Technical Memorandum

South Coast Wastewater Reclamation Project
Groundwater Modeling of Christ Church Aquifer

Barbados Water Authority

March 31, 2021
Revised and Updated May 21, 2021

Table of Contents

Figures

Tables

1. Project Background, Objectives and Approach

1.1 Project Background

The Barbados Water Authority (BWA) is evaluating the feasibility of upgrading its South Coast Sewage Treatment Plant (SCSTP) from existing advanced preliminary wastewater treatment with a tertiary/advanced treatment plant capable of producing water suitable for groundwater recharge in a potable aquifer and/or a non-potable aquifer, or suitable for edible food crop irrigation. The proposed South Coast Water Reclamation Project (Project) is a vital and sustainable water initiative that helps BWA and its partners in transforming the existing SCSTP into a futuristic South Coast Water Resource Recovery Facility (SCWRRF). Goals of the Project are multiple: augment existing water supplies, mitigate climate change effects, address seawater intrusion and sea level rise, diversify potable water sources, enhance water supply resiliency, and reduce the impact of treated effluent on marine life and the environment.

In November 2020, AECOM completed its report, “South-Coast Water Reclamation Pre-Feasibility Study” for BWA. The pre-feasibility study considered possible end uses for reclaimed water, water-reclamation treatment options, life-cycle costs and a variety of other technical criteria. Among other things, AECOM concluded that direct or indirect recharge of Barbados’ karst limestone aquifer using reclaimed water is conceptually feasible. AECOM concluded that several hypothetical recharge well options in southern Barbados, including the Christ Church area, were also conceptually feasible.

1.2 Project Objectives

In further support of the SCSTP project, BWA has authorized AECOM to use the existing Burnside/XCG (2010) groundwater flow model to further evaluate the prospect of returning treated wastewater to the Christ Church aquifer through recharge wells. The modeling effort is intended to support the preparation of an Environmental Impact Assessment (EIA) currently in preparation for the SCWRRF project.

BWA’s overarching objective can be stated as follows:

What would be the outcome if 9 million liters per day (ML/d) (approximately 2 million Imperial gallons per day, MIGD) of treated wastewater were recharged through wells to the “non-potable” aquifer in the Christ Church area?

BWA’s specific concerns are:

1. Would the recharged water flow into the adjacent potable aquifers to the north and, if so, what would be the effects?
2. What impacts would the recharged water have on a proposed 3 or 6 MIGD Brackish Water Reverse Osmosis (BWRO) plant now being considered in the area of Wilcox Ridge/Providence?
3. What impacts could be expected, in terms of quality and quantity, on downstream private wells currently used for irrigation?
4. Where will the recharged water reach the coast, and what environmental impacts will ensue, especially in terms of contaminant loading of coastal waters (nitrogen, phosphorous, microbiological, total organic carbon)?
5. Is recharging the Christ Church aquifer at this chosen site technically, economically and environmentally sustainable over the next 20 years?
6. What impact would recharge of the Christ Church aquifer and the groundwater extraction from the BWRO facility have on the reported hydrocarbon contamination of that aquifer?

During the proposal stage, AECOM reviewed the Burnside/XCG groundwater flow model and concluded that the model, while suitable for delineating wellhead protection areas, was somewhat limited in its ability to answer broader questions of groundwater flow. Accordingly, AECOM stated that the model may be suitable for addressing objectives 1 and 2, pending formal AECOM review of the model files. We further stated that objectives 3 and 4 could be addressed in a qualitative way, in terms of generalized groundwater flux originating at the recharge wells.

1.3 Project Approach

The approach AECOM used to meet the project objectives is summarized below:

1. Formal review of the Burnside/XCG (2010) groundwater model; this step was completed before running any simulations to identify model limitations and uncertainties.
2. Review relevant available reports, maps and documentation relative to the hydrogeology of Barbados, with emphasis on the Christ Church aquifer.
3. Update the existing Conceptual Site Model (CSM); the CSM is a description of the aquifer structure and how water enters, flows through, and exits the aquifer.
4. Update the Burnside/XCG model to the GMS platform; attempt to replicate the simulations performed by Burnside/XCG; identify model issues, uncertainties, and limitations.
5. Host a webinar with BWA and other interested parties to report on the model's predictive capabilities.
6. Run the model to simulate 2 MIGD subsurface recharge at the proposed site; evaluate changes in groundwater elevations and flow paths using MODPATH near the recharge well, near the proposed BWRO plant, and in the vicinity of the downstream private wells along the south coast.
7. Identify areas of data gaps and features for model improvements.
8. Prepare a technical memorandum summarizing the work completed along with recommendations.
9. Prepare for and attend one web-based meeting to discuss results.

AECOM completed the above-stated scope of work and submitted its report on March 31, 2021. BWA provided feedback on the report in April and May 2021, and requested that AECOM add two model simulations to more fully evaluate potential impacts to the coast, hydrocarbon releases and irrigation wells, namely:

1. 4-month recharge (of treated wastewater) of 2 MIGD at A1-Alt1 and year-round BWRO withdrawals of 6 MIGD
2. Full-year recharge (of treated wastewater) of 2 MIGD at A1-Alt1 and 0 MIGD BWRO withdrawal

BWA also requested that AECOM consider, at a conceptual level, the impacts of recharge of treated wastewater on existing nitrate levels in the Christ Church Aquifer.

Revisions and updates to AECOM's original report are contained largely in Sections 3.4 to 3.8 and Attachment A (now annotated) of this May 21, 2021 report. Other sections remain largely or entirely unchanged.

2. Conceptual Site Model (CSM)

2.1 Overview of Barbados Hydrogeology

In November 2020, AECOM completed its report “South-Coast Water Reclamation Pre-Feasibility Study” for BWA as a basis for understanding aquifer recharge and groundwater flow and for selecting potential scenarios for reclaimed water use. The overview of Barbados Hydrogeology presented herein is partially excerpted from that report and updated with information from the following investigations:

- Burnside, R.J., International Limited, November 2010, *Comprehensive Review and Overhaul of Barbados' Groundwater Protection Zoning Policy and System, Volume 3 – Water Resources and Hydrogeolog*y.
- Burnside, R.J., International Limited, June 2011, *Comprehensive Review and Overhaul of Barbados' Groundwater Protection Zoning Policy and System," Volume 3 – Water Resources and Hydrogeology*.
- Farrell, D.A. et al., 2008, *Characterization and Modeling of Seawater Intrusion In An Aquifer Along the West Coast of Barbados*, SAGEEP Proceedings.
- Humphrey, J.D., 1997, “Geology and Hydrogeology of Barbados”, Chapter 11 in *Geology and Hydrogeology of Carbonate Islands, Developments in Sedimentology*, 54, edited by Vacher, H.L., and Quinn, T., Elsevier B.V.
- Jones, Ian, December 2002, *Geochemical Evolution of Groundwater in the Pleistocene Limestone Aquifer of Barbados*, PhD Thesis of Ian Jones, University of Texas at Austin, December 2002.
- Jones, I. and J. Banner, September 2003, “Hydrogeologic and climatic influences on spatial and interannual variation of recharge to a tropical karst island aquifer”, *Water Resources Research*/Volume 39, Issue 9, September 2003.
- Klohn-Crippen Consultants Ltd/Stanley Associates Engineering Ltd, 1997, *Draft Report on Task 2 – Reliable Yield Analysis for the Water Resources Management for the* Water Loss Study.
- Poole, E.G. and Barker, L.H., 1983, The Geology of Barbados, 1:50,000 Sheet, Directorate of Overseas Surveys and Government of Barbados, St Michael.
- Stanley Associates Engineering Ltd, 1978, *Barbados Water Resources Study*.
- XCG Consultants Ltd, January 2010, *Draft Final Report, Barbados Regional Groundwater Model – Developed for Planning Purposes*.

AECOM also reviewed information provided by BWA, such as water quality, soil-types, and supply-well data. Key elements of the physiography, geology, groundwater occurrence, groundwater recharge, groundwater resource potential, water-supply wells and groundwater quality of Barbados are summarized below. Refer also to maps prepared by or adapted from previous investigators.

2.1.1 General Physiography

Barbados is an island of roughly 432 square kilometres (km^2) (167 square miles), whose land-surface elevation ranges from sea level along the coastline to roughly 335 metres (m) (1100 feet) near the center of the island at Sugar Hill.

2.1.2 Generalized Geology

The main geologic feature is a Pleistocene coral-reef limestone up to 90 m thick, which caps 87% of the island. The limestone rests unconformably on Tertiary (Eocene to Miocene age) basement bedrock of deep-sea origin, which consist of mudstones and marls up to 350 m thick. The Tertiary rocks are exposed only in the highlands in the east-central portion of the island. For the most part, the Tertiary rocks are assumed to act as an aquiclude, preventing downward movement of groundwater from the limestone. (See Figure 2-1, Barbados Geology, below; note that the Joe's River, Scotland formations, Oceanics Group, and Bissex Hill formation are the Tertiary rocks.)

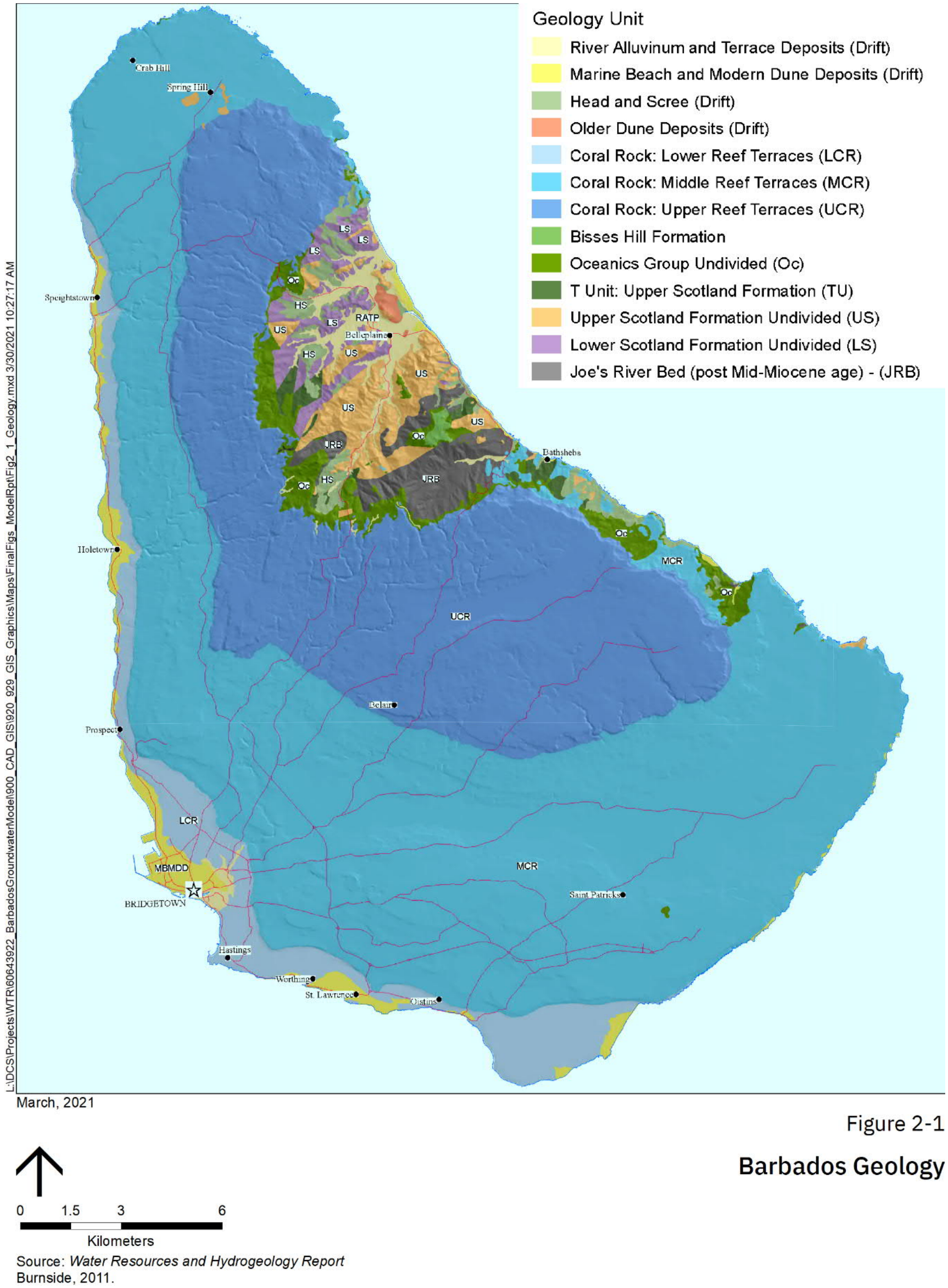


Figure 2-1 Barbados Geology

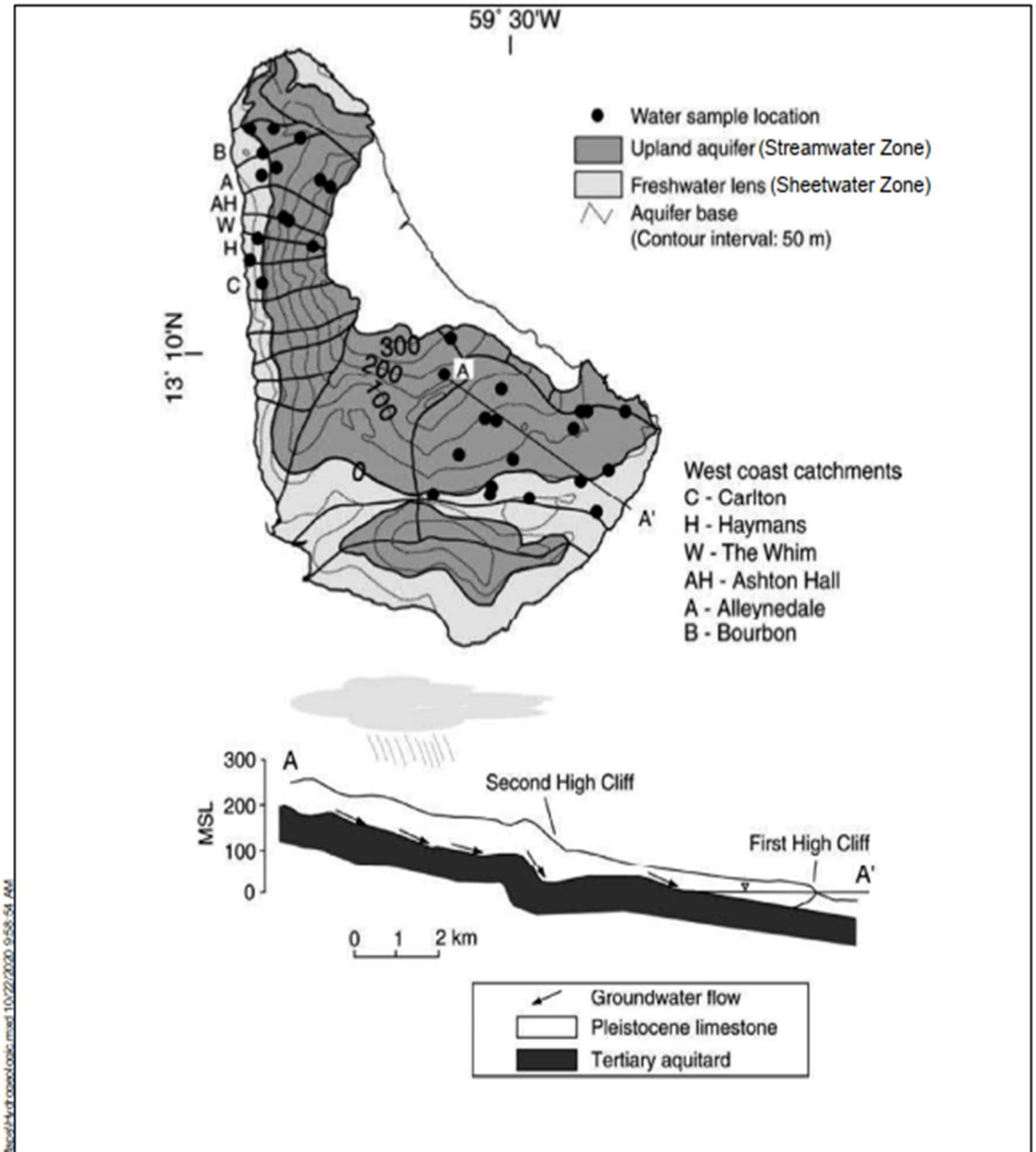
Barbados has been continuously uplifted from the east due to the collision of the Atlantic and Caribbean plates. Uplift has caused the top of the Tertiary rocks (and the base of the limestone) to arch radially and slope generally to the northwest, west, southwest, and south (Figure 2-1).

2.1.3 Groundwater Occurrence

Groundwater in the coral-reef limestone aquifer is unconfined. Near and along the coast, the base of the limestone in contact with the Tertiary basement rock slopes downward, extending beneath sea level. Groundwater in this zone, which pools at elevations slightly above sea level, is categorized as “sheet-water.” Groundwater in the sheet-water zone is assumed to flow laminarly towards the ocean and to float on seawater or brackish water, creating a lens of freshwater 10 to 25 metres thick (Figure 2-2 and Figure 2-3).

Inland, the base of the limestone extends above sea level, sloping upward toward the highlands and reaching elevations of perhaps 250 metres. Groundwater in this zone is categorized as stream-water. While water-table elevations in the stream-water zone have not been systematically measured, groundwater modeling suggests hydraulic gradients ranging from about 0.01 to 0.06. Groundwater in the stream-water zone is assumed to flow predominantly in conduits in karstic limestone. The saturated thickness of groundwater in the stream-water zone may be less than a metre (Figure 2-2 and Figure 2-3).

Borehole video inspections, and borehole- and surface-geophysical surveys conducted by Burnside (2011) provide insight into the makeup of the coral-limestone aquifer. The limestone is described in some areas as banded with “variations from sandy to clayey layers.” Clay-rich zones occur frequently, which can perch groundwater locally. The limestone commonly contains vugs, conduits, fractures, joints, fissures, cavities, caverns, and other karstic features, all of which enhance the porosity and permeability. While intergranular porosity undoubtedly exists in the limestone, much of the flow of groundwater in both the stream-water and sheet-water zones is assumed to flow through discrete conduits. It is noteworthy that the groundwater model developed by Burnside/XCG (2010) assumes intergranular (primary) porosity, as it would be impossible to account for the location and character of individual conduits in the limestone. This matter is discussed further in the limitations section.



Hydrogeologic map of Barbados. The Pleistocene limestone aquifer is divided into several groundwater catchments due to the topography of the Pleistocene-Tertiary contact. Adapted from hydrogeologic map by Stanley Associates (1978) and cross-section by Barbados Ministry of Health et al. (1991).

Figure 2-2 Stream-Water and Sheet-Water Zones of Groundwater Flow

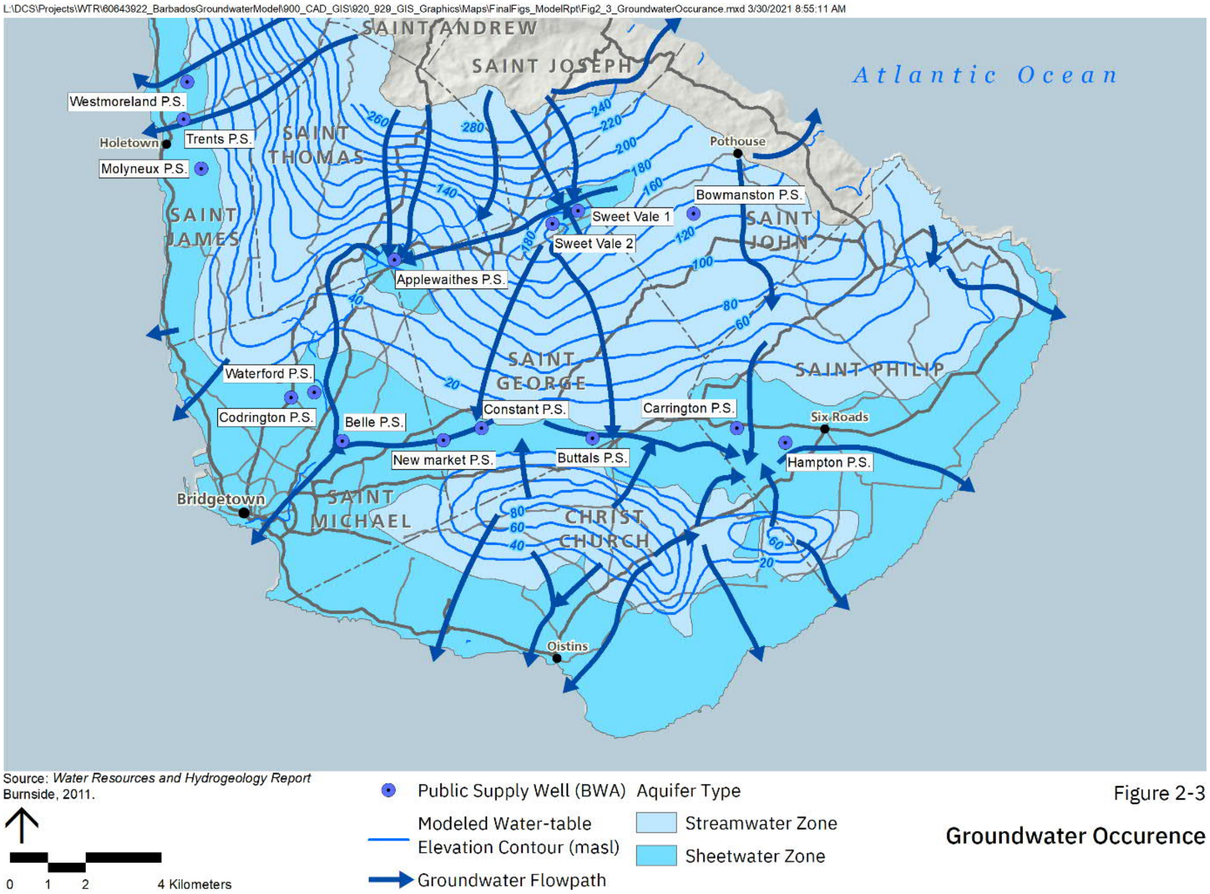


Figure 2-3 Groundwater Occurrence

2.1.4 Groundwater Recharge

The soils covering the limestone aquifer are typically 2 m thick and contain 60% to 70% clay minerals, which can swell when they become wet, reducing infiltration. The measured infiltration rates of the soils range from about 12.5 to greater than 250 millimetres per hour. In contrast, the underlying limestone has a measured infiltration capacity ranging from 700 to 70000 millimetres per hour.

Recharge to the coral-limestone aquifer occurs both diffusely through the soils and discretely through dry valleys and sink holes. Both dry valleys and sink holes are numerous, especially at elevations of 100 to 150 m. Most recharge to the aquifer generally occurs only after heavy rain events. Discrete recharge through dry valleys and sinkholes may take several minutes to a few days. Diffuse recharge through soils may take a few days to several months.

Evidence derived primarily from long-term groundwater hydrographs and oxygen isotope testing suggests that most of the annual recharge to the limestone aquifer may occur only in the wettest 1 to 3 months, typically August, September, and October. Monthly rainfall of less than 195 mm may contribute very little to aquifer recharge because of high evapotranspiration rates.

Average annual recharge is roughly 15% to 30% of annual rainfall, which ranges from 1000 to 2000 millimetres per year. (Note that the Burnside model, discussed below, assumes 35% of annual rainfall as the recharge.)

2.1.5 Groundwater Resource Potential

Based on studies performed in 1966 and 1978, the potential groundwater resource on Barbados has been estimated to range from 59 to 84 million m3/year. Groundwater recharge rates estimated by Burnside in 2011 suggest that the actual groundwater resource could be higher than the earlier estimates. Groundwater use has been estimated to range from 47 to 50 million m3/year.

2.1.6 Water-Supply Wells

Figure 2-4 shows the BWA water supply wells and other private well locations in the southern half of the island. Most of BWA's wells are constructed in the sheet-water zone where well capacities are highest. The Belle Pumping Station, for example, typically produces nearly 38,000 cubic metres per day (about 8.35 MIGD) of potable water. Wells constructed in the sheet-water zone benefit from high hydraulic conductivity, estimated from groundwater modeling to average 1,300 metres per day. In addition, the saturated thickness of 10 to 25 metres, the flat water-table and the large catchment areas undoubtedly contribute to the high well capacities of wells in the sheet-water zone. Wells built in the stream-water zone are typically far less productive (Figure 2-4).

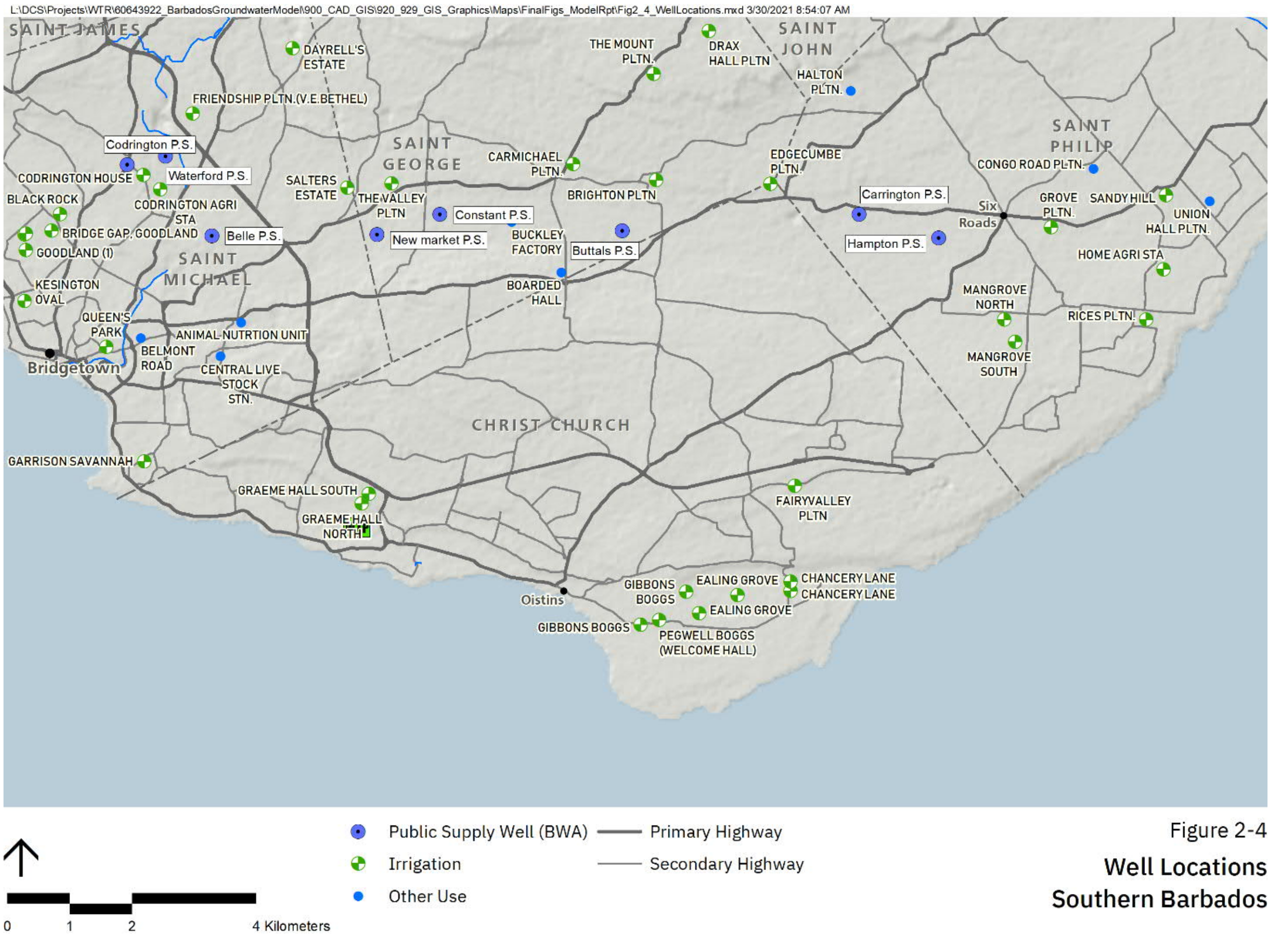


Figure 2-4 Well Locations - Southern Barbados

2.1.7 Groundwater Quality

Table 2-1 summarizes the overall groundwater quality tested by BWA at the Belle Pumping Station and the Hampton Pumping Station for the period 2015 to 2020. These data are presumed to be representative of groundwater quality in the sheet-water zone of the Saint George Valley, but not necessarily elsewhere. Table 2-1 also shows the water quality in the Thomas Well (irrigation well) in August 2005 (BADMC data). The Thomas Well water-quality represents only a snapshot in time at one particular well but suggests brackish quality in the Christ Church aquifer.

Table 2-1 Summary of Key Water Quality Parametres, Belle and Hampton Aquifers (2015 – 2020) and Christ Church Aquifer (BADMC, August 2005)

		Belle PS (Belle Aquifer)		Hampton PS (Hampton Aquifer)		Christ Church (Non-Potable Aquifer)
Parametre	**Units**	Minimum	Maximum	Minimum	Maximum	Thomas Well
Total Alkalinity (as CaCO3)	mg/L	212	299	118	242	
Ammonia-N	mg/L	<0.05	0.27	<0.05	0.26	
Bicarbonate	mg/L	259	362	144	289	
Calcium	mg/L	190	322	133	278	
Chloride	mg/L	45	97	79	117	256
Conductivity	µmho/cm	637	913	531	852	1,373
Magnesium	mg/L	26	68	31	70	
Nitrate-N	mg/L	5.9	11	<1	11.2	1.98
pH	Std Units	6.4	7.4	6.2	7.5	7.8
Potassium	mg/L	3.0	6.3	2.8	4.8	
Sodium	mg/L	30	77	24	73	179
Sulfate	mg/L	26	42	10	35	
TDS	mg/L	360	543	290	525	754
Total Phosphate	mg/L	<0.05	0.22	<0.05	0.3	
Total Hardness (as CaCO3)	mg/L	230	386	165	329	

2.1.8 Conceptual Site Model – Christ Church Aquifer

As stated above, BWA's overarching concern relates to the possible outcome of recharging 9 ML/d or about 2 MIGD of treated wastewater to the "non-potable" aquifer in the Christ Church area. Specifically, BWA is concerned about possible impacts on the following: 1) BWA water-supply wells in the St. George valley (to the north), 2) private irrigation wells in the Christ Church aquifer, 3) a possible BWRO plant at Wilcox Ridge/Providence, 4) coastal waters, and 5) hydrocarbon contamination in the Christ Church Aquifer.

The Christ Church aquifer is defined, herein, as the roughly 52.1 square-kilometre watershed, that covers the southern tip of the island, shown on Figure 2-5 below. AECOM has adopted the sub-catchments shown on Figure 11-11 of Humphrey (1997), assuming surface and groundwater divides are coincident. The groundwater basin divide shown on Figure 2-5 extends in a somewhat arc shape through Christ Church to both the southeast and southwest coasts. The bow-shaped ridge seen at the ground surface is a rough expression of an underground ridge of Tertiary basement rocks that extend above sea level, creating a groundwater divide in the stream-water zone (See Figures 2-2 and 2-3). In the sheet-water zone, no such geologic structure exists that controls the groundwater divide. Instead, the divides in the sheet-water zone coincide with groundwater flow paths in the direction of the coast. The divides in the sheet-water zone could vary with time, for example, responding to transient recharge and/or to nearby groundwater withdrawals.

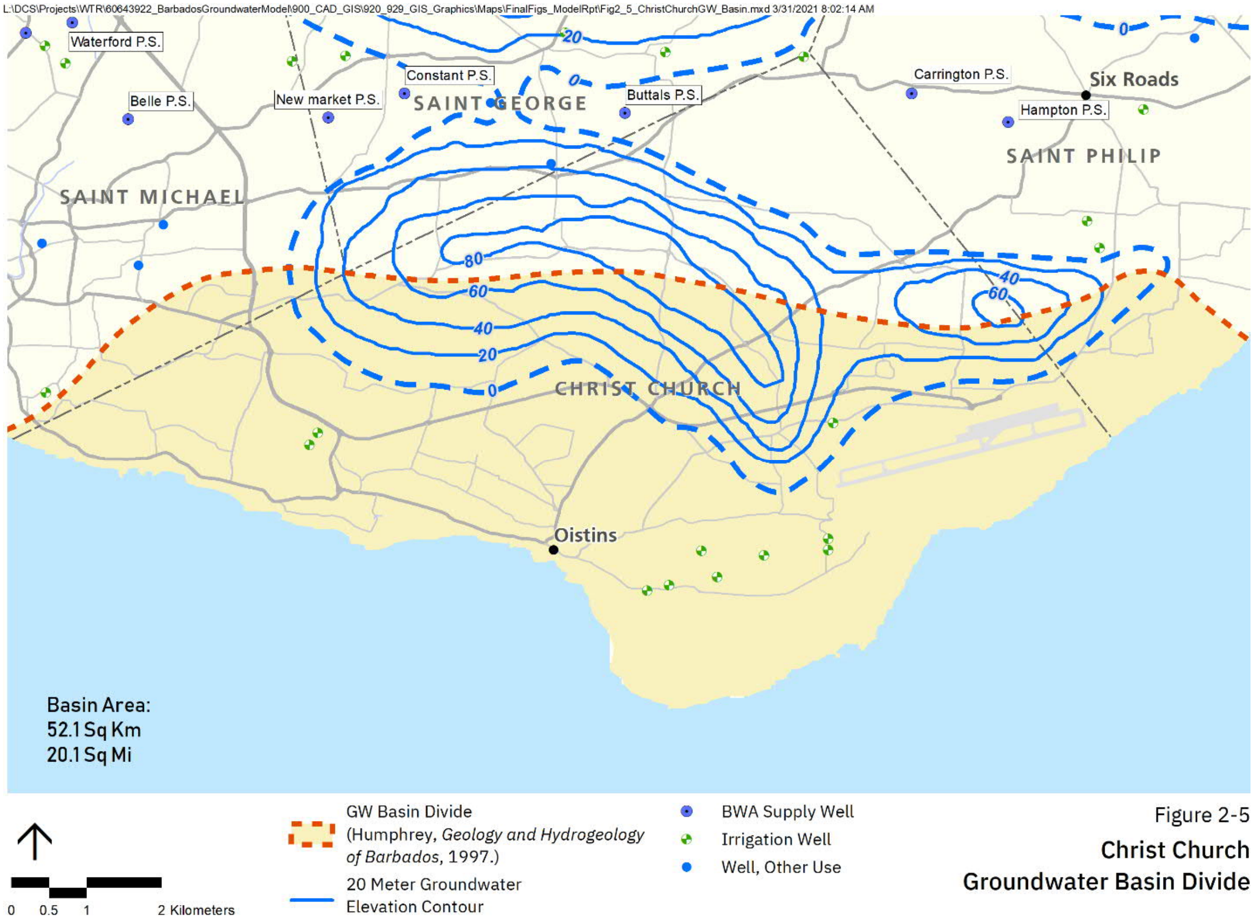


Figure 2-5 Christ Church Aquifer – Groundwater Basin Divide

The stream-water zone represents only about 14.3 square kilometres or 25% of the Christ Church aquifer. If recharge occurs predominantly during the three wettest months of the year and fracture flow is dominant, much of the recharge may run out of the stream-water zone quickly, leaving a very thin saturated zone for much of the year. The saturated zone of the stream-water zone could be much less than one metre thick, and as little as 0.1-metre thick, according to the Burnside/XCG model. This is perhaps why groundwater withdrawals from the Christ Church aquifer are almost exclusively in the sheet-water zone. Based on Stanley (1978), the freshwater lens in the sheet-water zone beneath the Lower Coral Reef (LCR) is about three metres thick and likely floats on brackish water, underlain by saltwater, as shown Figure 2-6 (note that the vertical scale is in feet). Figure 2-6 also suggests that the freshwater lens does not extend all the way to the coast, but instead thins oceanward and terminates about 300 metres inland.

Based on estimates by Burnside/XCG (2010) the Christ Church Aquifer receives approximately 23 million cubic metres of recharge annually. In the Christ Church watershed area (52.1 square kilometres), the average annual recharge rate is 441 millimetres per year. Without groundwater withdrawals, recharge would flow southerly from the groundwater divide and eventually discharge near the coast. Known groundwater extraction rates for irrigation wells in the Christ Church area total just over 1,000 cubic metres per day.

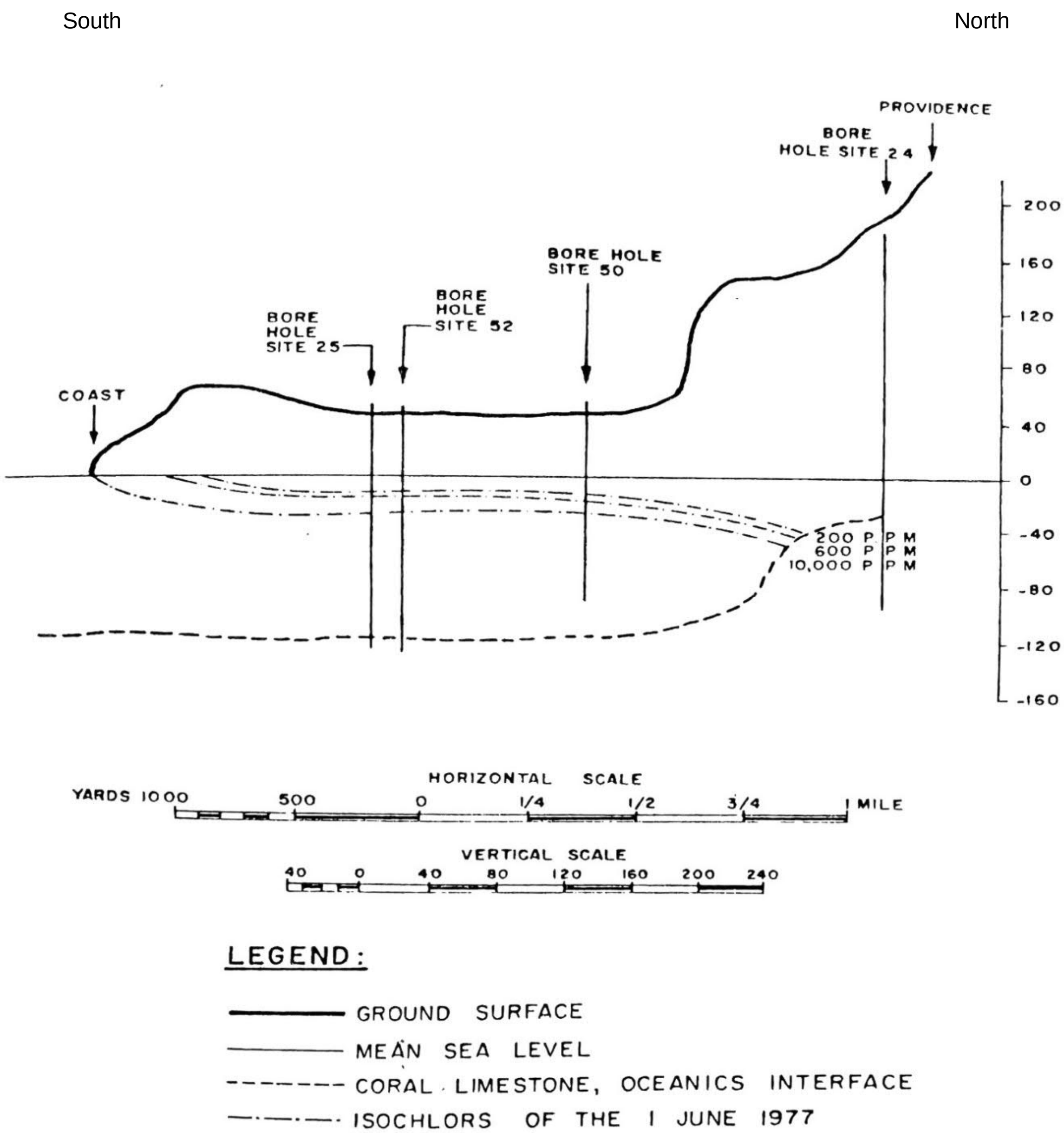


Figure 2-6 Measured Groundwater Salinity – Christ Church Aquifer (after Stanley Assoc., 1978)

Despite the many hydrogeological investigations of the coral limestone aquifer over the last eight decades, it has been difficult to establish values for hydraulic conductivity that can be applied in groundwater modeling. As mentioned above, groundwater is believed to flow predominantly in discrete conduits in the karst limestone, but also in the intergranular pore space. As shown on Figure 2-1, the southernmost tip of Barbados is underlain by rock of the Lower Coral Reef (LCR), the youngest of the karst limestone members, which is less than 127,000 years old (Poole and Barker, 1983). The remainder of the Christ Church aquifer is mapped as Middle Coral Reef (MCR) rock, which is 127,000 to 484,000 years old (Poole and Barker, 1983). The MCR has been exposed to processes of weathering and solutioning for longer than the LCR, and theoretically should generally be more permeable than the LCR. However, because coral reef deposition has been more-or-less continuous, variations in porosity (both primary and secondary) and permeability may vary over the area gradationally. If this is the case, the limestone closest to the coast would be expected to have the lowest porosity and permeability. If discrete conduits of groundwater flow occur in the limestone in the Christ Church Aquifer, the landscape does not betray their presence. Dry valleys that might suggest bedrock fracturing are largely absent from the Christ Church aquifer. Sink holes, while common in the stream-water zone of the Christ Church Aquifer, are rarer in the sheet-water zone and nearly absent from the LCR (Figure 2-7).

Published values for hydraulic conductivity are shown in the Table 2-2 below.

Table 2-2 Summary of Hydraulic Conductivity Estimates

Location	Permeability	Hydraulic Conductivity, K	Reference
Stream-water zone, Island-Wide		90 m/day (300 ft/day)	Burnside/XCG (2010)
Sheet-water zone, Island-Wide		1,300 m/day (4,300 ft/day)	Burnside/XCG (2010)
Applewhaites P Sta.		90 m/day (300 ft/day)	Humphrey (1997)
Porters/Trents Well Fields, Holetown	1 x 10-11 m2	8 m/day (25 ft/day)	Parallel to coast, Farrell et al (2008)
Porters/Trents Well Fields, Holetown	5 x 10-11 m2	40 m/day (125 ft/day)	Perpendicular to coast, Farrell et al (2008)
Island-Wide, excludes Christ Church		4,300 to 17,300 m/day	Klohn-Crippen (1997), model-calibrated K; (field testing indicates much lower K)

L:\DCS\Projects\WTR\60643922_BarbadosGroundwaterModel\900_CAD_GIS\920_929_GIS_Graphics\Maps\FinalFigs_ModelRpt\Fig_2_7_Sinkholes.mxd 3/31/2021 8:03:39 AM

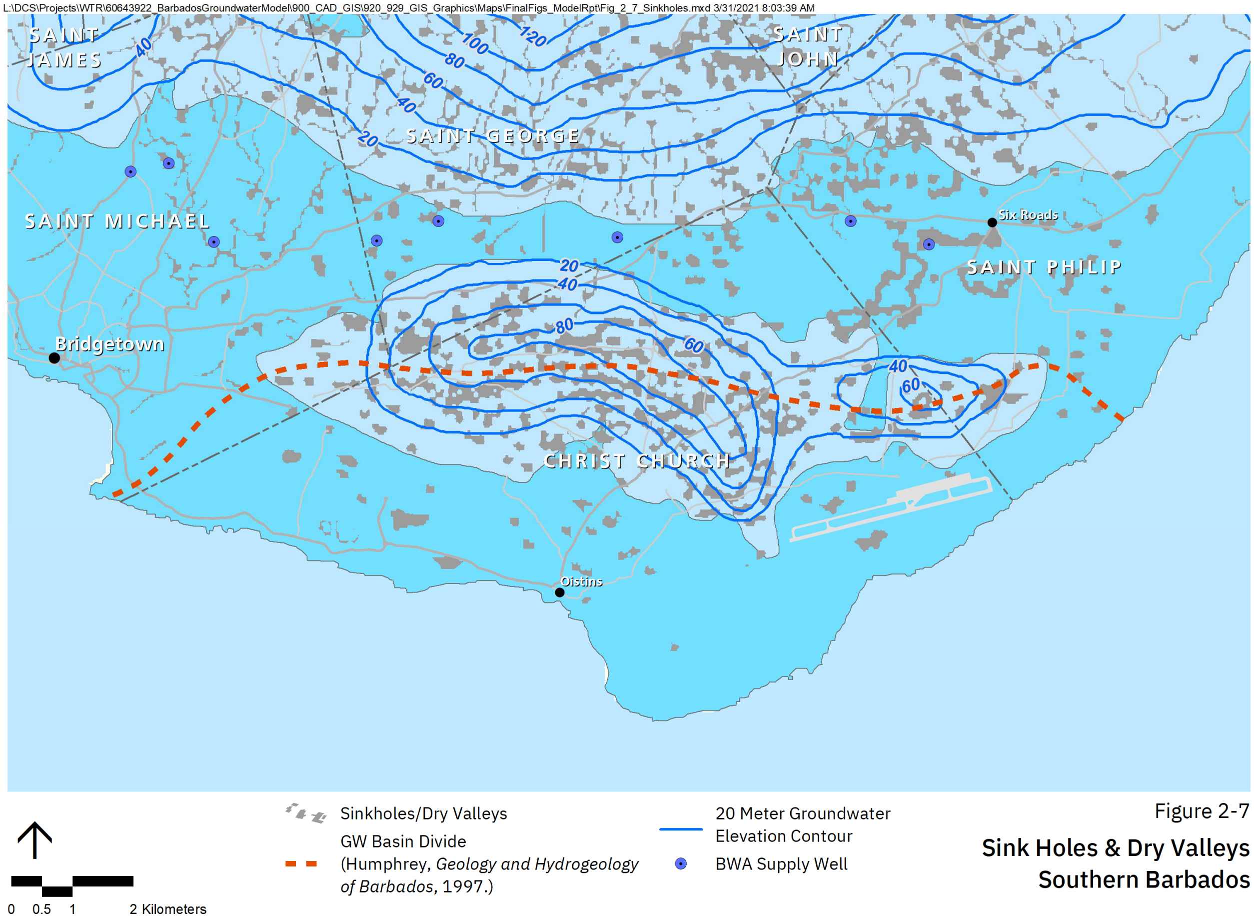


Figure 2-7 Sink Holes and Dry Valleys – Southern Barbados

3. Numerical Groundwater Flow Modeling

3.1 Modeling Approach

To address the project objectives, AECOM used a numerical groundwater flow model to simulate groundwater flow for the Christ Church Aquifer. The model simulated the local sources and sinks of water to the Christ Church aquifer, the proposed recharge of treated wastewater (2MIGD), and withdrawal of groundwater from the proposed Brackish Water Reverse Osmosis (BWRO) plant (0, 3 and 6 MIGD). The groundwater flow directions and gradients can be visualized using particle tracking and the changes in groundwater flow fluxes can be calculated to characterize the potential impacts to receptors.

3.2 AECOM Updates to Burnside/XCG Model

AECOM's numerical groundwater flow model was based on the model originally created by Burnside/XCG (2010). The objective of the original model was to simulate zones of contribution, or capture zones, for each public water supply well/well groups. These zones were then used to establish land-use regulations aimed at water supply protection. To meet this objective, it was important to have the water budget and the subsurface hydrogeology established at the scale of the island. The Burnside/XCG model simulates this and yields a simulated groundwater contour map for the entire island that is, thus far, the most current representation of island-wide groundwater flow. These contours give good insight into the regional and watershed-by-watershed divides and gradients.

The model is a valuable tool to consider other future scenarios. For instance, questions that arise from the addition of treated wastewater and the withdrawal of drinking water in the Christ Church Aquifer can be addressed. To that end, AECOM's approach for the groundwater modeling phase of work was to use the Burnside/XCG groundwater flow model "as is", and with some small modifications, then simulate the recharge and withdrawals.

The modifications were as follows:

- The Burnside/XCG model used MODFLOW-2000 on the Groundwater Vistas Platform. AECOM updated the model to use MODFLOW-USG on the GMS (v.10.4.10) platform.
- AECOM's use of MODFLOW-USG allowed for the use of the sparse-matrix solver (SMS) package which generates more stable simulations. As such, AECOM could lengthen the time steps from 0.1-day (Burnside/XCG) to one day, which saved on computational time especially as the simulation time increased. AECOM increased the simulation time from 2 years (Burnside/XCG) to 30 years in order to track particles to their discharge point.
- The groundwater contours generated by AECOM (Figure 3-5, below) matched very well to the groundwater contours depicted in the Burnside/XCG modeling report (Figure 6). Particle path lines originating from the BWA supply wells also compared favorably to the ones presented by Burnside/XCG (not shown). Deviations can be explained by the different ways that particle-starting-points were assigned in each model and slightly different starting head conditions. Ultimately, the AECOM model is a good representation of the Burnside/XCG model and therefore considered a good tool to evaluate changes in regional scale groundwater flows, gradients, and fluxes.

Other features of AECOM's numerical groundwater flow model include the following:

- The model is transient with 1-day time-steps extended over 30 years, a total of 10,950 days. The MODFLOW simulations took around 15 minutes to run and the MODPATH simulations took between 1 and 2 hours to complete.
- Figure 3-1 shows the 200m by 200m grid spacing over the full model domain/island. The model is one layer thick with land surface elevations assigned to the top of the layer and the bottom of the limestone unit assigned to the bottom of the layer. Figure 3-2 shows contours of the bottom of the limestone surface.
- Figure 3-3 shows the distribution of hydraulic conductivity. The distribution is identical to that used in the Burnside/XCG model with 1,300 metres per day representing the lower elevation sheet-water zone and 90

metres per day representing the steeper topographic stream-water zone. Specific storage was set to 0.01 and specific yield was set to 0.35, no change from the Burnside/XCG model.

- Water enters the groundwater system via rainfall recharge. The distribution of recharge over the year was changed every 2 months, per the Burnside/XCG model. AECOM made no changes to this. Recharge applied to each of the two-month intervals was identical for all 30 years. Recharge was distributed over the island in two zones. Overall, recharge was set to 35% of precipitation. Figure 3-4 shows the two-zone distribution of rainfall recharge.
- Table 3-1 shows the pumping rates used within the model domain. Production well rates were maintained from the Burnside/XCG model. In addition, BWA provided AECOM pumping rates for selected private irrigation wells and these were included in the Christ Church portion of the model domain in order to better represent current conditions. Figure 3-5 shows the groundwater contour map of the Christ Church Aquifer area prior to simulating the recharge of treated wastewater and BWRO withdrawals (“baseline”).

Table 3-1 Groundwater Pumping Simulated in the Model

Pumping Provided by the Burnside/XCG Model				
Column[1]	**Row[1]**	**Layer[1]**	**Name[2]**	**Pumping Rate (m3/d)[3]**
94	53	1		-819
127	55	1		-5780
28	14	1		-59
137	32	1	Pine Hampshire	-3895
37	14	1		-3391
122	102	1	Corbin	-654
131	59	1		-98
101	12	1	HoldersHIll Norwoods	-10598
124	42	1	Salters	-6945
149	43	1		-5964
148	44	1		-4497
127	18	1		-150
79	19	1		-131
88	44	1		-104
28	32	1		-98
115	67	1		-78.559998
99	82	1		-78
111	71	1		-65.5
98	39	1		-39
105	74	1		-6.5
94	61	1	Irrigation	-1.8200001
29	21	1		-454.60001
15	22	1		-851
12	16	1		-164
94	9	1		-91
74	24	1		-65
57	9	1		0
40	10	1		0
38	10	1	Alleyndale	-3454
126	50	1	Constant	-2151
127	45	1	Newmarket	-14844
97	63	1	Sweet Vale 1	0
128	32	1	Belle	-38566
122	25	1	Codrington	-1000
121	28	1	Waterford	-7082
104	38	1	Applewhaites	-970.5
127	64	1	Buttals	0
97	79	1		-8574
126	83	1	Carrington	-1084
128	90	1	Hampton	-18897
15	23	1	Hope	0
40	6	1	Colleton	0

Table 3-1 Continued

48	11	1	Ashton Hall	-3498
68	10	1	Carlton	-2343
58	8	1	Haymans	-4861
92	13	1	Molyneux	-1703
82	10	1		-3718
53	9	1	Whim	-4308
85	11	1	Trents	-1219
106	39	1	Applewhaites WF	-970.5
47	10	1		0
106	39	1	Applewhaites WF	-970.5
106	39	1	Applewhaites WF	-970.5
105	38	1	Applewhaites	-970.5
105	38	1	Applewhaites	-970.5
96	78	1	Bowmanston	0
106	39	1	Applewhaites WF	-970.5
107	39	1	Applewhaites WF	-970.5
99	59	1		-3084
81	9	1	Westmoreland	-4006
81	9	1	Westmoreland	-3967
80	10	1		-3568
104	80	1		0
130	84	1		0
126	98	1	Marchfield	0
107	115	1		0
Additional Pumping Included [4]				
124	92	1	PatrickFairview	-48.44
152	53	1	Silver Hill	-27.47
158	63	1	Thomas	-131.57
158	65	1	Dodson	-71.27
155	74	1	Straker	-12.7
157	75	1	Daniel	-427.9
158	75	1	Stuart	-287.07

Notes:

1 - Column, Row, Layer of Model Grid.

2 - Well Name estimated by AECOM.

3 - Pumping rate, negative indicates withdrawals.

4 - Sum of monthly (12) volumes provided/365 in 2020.
Data provided by BWA via email on 18 Mar.

Figure 3-1 Model Domain and Grid Spacing

Figure 3-2 Bottom of Limestone Elevation Contour Map

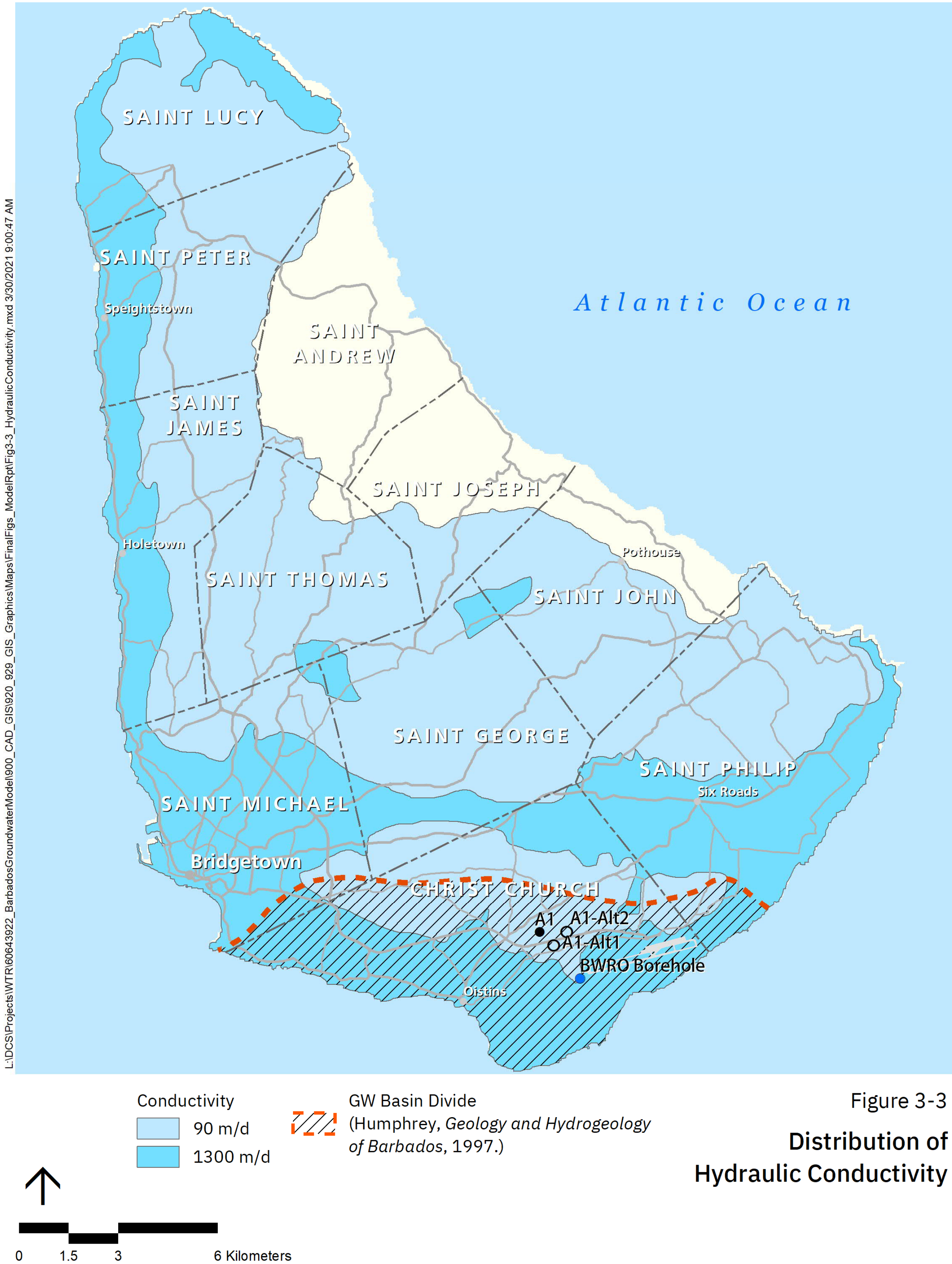


Figure 3-3 Distribution of Hydraulic Conductivity

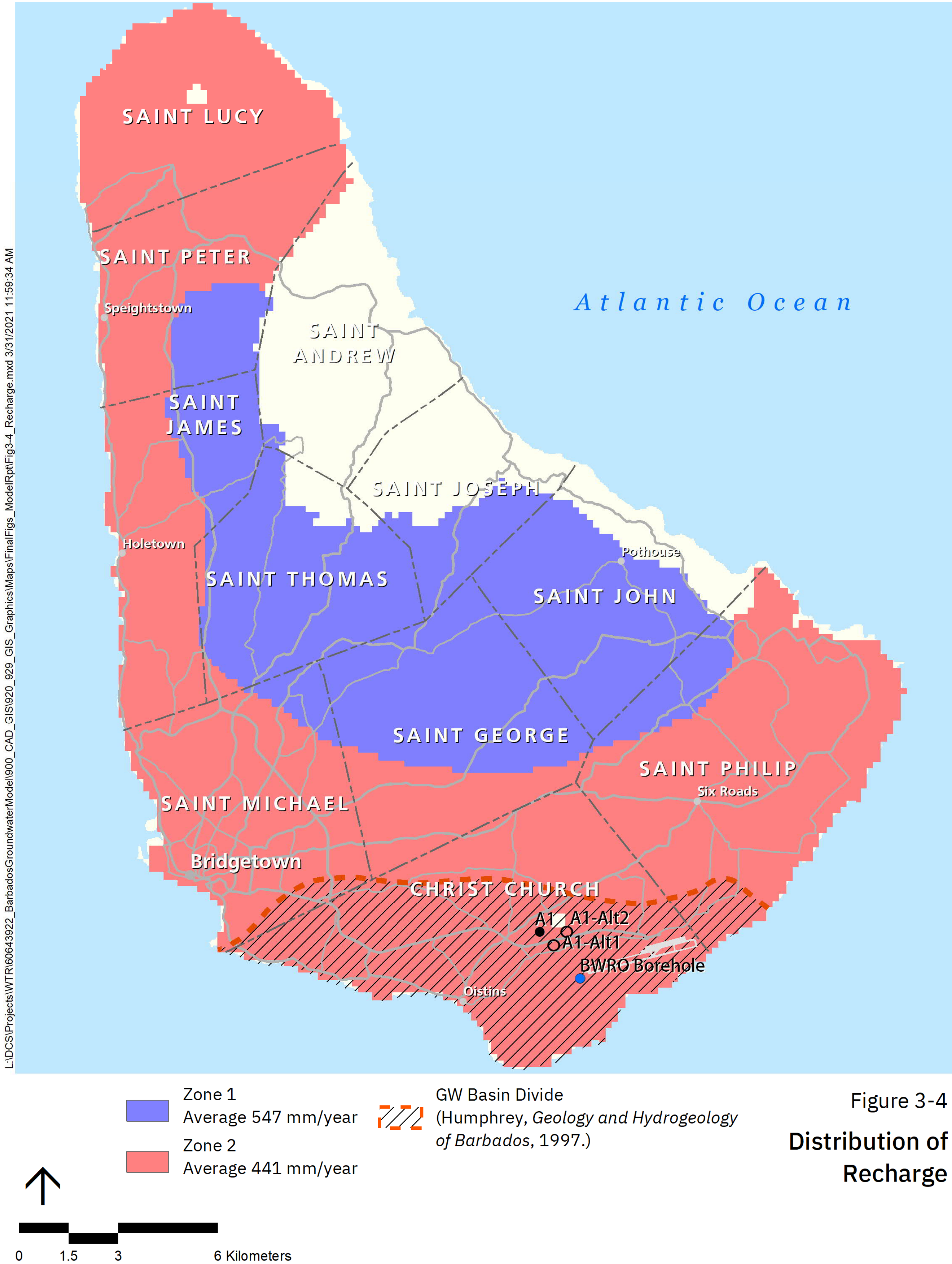


Figure 3-4 Distribution of Recharge

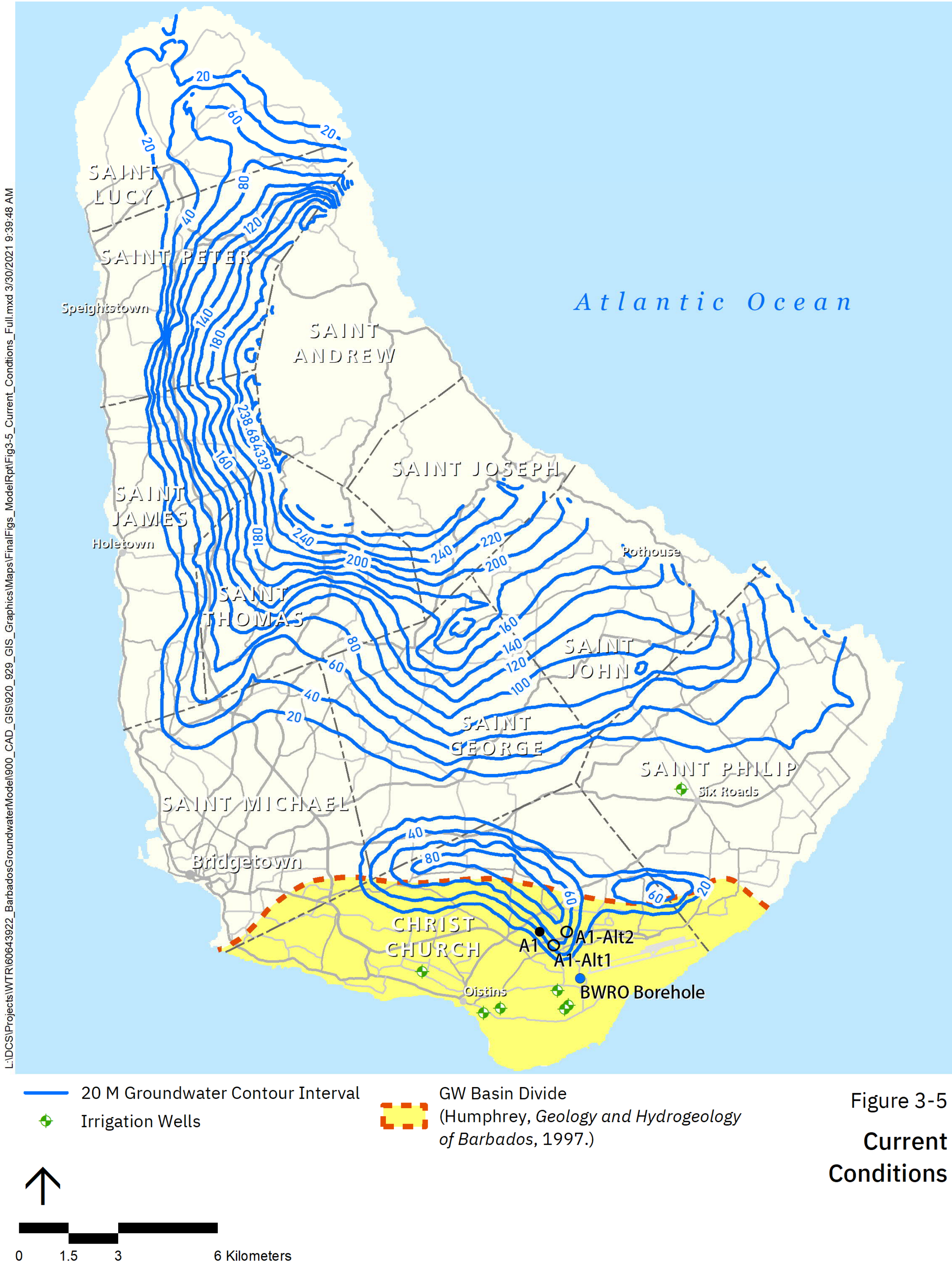


Figure 3-5 Current Conditions

3.3 AECOM Preliminary Model Scenarios

Initial scenarios simulated by AECOM consisted of the recharge (2 MIGD) of treated wastewater into the Christ Church Aquifer just south of the groundwater divide and the withdrawal of groundwater from the proposed BWRO facility at rates of 3 and 6 MIGD. The recharge of treated wastewater was simulated as additional water in one model cell (through the MODFLOW WEL package). The recharge cell was initially located at site A1 (AECOM, 2020), but two alternate locations (A1-Alt1 and A1-Alt2) were also simulated to optimize capture of the recharged water by the BWRO (the recharge locations and the BWRO location are shown on Figure 3-5). The goal was to find a recharge location where the particle path lines originating from the recharge location end up withdrawn at the BWRO extraction well. Similarly, the particle path lines that originate in the BWRO extraction well(s) and are tracked backward originate at or near the recharge location. This assumes that both recharge and withdrawals are simultaneously and continuously operational.

Initial modeling of recharge at the A1 location indicated that the recharge should be shifted slightly south and east in order to capture more recharge at the BWRO location. AECOM selected location A1-Alt1 for the second set of simulations. Figure 3-6 depicts the particle paths resulting from the recharge of 2 MIGD at A1-Alt1 AND groundwater withdrawals at the BWRO at a rate of 3 MIGD. Figure 3-7 is identical to Figure 3-6 except that groundwater is extracted at the BWRO at the rate of 6 MIGD. Another location (A1-Alt2) was also tested but did not prove to be optimal in terms of capture of recharged water. Results of these simulations (among others) are included in Attachment A and may provide additional insight into site selection for the disposal of treated wastewater. A site-specific sub-surface hydrogeologic field investigation is recommended before final selection of any recharge location.

Three sets of particle path lines are shown on Figures 3-6 and 3-7. Particle path line visualization was completed with MODPATH, an add-on module to MODFLOW. MODPATH uses the simulated groundwater elevations to depict groundwater flow paths based on a user-defined particle starting location. MODPATH only describes groundwater movement via advection associated with groundwater velocity. While it can be used to understand dissolved phase chemical transport, that understanding is approximate as it does not account for dispersion, retardation, or first-order decay. In future investigations, other modeling tools could be used to simulate dissolved phase fate and transport, as needed.

In Figures 3-6 and 3-7:

- Green path lines originate from the A1-Alt1 recharge location and are tracked forward.
- Red path lines originate from the BWRO recharge locations and are tracked backward.
- Pink path lines originate from the locations where hydrocarbon leaks and spills have been identified.

Arrows along the particle path lines indicate 2 years of travel time. The path lines show that most of the particles move from the A1-Alt1 location to the BWRO extraction well for both 3 and 6 MIGD withdrawal rates. Also, the path lines show that many particles that originate from hydrocarbon sources move toward the BWRO, and entirely so at the higher withdrawal rate of 6 MIGD.

The estimated groundwater rise (mound) resulting from recharging treated wastewater at A1-Alt1 is around 3.4m depending on the BWRO withdrawal rate. Even with this height there is still over 20m of unsaturated zone; that is, water levels are not simulated to rise above the land surface. At the BWRO, drawdown is estimated at 0.3m for a 3 MIGD withdrawal and 0.6m for 6 MIGD.

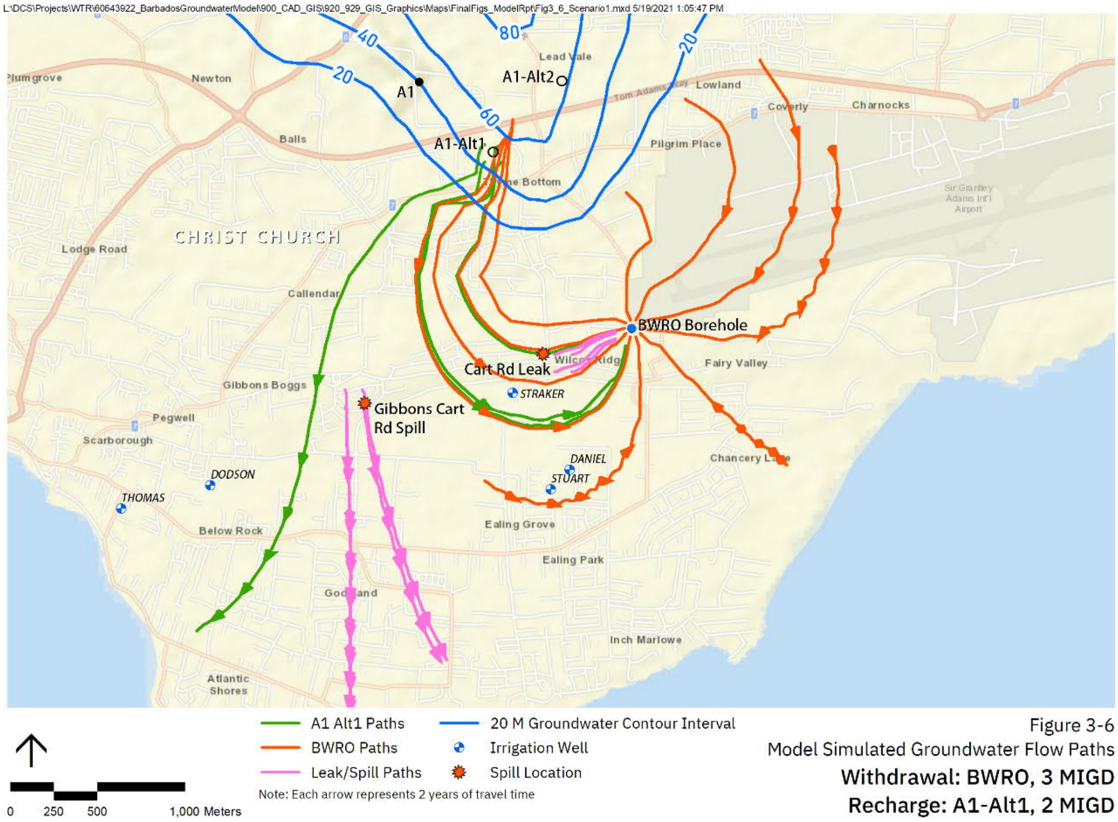


Figure 3-6 Withdrawal: BWRO 3 MIGD, Recharge: A1-Alt1 2MIGD

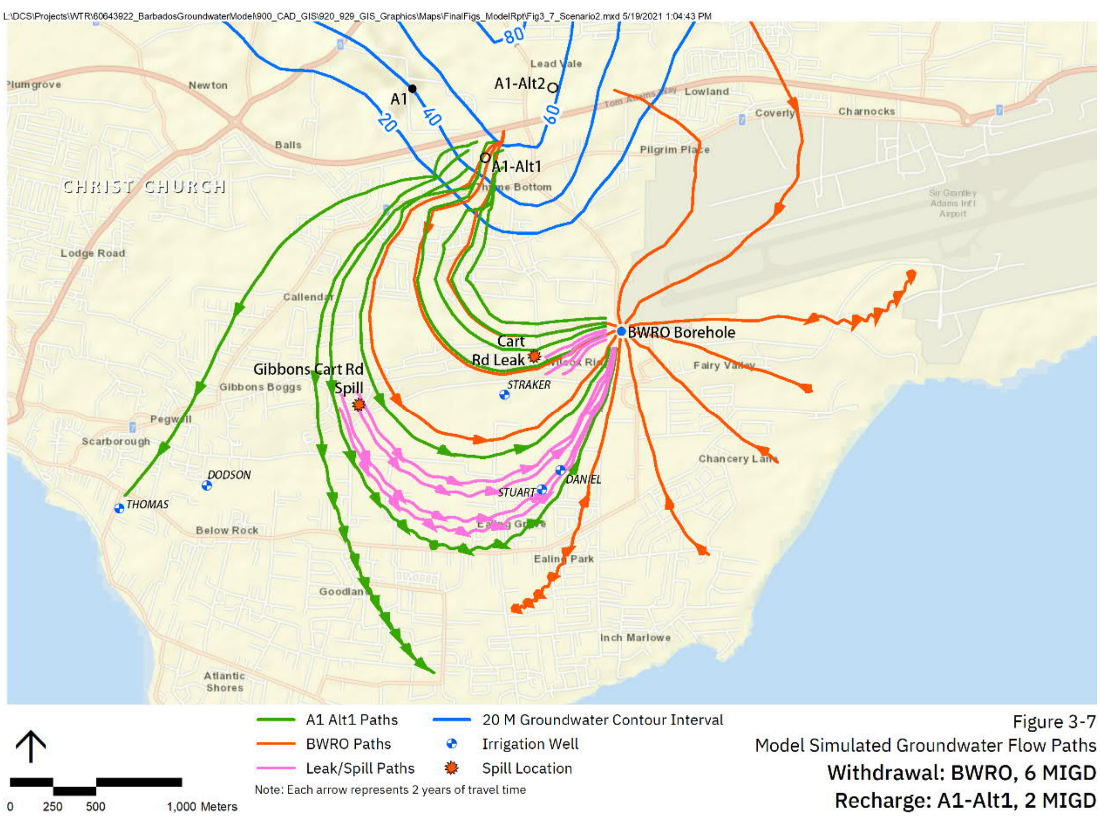


Figure 3-7 Withdrawal: BWRO 6 MIGD, Recharge: A1-Alt1 2MIGD

3.4 Coastal Evaluation Scenarios

To more fully evaluate potential impacts to the coast from the recharge at the A1-Alt1 location, BWA requested that two additional model scenarios be simulated. The intent of these model simulations was to bracket what BWA expects could be the two extreme cases of wastewater recharge and BWRO withdrawals, namely:

- 4-month recharge of 2 MIGD at A1-Alt1 and year-round BWRO withdrawals of 6 MIGD
- Full-year recharge of 2 MIGD at A1-Alt1 and 0 MIGD BWRO withdrawal

Figure 3-8 incorporates 2 MIGD recharge at the A1-Alt1 location, but for only four (4) months of the year (August-November). For the remainder of the year, BWA expects that treated wastewater will be used for irrigation, will fully go to evapotranspiration and will not recharge the groundwater system. Additionally, in this scenario, the BWRO withdrawals will be at the maximum expected: 6 MIGD. Conceptually, this results in an overall net reduction of flow to the coast. Figure 3-8 shows the groundwater flow paths resulting from this simulation.

In Figure 3-8, particles that originate at the A1-Alt1 location move downgradient but are influenced by pumping at the BWRO location and all particles move toward the BWRO. The combination of mounding and withdrawals results in relatively short travel times, i.e., between 2 and 5 years. The mound generated by the recharge is approximately 3m. Groundwater at or near the hydrocarbon spills also moves to the BWRO facility. The slightly wavy lines shown in this figure reflect the pulse of water recharged for four months followed by no recharge for eight months.

L:\DCS\Projects\WTR\60643922_BarbadosGroundwaterModel\900_CAD_GIS\920_929_GIS_Graphics\Maps\FinalFigs_ModelRpt\Fig3_8_BWRO_6.mxd 5/19/2021 10:58:48 AM

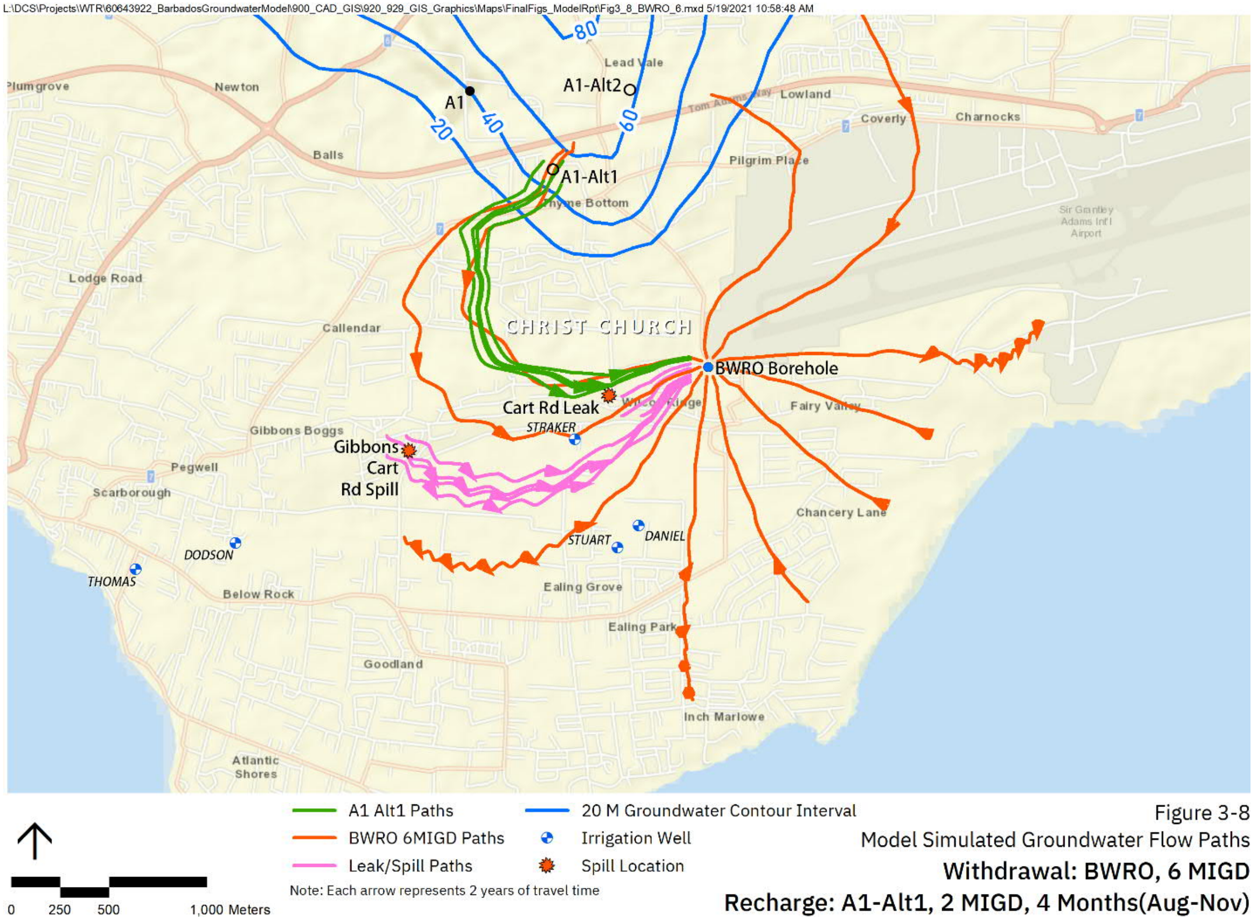


Figure 3-8 Withdrawal: BWRO, 6 MIGD, Recharge: A1-Alt1, 2 MIGD, 4 Months (Aug-Nov)

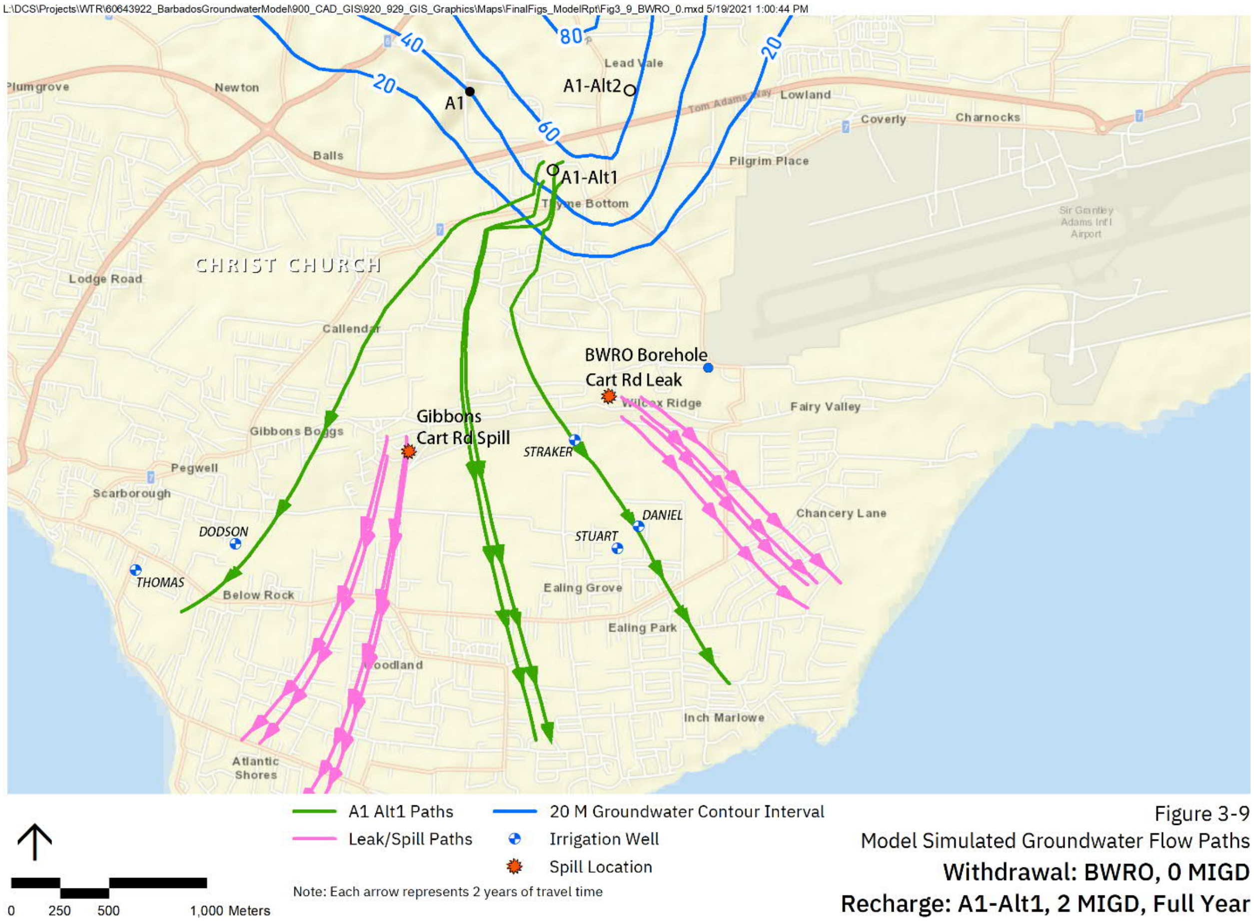


Figure 3-9 Withdrawal: BWRO, 0 MIGD, Recharge: A1-Alt1, 2 MIGD, Full Year

Figure 3-9 considers the other extreme-case scenario, where there is full-year recharge at A1-Alt1 (2 MIGD) and no withdrawal from the BWRO location. Conceptually, this scenario results in a net increase of water into the groundwater system, ultimately reaching the coast.

In Figure 3-9 the particles that originate at the A1-Alt1 location move downgradient to the coast, arriving in around 10 years. The mound generated by the recharge is approximately 3.5m. Groundwater at or near the hydrocarbon spills also moves downgradient to the coast, arriving in a similar time frame.

The last page of Attachment A compares the runs relative to irrigation well capture zones. Current simulated groundwater conditions indicate that the irrigation wells pull water from areas within the Christ Church aquifer, generally north of the well position. With the increase in recharge (A1-Alt1) and/or withdrawals (BWRO), the footprint of the capture zone becomes longer and thinner and reaches back to the recharge (A1-Alt1) location. This applies to three scenarios (Figure 3-6 through 3-8). The scenario represented in Figure 3-9 includes 6 MIGD withdrawal and only periodic recharge. As a result, the capture zones for the Daniel and Stuart wells are actually reversed; that is, they draw water from the south.

3.5 Water Budget for Christ Church Aquifer

ZONEBUDGET is a modeling tool that tracks inflows and outflows over user-defined areas of the model. This tool was used to evaluate changes in the water balance for the Christ Church Aquifer, for various rates of recharge of water at the A1-Alt1 location and withdrawal of water at the proposed BWRO. Specifically, ZONEBUDGET was used to evaluate changes in groundwater flux through the constant head cells along the coastline. This analyzes the changes in flux to the ocean, which may be an indicator of impact of wastewater disposal and withdrawals on receptors. Figure 3-10 highlights the ocean front (blue dashed line) segment of the Christ Church Aquifer.

The net flux through the Christ Church Aquifer coastline is as follows:

- Baseline (current conditions): 11.4 MIGD
- Figure 3-6 (+2MIGD at A1-Alt1; -3 MIGD at BWRO): 10.44 MIGD (8% reduction)
- Figure 3-7 (+2MIGD at A1-Alt1; -6 MIGD at BWRO): 9.16 MIGD (20% reduction)
- Figure 3-8 (4 months +2MIGD at A1-Alt1; -6 MIGD at BWRO): 5.98 MIGD (48% reduction)
- Figure 3-9 (Full Year +2MIGD at A1-Alt1; 0 MIGD at BWRO): 13.13 MIGD (15% increase)

For the scenarios represented on Figures 3-6, 3-7 and 3-8, the model indicates that even though 2 MIGD are added at the recharge location, the withdrawal from the BWRO results in a net reduction of flux into the ocean. For the scenario represented on Figure 3-9, the model indicates that adding recharge without withdrawals from the BWRO, yields a net increase of water discharging to the ocean compared to current conditions. These outcomes are not surprising. The reader will note that there is not an exact 1:1 correspondence between any combination of recharge/withdrawal and reduction/increase in flux at the coastline. For example, for the scenario represented on Figure 3-9, the addition of 2 MIGD in recharge results in an increase of 1.73 MIGD flux at the coastline. The discrepancy of 0.27 MIGD reflects an increase in groundwater storage.

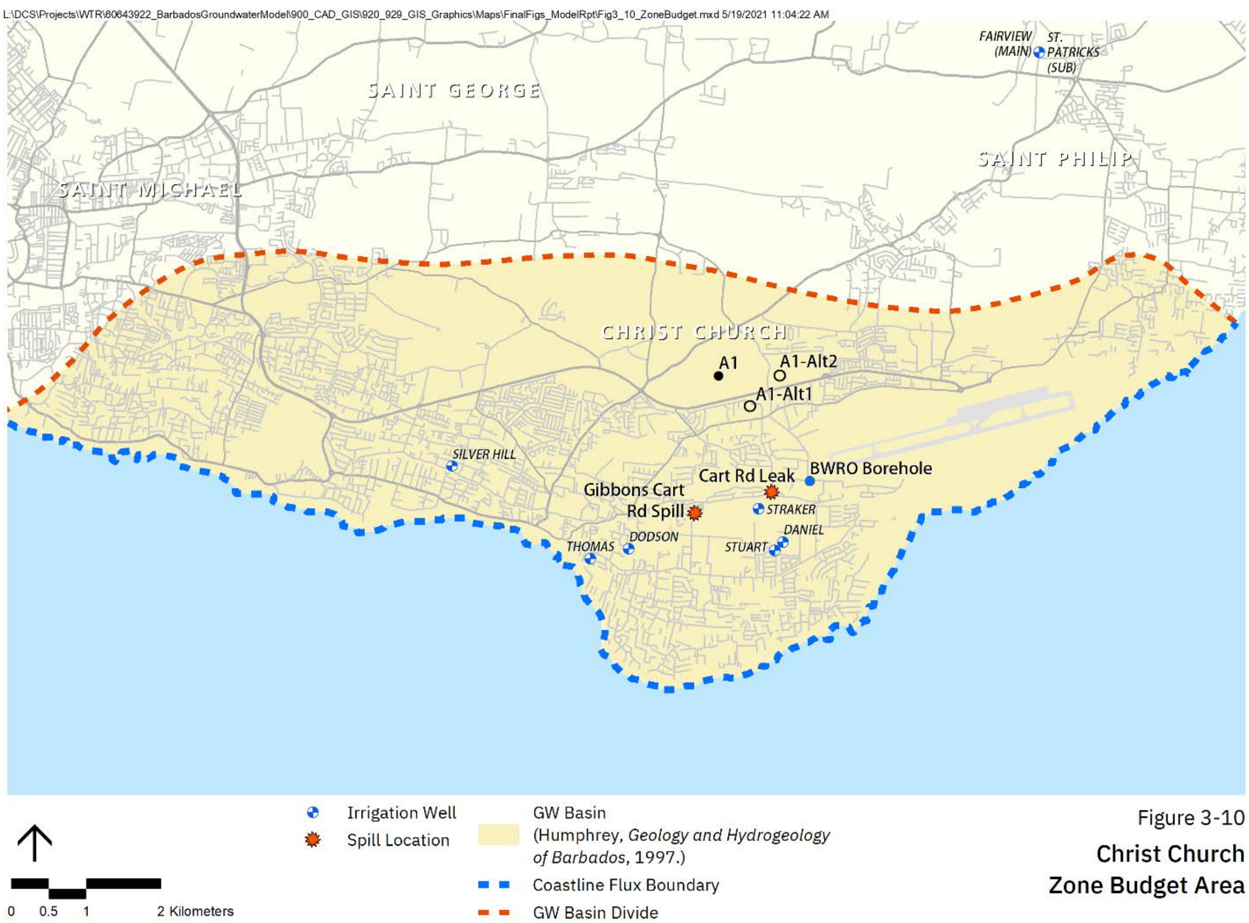


Figure 3-10 Christ Church Zone Budget Area

3.6 Nitrate

Simply put, the recharge of treated wastewater will add nitrate to the groundwater system consistent with the design treatment level (Total Nitrogen < 5 mg/L). Nitrate mass can be calculated based on the recharge rate (2 MIGD for a full year or 4 months). In general, in the absence of pumping at the BWRO facility, groundwater that originates at the recharge location will arrive at and impact the coastline. Depending on groundwater extraction rate at the BWRO facility, some or all of the recharged water will be captured and will not impact the coast.

Table 3-2 below summarizes nitrate levels for irrigation wells in the Christ Church Aquifer, based on the most recent data provided by BADMC. Nitrate levels range from < 1 to 70.50 mg/l. However, for the most part, nitrate levels exceed 10 mg/l. If these levels are representative of current conditions, then we would expect that recharge of treated wastewater would reduce overall nitrate levels in the Christ Church Aquifer. As stated above, nitrate levels in the treated wastewater will be less than 5 mg/l, and typically values of 2 to 3 mg/l can be achieved.

Table 3-2 Historical Nitrate Levels (milligram per liter), Irrigation Wells, Christ Church Aquifer

Irrigation Well ID	May-05	Jun-05	Jul-05	Aug-05	Sep-05	Oct-05	Nov-06	Dec-05
DANIEL	55.40	70.40	63.10	69.60	60.30	58.10		70.50
DODSON	11.80	10.90	10.00	11.00	10.40	10.60	11.50	10.50
STRAKER		12.40		10.50	8.75	37.70		7.32
STUART	11.90						38.40	
THOMAS	11.90	10.60	9.37	1.98	9.03	7.36		< 1

Treated wastewater recharge and BWRO withdrawals may also cause migration of the existing nitrate distribution. The interplay of recharge and withdrawal will certainly alter the aquifer gradients such that both nitrate impact to the coastline and/or nitrate capture by BWRO are reasonably expected. Additional quantitative analysis (including numerical modeling) can be completed in the future.

3.7 Sensitivity

Table 2-2 and the accompanying discussion indicate that the hydraulic conductivity in the Burnside/XCG model are high compared to data cited by Farrell, et.al. (2008). In order to evaluate model sensitivity, the hydraulic conductivity was reduced to one-tenth of the values used for Figures 3-6 and 3-7. That is, hydraulic conductivity was reduced from 1,300 and 90 metres per day to 130 and 9 metres per day. These values are not meant to be better values. Rather, they are meant to demonstrate the range in possible outcomes with alternate inputs. Attachment A includes images of these sensitivity runs.

When the hydraulic conductivities are reduced, the resistance to flow is increased. As such the hydraulic gradients are increased. Perhaps counter-intuitively, this means that travel times using lower conductivities can be faster than with higher hydraulic conductivity. For instance, for Figure 3-6 runs, the travel times with reduced hydraulic conductivity ranged from 48% to 90% of the travel times for higher hydraulic conductivity. For Figure 3-7, the travel times ranged from 91% to 175% with a decreased hydraulic conductivity. The range was a function of proximity to boundary conditions (recharge, ocean, pumping, etc.).

This effort was completed to demonstrate potential variation in travel times with different inputs. Depending on the location in the aquifer, the increase/decrease may have implications for management of groundwater resources. This was a limited evaluation. As site-specific data become available and/or the need arises, this evaluation can be more focused.

3.8 Outcome of Groundwater Modeling

The project objectives, listed in Section 1.2 of this report, are restated below. With respect to each of these objectives, and based on the groundwater modeling effort, AECOM concludes the following:

1. *Would the recharged water flow into the adjacent potable aquifers to the north and, if so, what would be the effects?*

   Groundwater modeling indicates that reclaimed water recharged at location A1-Alt1 will not travel north and will not impact potable aquifers to the north, particularly if BWRO is pumping. Figure 3-5 shows that the recharge location is definitively on the south side of the simulated groundwater divide and, as shown on Figures 3-6 through Figure 3-9, additional groundwater will not raise groundwater elevation enough to change that divide.

2. *What impacts would the recharged water have on a proposed 3 to 6 MIGD Brackish Water Reverse Osmosis (BWRO) plant now being considered?*

   In order to increase the capture of recharged water by the BWRO, AECOM shifted the recharge location (in the model) to the south and east of the original location, A1. Attachment A shows AECOM's evaluations of water recharge at A1 and the two alternate locations. Figures 3-6 through 3-8 show simulations assuming recharge at A1-Alt1 and BWRO withdrawals. In Figure 3-6, three-quarters of the particles originating at A1-Alt1 arrive at BWRO within about 6 years. One-fourth of the particles move to the ocean and arrive in about 13 years. In Figure 3-7, three-quarters of the particles originating at A1-Alt1 arrive at the BWRO over a timeframe ranging from 1 to 20 years. In Figure 3-8, all the particles originating at the recharge location arrive at the BWRO wells in less than 4 years. In Figure 3-9, all particles reach the coastline in around a decade.

3. *What impacts could be expected, in terms of quality and quantity, on downstream private wells currently used for irrigation?*

   Attachment A compares the capture zones of irrigation wells for current conditions and for the four simulations. The model predicts that the capture zones of all irrigation wells originate at the A1-Alt1 recharge location, except for the extreme case of 4-months of 2 MIGD recharge AND 6 MIGD BWRO withdrawals.

4. *Where will the recharged water reach the coast, and what environmental impacts will ensue, especially in terms of contaminant loading of coastal waters (nitrogen, phosphorous, microbiological, total organic carbon)?*

   Figures 3-6, 3-7, and 3-8 indicate that most groundwater recharged at A1-Alt1 is captured by BWRO extraction. In certain cases, a small (25% or less) percentage of the A1-Alt1 recharge that escapes the capture of BWRO will flow toward the coastline to the southwest. Figure 3-9 shows, as expected, that all the water recharged at A1-Alt1 reaches the ocean, representing an increase of 15% discharge compared to current conditions. It is beyond the scope of this study to simulate concentrations.

5. *Is recharging the Christ Church aquifer at this chosen site technically, economically, and environmentally sustainable over the next 20 years?*

   This question is broad and beyond the scope of our investigation.

6. *What impact would recharge of the Christ Church aquifer have on the reported hydrocarbon contamination of that aquifer?*

   Figures 3-6 through 3-8 show that particles seeded at the locations of known hydrocarbon releases can end up in the BWRO, more so if the pumping rates are at the high end of the range (6 MIGD). Otherwise, (Figure 3-9, no pumping at BWRO), hydrocarbons may flow to the ocean. However, the travel times (around a decade) would normally allow attenuation of hydrocarbon concentrations, depending on the chemical. It is beyond the scope of this study to simulate concentrations.

4. Technical Limitations – Groundwater Model

As stated above, the numerical groundwater flow model originally created by Burnside/XCG (2010) was slightly modified by AECOM for this assignment with BWA. Generally speaking, the historic model was used “as-is.” All groundwater flow models are simplified representations of often complex, natural hydrogeologic systems. This is true in the case of Barbados, and more particularly, the Christ Church aquifer.

The Burnside/XCG groundwater flow model was created with these simplifying features:

- The limestone aquifer is divided up into uniform cells of 200 x 200 metres.
- An assumption of uniform hydraulic conductivity in the stream-water zone of 90 m3/day.
- An assumption of uniform hydraulic conductivity in the sheet-water zone of 1,300 m3/day.
- An assumption of uniform aquifer specific yield (akin to porosity) of 20%.
- An assumption of groundwater flowing through a uniform porous medium, i.e., the limestone aquifer (even though conduit flow is known to be a significant factor in groundwater flow).
- An assumption of a sloping aquifer bottom (the underlying Tertiary basement bedrock) as depicted by Poole and Barker (1983).
- In the sheet-water zone, the aquifer thickens oceanward, in accordance with Poole and Barker’s mapping.
- For the Christ Church aquifer, rainfall recharge of 0.44 metres per year (35% of annual rainfall) was distributed over two-month increments and two zones, (Burnside/XCG (2010)). The rainfall distribution for one year was assumed for each of 30 years.
- The aquifer is bounded by the ocean along the shore, at an elevation of mean sea level.
- Mixing of freshwater with ocean water, neither on-shore nor off-shore, is represented in the model.

The power of the numerical groundwater flow model rests in its ability to simultaneously solve tens of thousands of groundwater-flow equations quickly, accurately, and reliably. It would be impractical to attempt to replicate this manually. In so doing, the numerical model can broadly represent how groundwater flows through a hydrogeologic system at a regional scale or sub-regional scale.

The Burnside/XCG model was originally designed to evaluate water budget and regional groundwater flow at the scale of the model. In the AECOM version of the model, we considered a small area of the island (Christ Church Aquifer) relying on the assumptions from the historic model. It appears that the Christ Church Aquifer is complex and unique (relative to the rest of the island). Specifically, here are some of the complexities that impact simulations of recharge of reclaimed water and withdrawal at the BWRO location:

- Hydraulic conductivity in the limestone aquifer is not uniform. In fact, the large contrast in modeled hydraulic conductivity between the stream-water and the sheet-water zone is unlikely to exist in nature. Actual flow through the limestone aquifer may be predominantly along discrete fractures or channels in the more mature coral-reef limestone inland. Along the coast, it has been theorized that porous medium flow may dominate because the coral-reef limestone is relatively young and has not been subjected to fracturing, extended weathering and subsequent solutioning. And, if the contrast between mature and younger limestone exists, then there is likely a gradual transition of permeability and porosity from channel to porous medium flow.
- Rainfall recharge is not likely to be distributed uniformly geographically. Where the ground surface is gullied, discrete recharge likely predominates, but only in those gullies. Where gullying is absent, which appears to be the case in the Christ Church Aquifer, diffuse recharge would be the predominant mechanism for recharging the limestone aquifer. But diffuse recharge could be substantially lower than 0.44 metre per year where rainfall must percolate through clayey soils that occur at the land surface. The current model introduces recharge in 2-month periods. As a more detailed evaluation of the Christ Church aquifer is considered, additional analysis of island rainfall and recharge may suggest that simulation of recharge could be refined/updated.

- The relationship between ocean water and freshwater at the coast and the possible mixing of the two is not fully understood. One representation (Figure 2-6 above) suggests that the freshwater lens beneath Christ Church is only 3 metres thick and that most of the groundwater in the LCR of the Christ Church Aquifer is saltwater or brackish water.

The upshot of this discussion of modeling limitations is that detailed hydrogeologic field investigations would be necessary to clarify the nature of groundwater flow in the Christ Church aquifer with a higher degree of confidence. These investigations – which could entail borings, pumping tests, water-quality testing, long-term water-level measurements and geophysical surveys (both borehole and surface methods) – would be helpful in the preliminary design stage to assess local conditions of groundwater flow at both the proposed recharge-well and BWRO sites. Field investigations could be done in phases, in which case, an understanding of groundwater flow would be refined with each successive phase. The groundwater model could then be updated to account for these newly characterized conditions, and to more accurately evaluate groundwater movement on a qualitative and quantitative level for the Christ Church Aquifer and the recharge and withdrawal locations specifically.

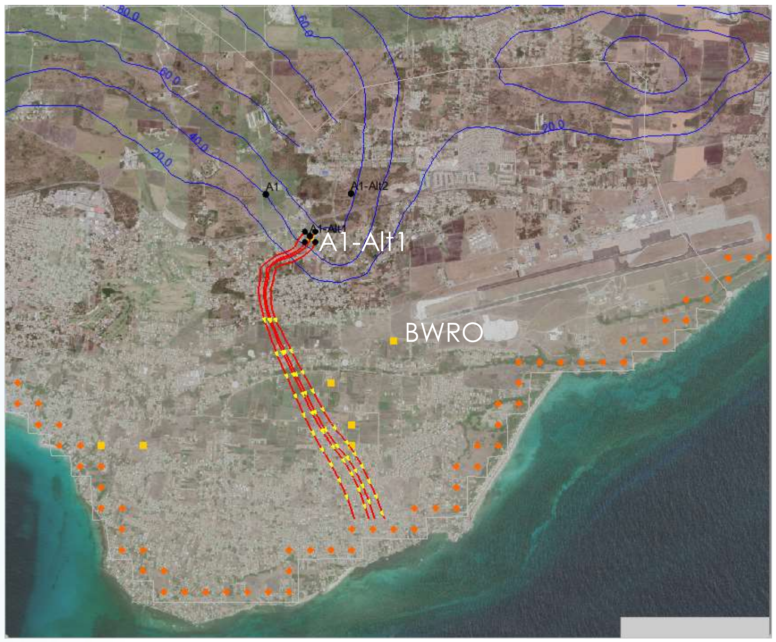
Attachment A Model Runs

This slide compares the current conditions with the impact of recharging A1-Alt1at 2 MIGD (no BWRO withdrawals).

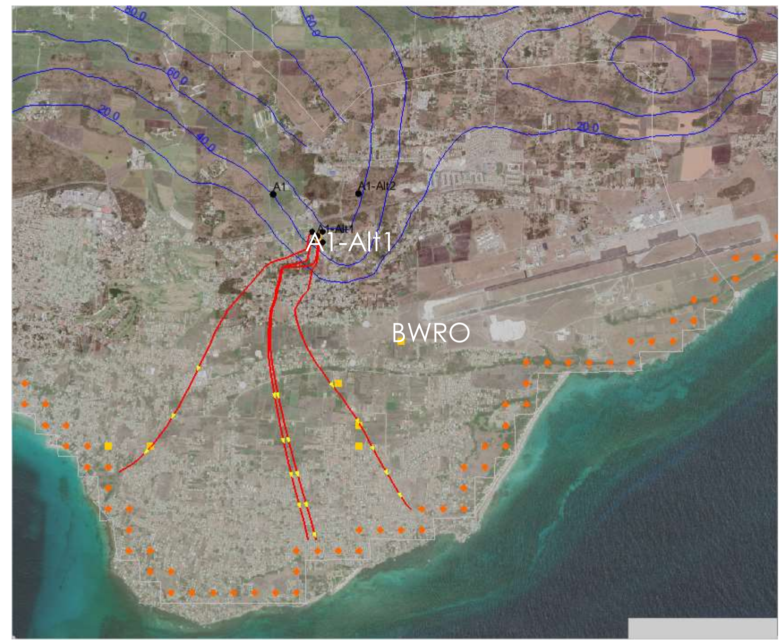
Where path lines (red) meet the orange dots is where the coast may be impacted by changes in flow and dissolved phase transport/discharge.

Each yellow dot on the red path line represents 2 years of travel time. For instance, on the image, particles take around 24 years to arrive at coast.

Current Conditions
0 migd RECHARGE at A1-Alt1, full year
0 migd WITHDRAWALS at BWRO



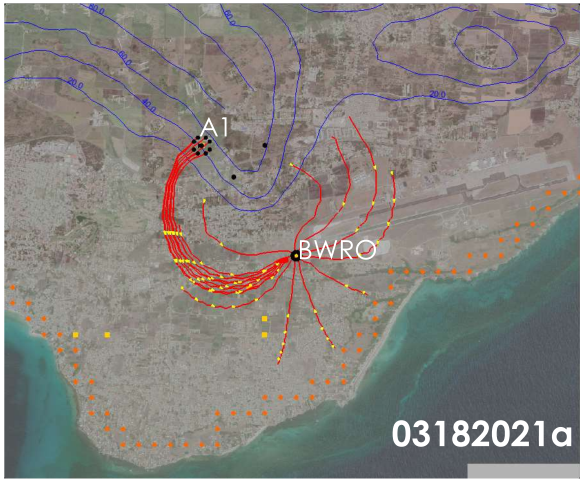
2 migd RECHARGE at A1-Alt1, full year
0 migd WITHDRAWALS at BWRO



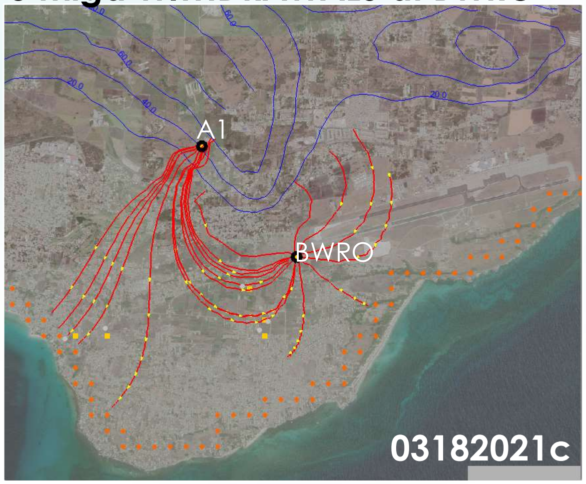
0 migd RECHARGE at A1
3 migd WITHDRAWALS at BWRO

This slide considers the impact of 3 MIGD withdrawal from BWRO with no recharge and with recharge at three locations, A1, A1-Alt1, A1-Alt2.

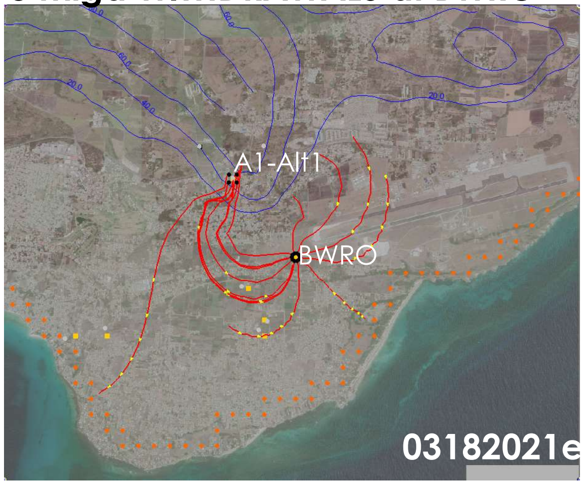
Each yellow dot on the red path line represents 2 years of travel time.



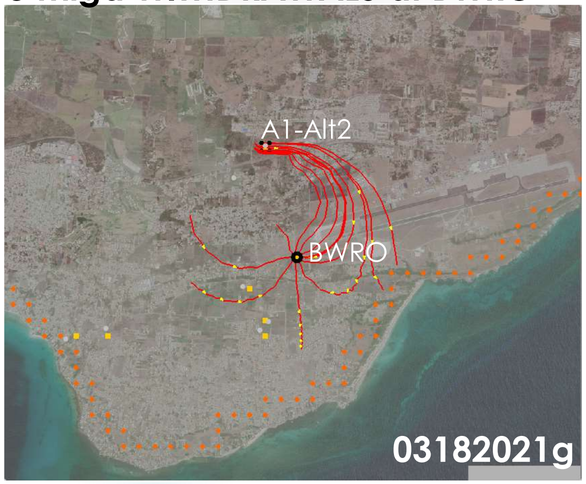
2 migd RECHARGE at A1, full year
3 migd WITHDRAWALS at BWRO



2 migd RECHARGE at A1-Alt1, full year
3 migd WITHDRAWALS at BWRO



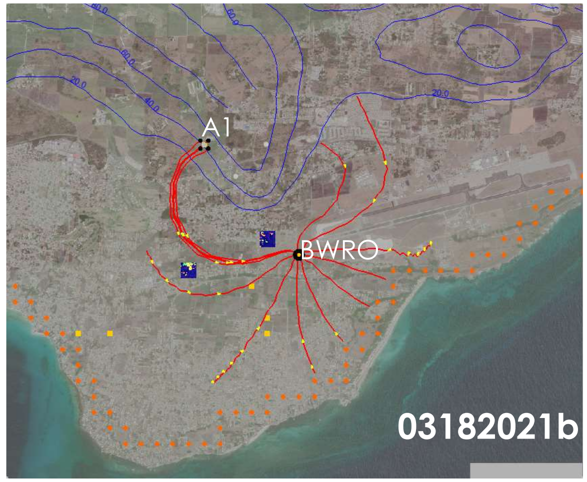
2 migd RECHARGE at A1-Alt2, full year
3 migd WITHDRAWALS at BWRO



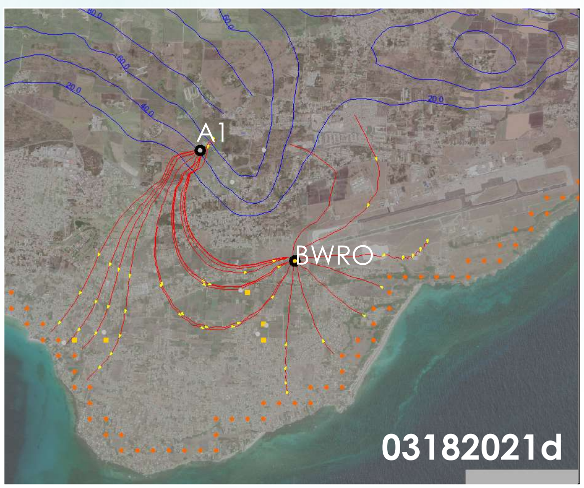
0 migd RECHARGE at A1, full year
6 migd WITHDRAWALS at BWRO

This slide considers the impact of 6 MIGD withdrawal from BWRO with no recharge and with recharge at three locations, A1, A1-Alt1, A1-Alt2.

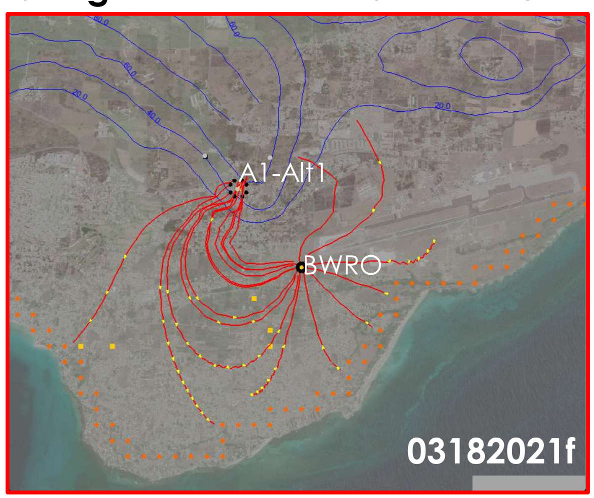
Each yellow dot on the red path line represents 2 years of travel time.



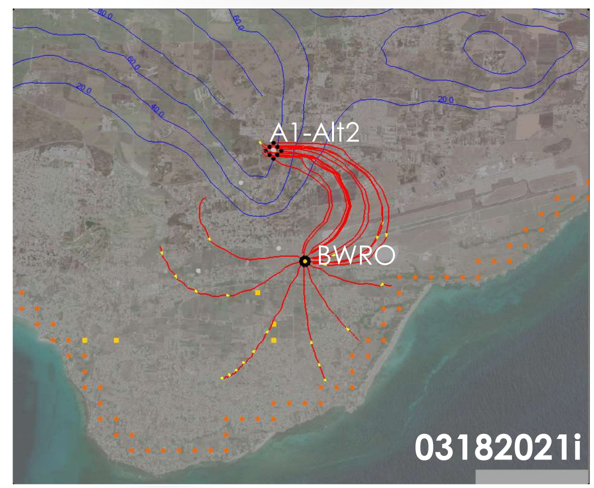
2 migd RECHARGE at A1, full year
6 migd WITHDRAWALS at BWRO



2 migd RECHARGE at A1-Alt1, full year
6 migd WITHDRAWALS at BWRO



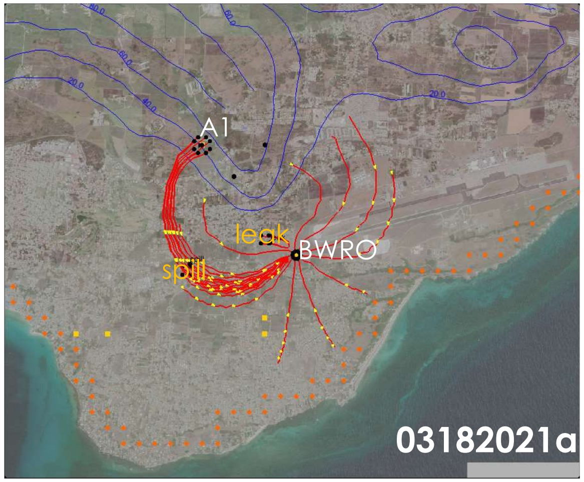
2 migd RECHARGE at A1-Alt2, full year
6 migd WITHDRAWALS at BWRO



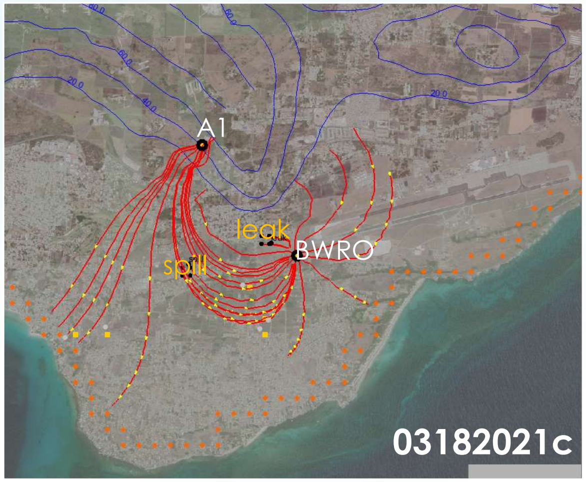
0 migd RECHARGE at A1, full year
3 migd WITHDRAWALS at BWRO

This slide considers potential groundwater flow paths from areas with hydrocarbons releases when BWRO pumping is 3 MIGD and recharge varies from 0 to 2 MIGD at three different locations.

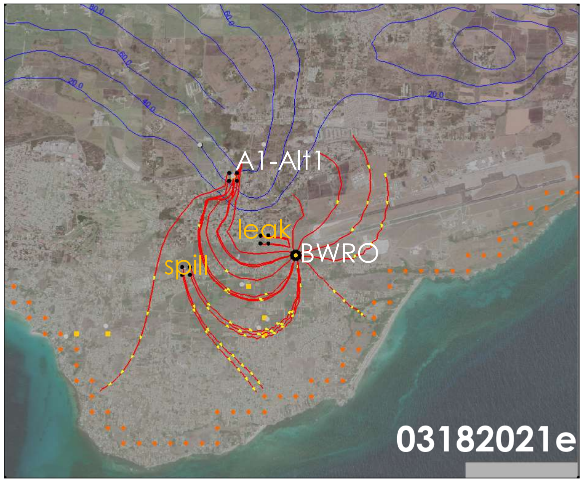
Each yellow dot on the red path line represents 2 years of travel time.



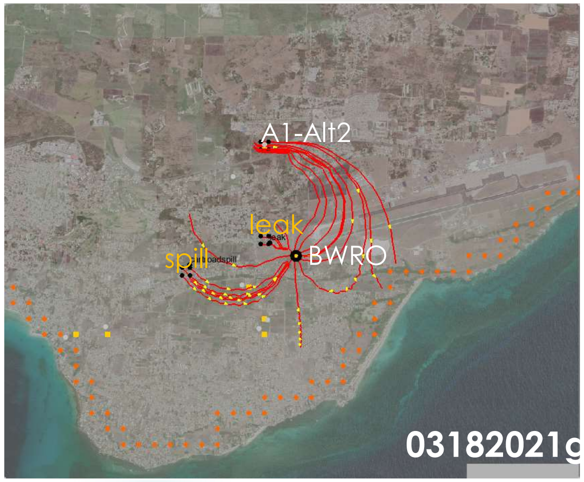
2 migd RECHARGE at A1, full year
3 migd WITHDRAWALS at BWRO



2 migd RECHARGE at A1-Alt1, full year
3 migd WITHDRAWALS at BWRO



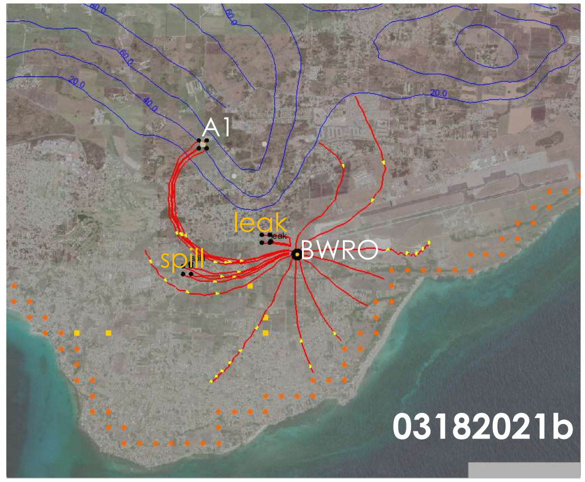
2 migd RECHARGE at A1-Alt2, full year
3 migd WITHDRAWALS at BWRO



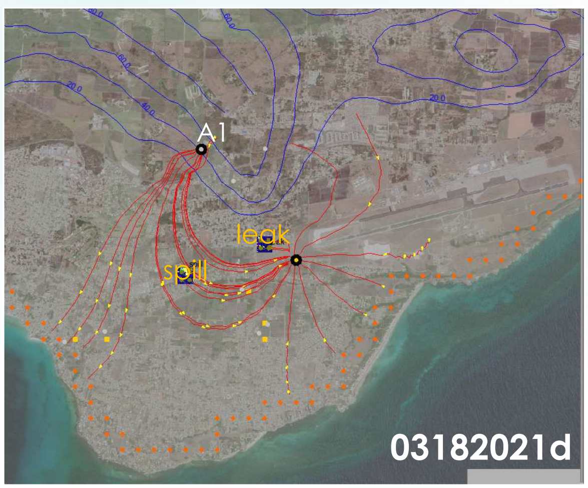
0 migd RECHARGE at A1
6 migd WITHDRAWALS at BWRO

This slide considers potential groundwater flow paths from areas with hydrocarbons releases when BWRO pumping is 6 MIGD and recharge varies from 0 to 2 MIGD at three different locations.

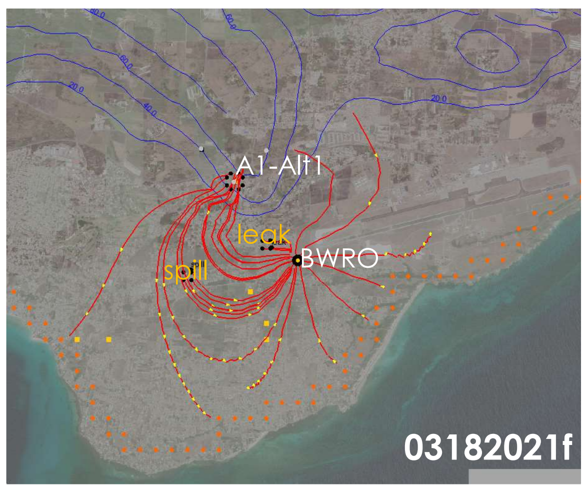
Each yellow dot on the red path line represents 2 years of travel time.



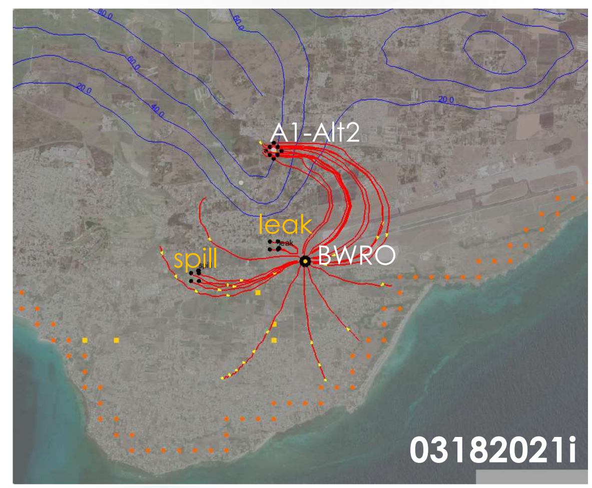
2 migd RECHARGE at A1
6 migd WITHDRAWALS at BWRO



2 migd RECHARGE at A1-Alt1
6 migd WITHDRAWALS at BWRO



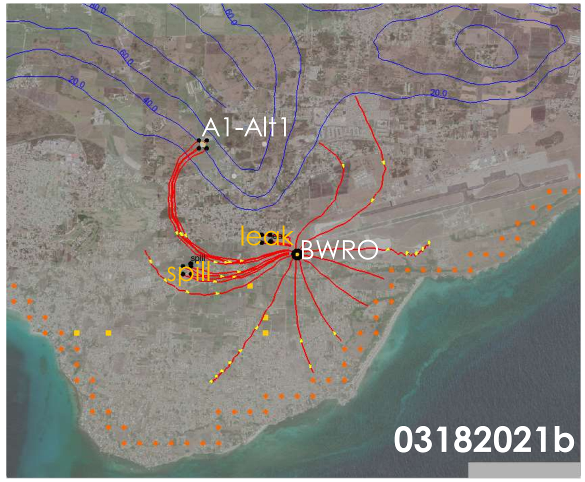
2 migd RECHARGE at A1-Alt2
6 migd WITHDRAWALS at BWRO



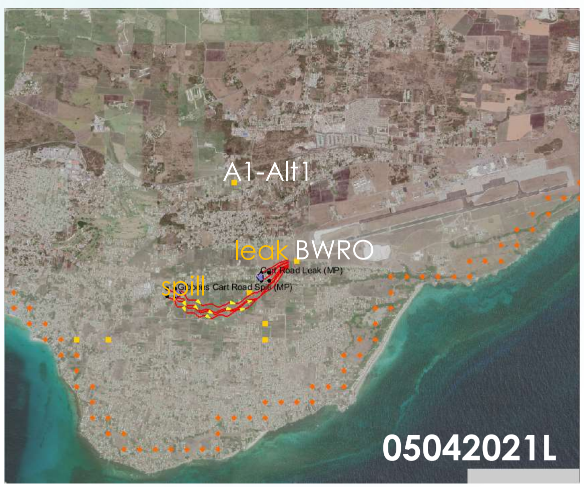
0 migd RECHARGE at A1-Alt1
6 migd WITHDRAWALS at BWRO

This slide considers potential groundwater flow paths from areas with hydrocarbons releases when BWRO pumping 0 and 6 MIGD and recharge varies from full year to 4 months of the year.

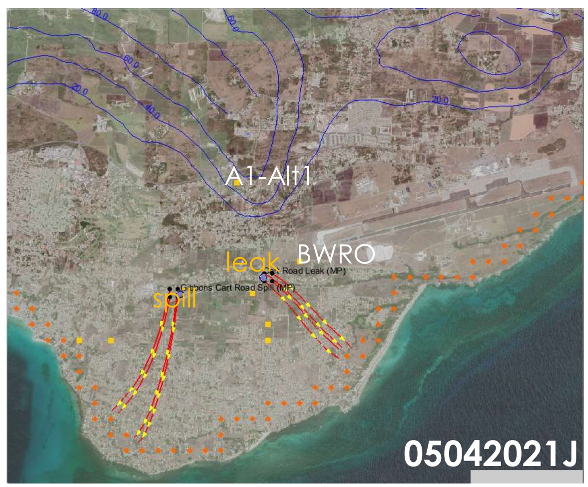
Each yellow dot on the red path line represents 2 years of travel time.



2 migd RECHARGE at A1-Alt1, 4 months
6 migd WITHDRAWALS at BWRO



2 migd RECHARGE at A1-Alt1, full year
0 migd WITHDRAWALS at BWRO



Sensitivity –
K multiplier = 0.1

This slide considers the sensitivity of the model to hydraulic conductivity by reducing the K by one-tenth. Groundwater flow paths and travel times changed.

Each yellow dot on the red path line represents 2 years of travel time.

Figure 3-6
2 migd RECHARGE at A1-Alt1
3 migd WITHDRAWALS at BWRO

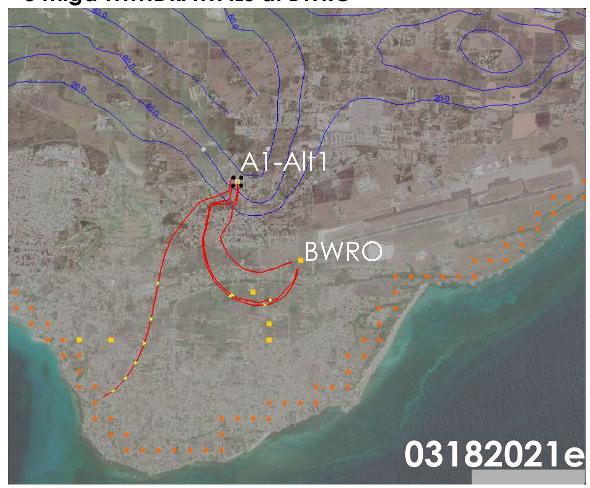
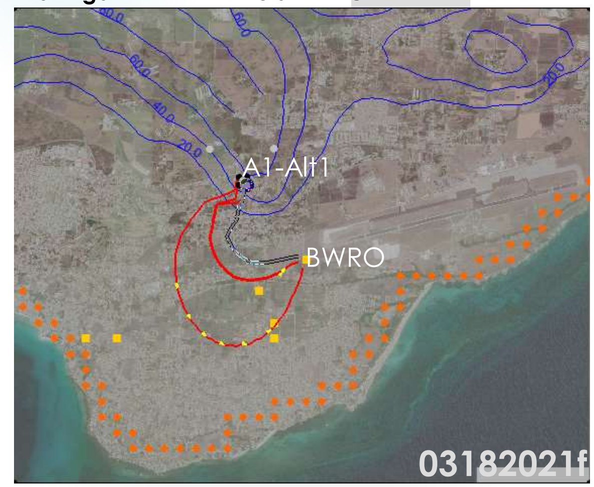
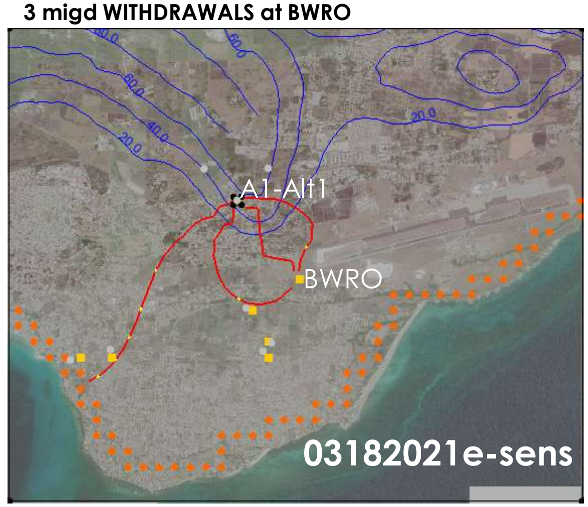


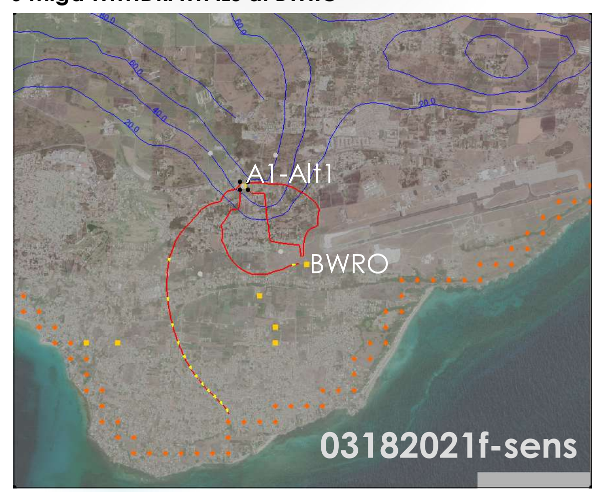
Figure 3-7
2 migd RECHARGE at A1-Alt1
6 migd WITHDRAWALS at BWRO



2 migd RECHARGE at A1-Alt1
3 migd WITHDRAWALS at BWRO



2 migd RECHARGE at A1-Alt1
6 migd WITHDRAWALS at BWRO



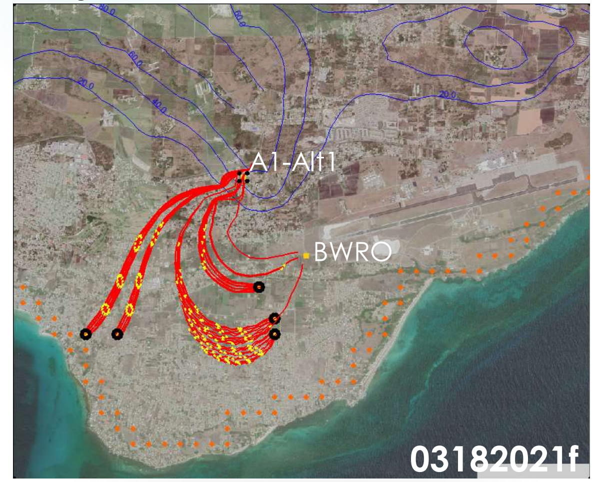
Irrigation Wells – Capture Zones

This slide considers the changes in irrigation well capture zones with variations in recharge at A1-Alt1 and withdrawals at BWRO.

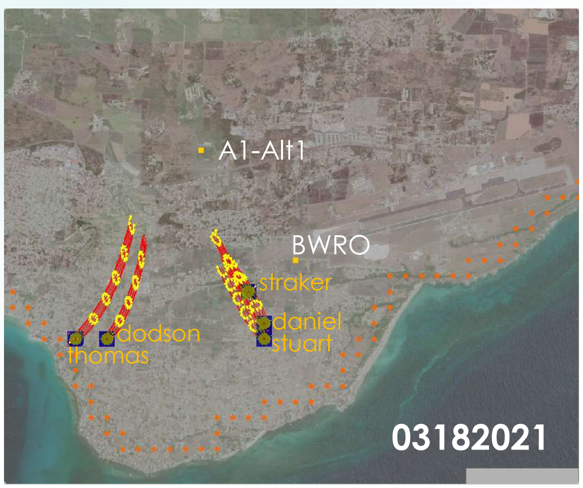
Each yellow dot on the red path line represents 2 years of travel time.

2 migd RECHARGE at A1-Alt1, full year
3 migd WITHDRAWALS at BWRO

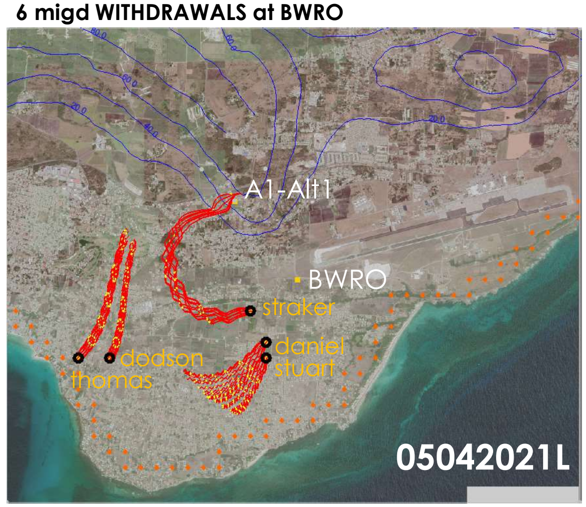
2 migd RECHARGE at A1-Alt1, full year
6 migd WITHDRAWALS at BWRO



0 migd RECHARGE at A1-Alt1
0 migd WITHDRAWALS at BWRO



2 migd RECHARGE at A1-Alt1, 4 months
6 migd WITHDRAWALS at BWRO



2 migd RECHARGE at A1-Alt1, full year
0 migd WITHDRAWALS at BWRO