits.

Component D, Capacity Building and Technology Transfer, consisted of training for Costa Rican water professionals on remote sensing, use of a software/hardware system for using the results of WATEX, construction of hydrogeologic framework models, and optimization modeling.

Recommendations

Sustainable groundwater use in Costa Rica is most effective when governed by management institutions, in conjunction with regional stakeholders, that are informed by science and consider hydrologic, environmental, and political constraints. In this investigation, multidisciplinary studies (remote sensing tool [WATEX], hydrogeologic assessment, and optimization assessment for groundwater development and use) were supported by the best available data. These data were compiled and evaluated for the remote sensing tool (WATEX), the hydrogeologic assessment, and the optimization. Considerable improvement of the regional water budgets could be obtained by additional research in ET and recharge.

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Appendix 1–Component A Reports, Maps, and Cross Sections

Report_CostaRica_RTI_Final.docx
Annex_Data_Collection_Report_Final.docx
Annex_Remote_Sensing_Data_Report_Final.docx
Annex_Potential_micro-dams_Report_Final.docx
Annex_CostaRica_Fieldtrip_Report_Final.docx
Annex_GENS_User_Guide_Final.docx
Cross_Sections.jpg
Potential_Aquifers_Map_0-30m_400K.jpg
Potential_Aquifers_Map_0-30m_E_200K.jpg
Potential_Aquifers_Map_0-30m_W_200K.jpg
Potential_Aquifers_Map_30-150m_400K.jpg
Potential_Aquifers_Map_30-150m_E_200K.jpg
Potential_Aquifers_Map_30-150m_W_200K.jpg
Potential_Aquifers_Map_below150m_400K.jpg
Potential_Aquifers_Map_below150m_E_200K.jpg
Potential_Aquifers_Map_below150m_W_200K.jpg
Structural_Map_400K.jpg
Structural_Map_E_200K.jpg
Structural_Map_W_200K.jpg

Appendix 2–Component B Hydrogeologic Framework Manual

HFM_Manual_Final.pdf

Appendix 3–Component C Reports, Model Files

(these reports in various formats are found in the accompanying folder named “Appendix 3”)

Optimization_Report_Final.pdf
GAMS_Manual_Final.pdf

ModelFiles_1019 folder:
CR_Sept_30_2019_257pm_usmdt.xlsm (Excel spreadsheet)
CR_Sept_30_2019_257pm_usmdt.gms (GMS model input – text file)