Executive Summary of Groundwater Modeling of the Laura Lens in the Marshall Islands Completed by AMPHOS21

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Managing Coastal Aquifers in Selected Pacific SIDS (MCA Project)

Development of a numerical groundwater model to assist with groundwater management in Laura, Majuro Atoll, Republic of Marshall Islands

Modelling carried out by AMPHOS21 (Tybaud Goyetche, María Pool, Jordi Guimerà and Elena Abarca)

Executive Summary by SPC

As part of the Managing Coastal Aquifers (MCA) Project funded by the Global Environment Facility (GEF), SPC contracted AMPHOS21 to construct a 3-D, variable density, numerical model to assess the resiliency of the freshwater lens in Laura on the Majuro Atoll in the Republic of the Marshall Islands. The numerical model provides guidance as a management tool to better understand how external forcings (i.e., groundwater abstraction, drought, sea-level rise, and storm surge inundation) impact the freshwater lens.

Atoll islands lack surface water resources and must rely on rainwater and groundwater for their freshwater needs. Due to the density differences between lighter freshwater and heavier saltwater, rainwater which percolates (recharges) through the sediments to the water table will ‘float’ on top of the saltwater, forming a freshwater lens. The volume of the freshwater lens is sensitive to changes in rainfall patterns, over-pumping, and inundation of seawater from storm surges and extreme tidal events.

The community of Laura is located on the western side of the Majuro Atoll in the Marshall Islands. Laura relies on groundwater pumped from seven galleries (shallow, horizontal wells) for its freshwater supply for its approximate population of 1500 residents. A large portion of the land in Laura is used for the cultivation of crops, including taro which is dependent on fresh groundwater for growth.

SPC provided AMPHOS21 with the available data to construct the model, including DEM files, rainfall data, location and pumping rates of wells, and water level and salinity measurements from observation wells. Pumping rate records were incomplete and led AMPHOS21 to use a combination of recorded values when available and calculated averages for periods which did not have records. AMPHOS21 used this information to design, calibrate, and validate the model using their own proprietary software COMSOL Multiphysics. The initial calibration and validation runs for the model were based on data from January 2007 to November 2022. SPC specified the hypothetical scenarios for which AMPHOS21 input into the model and reported on the results.

Scenarios

Scenarios were developed to understand the impacts climatic stressors (drought, sea-level rise, and storm surge inundation) as well as increased abstraction rates in combination with these stressors. For the future scenario runs, the rainfall (recharge) and pumping rates from January 2007 to December 2021 were repeated to represent January 2022 to December 2038 with the following alterations:

Drought (Scenarios A, B, and C)

SPC reviewed rainfall from 1955 to 2021 to assess normal rainfall amounts and drought events. The driest 24-month period during this span was from December 1982 through November 1984 with a total of 4831 mm of rain compared to the average amount of 6572 mm. Daily rainfall amounts from this period were used to replicate drought scenarios in the model and is referred to as the "representative drought rainfall". In Scenario A, rainfall amounts from December 2008 through November 2010 (Dec. 2024 – Nov. 2026 in the model run) were replaced with the representative drought rainfall values (Table 1). For Scenario B, the representative drought rainfall replaced the recorded rainfall from December 2014 - November 2016 (Dec. 2030 – Nov. 2032 in the model run) (Table 1). Scenario C was designed to assess the implications of an unprecedented four-year long drought. For this scenario, the representative drought rainfall was repeated back-to-back, replacing the rainfall from December 2016 – November 2020 (Dec. 2032 – Nov. 2036) (Table 1). During the constructed drought periods for Scenarios A and C, wells in the model were programmed to abstract constant average pumping rates, as recorded values were not available for those times. In Scenario B, daily pumping totals were available and used for the second half of the drought period. For all drought scenarios, the first runs (A1, B1, and C1) used current pumping rates, while for the second runs (A2, B2, and C2), pumping rates were increased by 30% to simulate where increased demands for freshwater can be expected. (Table 1).

Table 1. *Description of the differences between the drought scenarios.*

Scenario	Length of Drought (years)	Pumping Rates during Drought	Total Rainfall in Subsequent 12 months (mm)
A1	2	current average	3684 (approx. average annual rainfall)
A2	2	average +30%	
B1	2	recorded daily values	2492 (below average annual rainfall)
B2	2	daily values +30%	
C1	4	current average	4139 (above average annual rainfall)
C2	4	average +30%	

Sea-Level Rise (Scenario D)

For Scenario D runs, different rates of sea-level rise (SLR) in combination with increased pumping rates and a drought period were assessed. Scenario D1 served as a baseline with no SLR applied. In Scenarios D2, D3, and D4, SLR was applied linearly throughout the model runs (Table 2). For all these runs, pumping rates were increased by 30% compared to current recorded rates and averages and the Scenario A representative drought rainfall was applied.

Table 2*. SLR amounts and rates for Scenario D model runs.*

Scenario	Total SLR (m)	Annual Rate (cm/yr)
D1	0	0
D2	0.25	0.93
D3	0.5	1.85
D4	1	3.7

Inundation (Scenario E)

The E Scenarios assessed the impact of a two-day storm surge inundation event in combination with SLR and how subsequent rainfall amounts affected recovery rates of the freshwater lens (Table 3). Inundation levels were based on a storm event with a 25-year return period (4% chance of occurrence in any given year).

***Table 3**. Simulated time frames, sea-level rise, and subsequent rainfall amounts for the various inundation scenarios.*

			Subsequent Total Rainfall (mm)	
Scenario	**SLR (m)**	**Simulated Time Frame**	**6 Months**	**12 Months**
E1.1	0.25	2010 - 2015	1297 (average)	3634 (average)
E1.2		2016 - 2021	661 (Below average)	2617 (Below average)
E2.1	0.5	2010 - 2015	1297	3634
E2.2		2016 - 2021	661	2617
E3.1	1	2010 - 2015	1297	3634
E3.2		2016 - 2021	661	2617

Results

Model results show rainfall/drought greatly impact the total volume of the freshwater lens, while pumping rates affect salinity of individual wells. In all the drought scenarios, increased pumping rates had little additional effect on decreasing the volume of the freshwater lens (<1% difference between the 1 and 2 scenarios), but individual wells saw a 19 – 37% increase in salinity values when pumping rates were increased by 30% (Tables 4 and 5). Scenarios A and B saw approximately the same decrease in freshwater lens volume (~62%), but it took about an additional year for the lens to fully recover from the A scenarios (Table 6). However, in the B scenarios, when recorded daily pumping rates were used, five out of the six wells experienced salinization beyond the potability limit (2500 µS/cm), while only three wells in Scenario A1 and four wells in Scenario A2 were salinized. This increase in salinized wells is likely due to the B scenarios incorporating recorded daily pumping rates while the A scenarios used constant average rates during the drought period.

Sea-level rise did not greatly affect the freshwater lens volume or salinity at individual wells in the D scenarios (Tables 4, 5 and 6). The main threat of SLR stems from groundwater flooding (i.e., when the water table rises above the land surface) and exacerbating storm surge and tidal inundation events (Figure 1; Tables 3, 4 and 5). With 0.25 m of SLR, a 25-year storm inundation event would be expected to reduce the freshwater volume by about 30 – 35%, while the same storm with 0.5 – 1.0 m of SLR would salinize 87 – 100% of the freshwater lens (Table 4). The inundation experienced in Scenarios E1.1 and E1.2 was limited to the edges of the lens and thus did not cause the pumping wells to be salinized (Figures 2 and 3; Table 6). The increase in sea level caused the inundation in Scenarios E2 and E3 to extend farther inland, completely covering the island with seawater in the E3 scenarios. In the E2 and E3 scenarios, salinity levels in all wells returned to below the potability limit (2,500 µS/cm) within a year following the inundation event while the total volume of the freshwater lenses did not recover for more than four years (Tables 4 and 6).

Model Limitations

The main limitation of the model is due to the lack of pumping rate records. As daily pumping records were only available for limited portions of the modelled time frame (less than two years), average pumping rates were used which could greatly underestimate the salinity values at individual wells. Pumping rates had a greater impact on salinity levels in wells than drought conditions which the total freshwater lens volume as evidenced by the difference in results from Scenarios A and B. Pumping of wells at too high of rates can lead to upconing of saltwater and salinization of wells. Additionally, without knowing current accurate pumping rates, it is difficult to provide guidance on sustainable rates.

Recommendations

To improve the uncertainty of the model and to getter guide sustainable pumping rates, flow meters should be installed in each well. More accurate records will also help to inform water managers on the total demand of water and allow for better estimations of future needs. As highlighted by the drought scenarios, A, B and C, increase in total pumping does not have a large impact on the total volume of the freshwater lens but rather affects the salinity of individual wells. Water managers should be prepared for during drought events that some wells may become salinized above the potability limits for several months and will require attentive monitoring of salinity. To be able to use these vulnerable wells, water managers may want to consider investing in reverse osmosis systems to install on these wells or treatment plant and use during periods of salinization. While SLR does not pose a great threat to the volume of the freshwater lens, it may lead to groundwater flooding of low-lying areas. Attention should be paid to any infrastructure in such areas and steps taken to limit damage, such as elevating electrical boxes and relocating house and other buildings. This indicates that if there is need to increase production, new wells should be installed rather than increasing the pumping rates of existing wells. One of the most severe and abrupt risks to the freshwater lens is inundation from storm surges and extreme tidal events. Wells closer to the coastline are more vulnerable to salinization from inundation events than wells located farther inland. This should be considered when siting new wells and effort made to locate the wells as far inland as possible.

***Table 4**. Percent decrease in freshwater lens volume for each scenario, and the amount of time it took the lens to recover to 100% of its pre-event volume. In scenarios D1, D2, and D3, the freshwater lens only decreased in volume because of the drought event but did not experience additional decrease due to SLR.*

General Category	Scenario	Decrease in Freshwater Lens Volume	Full Recovery Time (months)
Drought	**A1**	62.2%	36
	A2	63.1%	36
	B1	61.7%	22
	B2	62.2%	22
	C1	78.4%	Full recovery not reached by end of simulation (28 months)
	C2	78.8%	
SLR	**D1**	--	--
	D2	--	--
	D3	--	--
	D4	5.0%	--
Inundation	**E1.1**	30.0%	55
	E1.2	36.7%	33
	E2.1	87.1%	53
	E2.2	93.3%	52
	E3.1	99.8%	59
	E3.2	100.0%	51

***Table 5**. Maximum electrical conductivity calculated at each pumping well during respective scenarios. Electrical conductivity is a proxy for salinity. Gray shading indicates value above the potability limit of 2,500 μS/cm.*

		Electrical Conductivity (μS/cm)					
Scenarios		**PW1**	**PW2**	**PW3**	**PW5**	**PW6**	**PW7**
Drought with constant average pumping	**A1**	**6800**	**3736**	2326	1190	1364	**8285**
	A2	**8862**	**5017**	**2915**	1499	1720	**10872**
Drought with recorded pumping rates	**B1**	**2914**	**5068**	1531	**3758**	**4613**	**5191**
	B2	**3978**	**6969**	1951	**5025**	**5693**	**6967**
Double Drought	**C1**	**3969**	**5347**	2498	**5979**	**5418**	**6762**
	C2	**5026**	**6805**	**2995**	**7113**	**6538**	**8457**
SLR		D Scenarios did not greatly increase EC in wells					
Inundation	**E1.1**	1139	500	388	236	134	1094
	E1.2	947	1908	1492	**2895**	2241	2041
	E2.1	**11290**	**10374**	**6300**	**12912**	**13514**	**20496**
	E2.2	**12151**	**10548**	**6620**	**14131**	**16278**	**32636**
	E3.1	**22067**	**21715**	**26939**	**17680**	**24076**	**23306**
	E3.2	**19910**	**15008**	**14677**	**18886**	**20932**	**17715**

***Table 6**. Number of months for electrical conductivity (salinity) to drop below the potability limit following the modelled events.*

		Months above potability limit (2,500 μS/cm)					
Scenarios*		**PW1**	**PW2**	**PW3**	**PW5**	**PW6**	**PW7**
Drought with constant average pumping	**A1**	32	10	--	--	--	32
	A2	36	26	6	--	--	36
Drought with recorded pumping rates	**B1**	1	7	--	4	2	12
	B2	7	20	--	9	10	22
Double Drought	**C1**	10.5	34.5	--	32	26	40
	C3	28	57	2.5	45	43.6	59
SLR		D scenarios did not increase electrical conductivity (salinity) in wells					
Inundation	**E1.1**	--	--	--	--	--	--
	E1.2	--	--	--	1	--	--
	E2.1	9.3	9.3	3.6	9.5	4.5	9.7
	E2.2	7.5	9.1	5.5	10.9	7.4	9.2
	E3.1	11.9	10.7	10.2	10.9	8.2	11.3
	E3.2	8.5	10	8.4	12.1	7.4	8.9

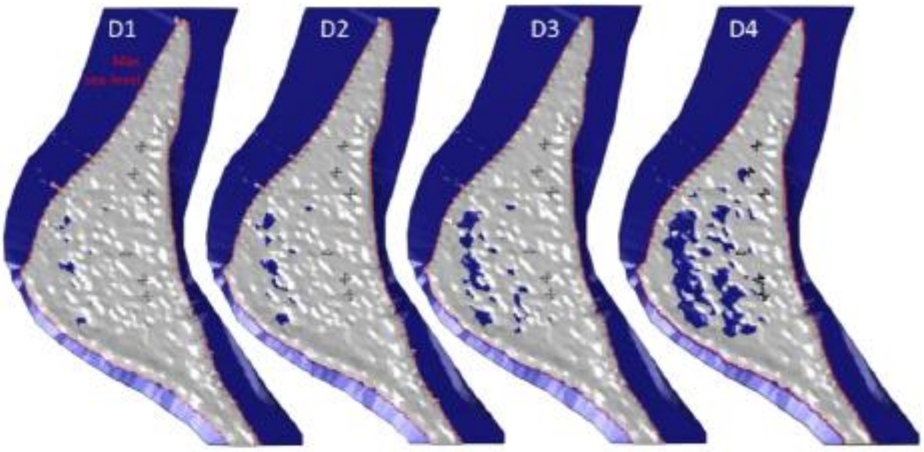

Figure 1. *Maps showing ponding of groundwater due to SLR pushing the water table about the surface in scenarios D1 – D4.*

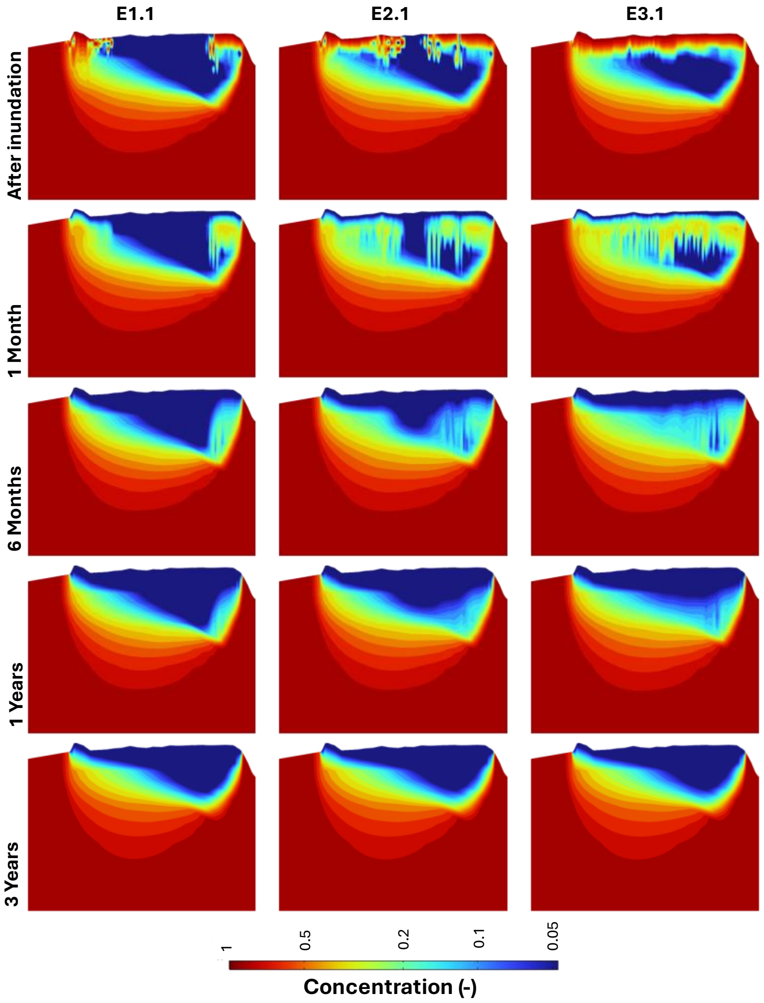

Figure 2*. Cross-section through the middle of the lens showing salinity levels relative to seawater for inundation scenarios followed by a period of above average rainfall.*

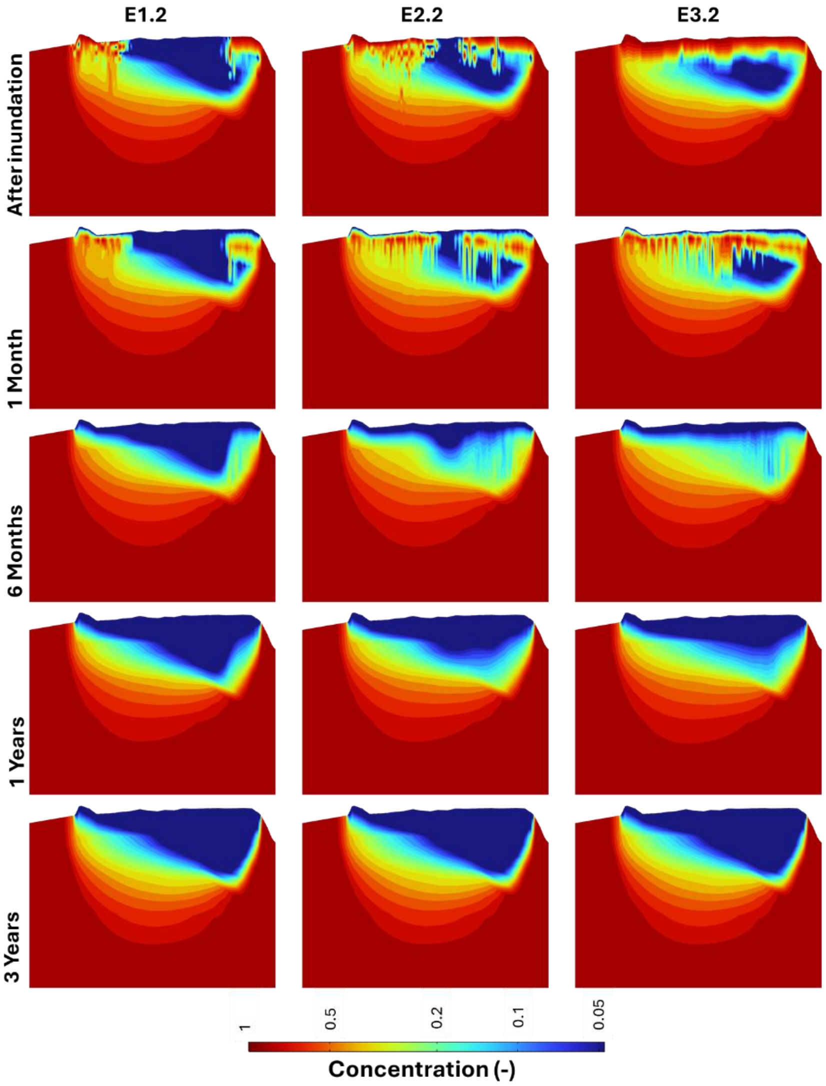

Figure 3. *Cross-section through the middle of the lens showing salinity levels relative to seawater for inundation scenarios followed by a period of below average rainfall.*