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Technical assessment combined with an extended cost–benefit analysis for the restoration of groundwater and forest ecosystem services – an application for Grand Bahama

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Table S1. Description of the input data for the holistic analysis of potential sustainability measures.

Input data	Units	Value/comment	Sources
Common data			
Daily precipitation rates	mm/day	Monitored time series	From meteorological station ECMWF ERA5 (1979-2000) and Freeport airport (2012-2021); provided by the meteorological department of the Grand Bahama Port Authority.
Monthly precipitation rates at the spatial level	mm/month	Maps from 1970 to 2000 (resolution: 1 km^2)	WorldClim 2.1, Fick and Hijmans (2017).
Land use/land cover	-	Raster file	Esri (2021); Ruesch and Gibbs (2008).
Digital elevation model (DEM)	m a.s.l.		Eurostat DEM (Eurostat, 2013)
Building footprints	Vector file		Provided by GBUC.
Evaluating the technical feasibility of MAR			
Samples from a sedimentation layer	mm	grain diameter	Grain size analysis according to DIN (2017) of soil sample taken on 6th of July 2021 in the west part of Wellfield 6 (coordinates: 26.613531, -78.542213).
Groundwater level measurements	m	below ground level	January and October 2020 (Dokou et al., 2020) January 2021, taken by IsraAID, published in the mWaterPortal (https://portal.mwater.co/)
CBA common data			
Discount rate	%	1-10	Flory (2013)
Reference years	years	30 (2020 to 2050)	European Commission (2015)
GB households	number of households	15140	Department of Statistics of The Bahamas (2012)
Costs common data			
Project manager costs	USD/hour	150	Phoenix Engineer (M. Gomez, personal communication, April 14, 2022)
Project administrator costs	USD/hour	125	as before
Work coordinator costs	USD/hour	125	as before
Financial manager costs	USD/hour	200	as before
Certificated expert for public procurement costs	USD/hour	150	as before
Study documentation costs	USD/hour	150	as before
Project documentation costs	USD/hour	100	as before
Permits obtaining costs	USD/hour	100	as before
Advertisement campaign costs	USD/unit	2180	Miller et al. (2014)

Table S1 (continued)

Input data	Units	Value/comment	Sources
Ecosystem services valuations: Carbon sequestration			
Carbon Pools	t C/ha	IPCC Tier 1 method	IPCC (2014, 2006)
Ecofloristic zones	Vector file		Ruesch and Gibbs (2008)
Carbon prices (social cost)	USD/tCO_2	17.90; 20.00; 55.91	Smith et al. (2014); The World Bank (2021); U.S. EPA (1999)
Ecosystem services valuations: Timber production			
Timber parcels	km^2	Assumptions: 88% survival rate when planting; 12 trees/ha left during harvesting.	Le et al. (2014) and Myers et al. (2004)
Percentage of harvesting	%	99	Myers et al. (2004)
Mass of wood harvested	ton/ha	(calculation-based) on the density of 420 kg/m³, 15 cm diameter and 30 m height for 30 year pine tree	The Engineering ToolBox (2004) and (Sanchez, 2020)
Frequency of harvest periods	years	30	Forest NSW (n.d.) (Forest NSW, n.d.)
Price of wood	USD/ton	91	Wood Resources International (2019)
Maintenance costs	USD/acre/year	0.70	Little et al. (1977)
Harvesting costs	USD/ton	11	Donagh et al. (2019)
Biomass conversion and expansion factors (BCEF)	-	range of default values	Sharp et al. (2015)
Ecosystem services valuations: Drinking water supply			
Water price: minimum monthly (0 – 2,000 gallons)	USD flat rate	12.83	GBUC (2022)
Water price: 2,001 – 10,000 gallons	USD/1000 gallons	4.37	GBUC (2022)
Water price: 10,001 – 20,000 gallons	USD/1000 gallons	5.25	GBUC (2022)
Water price: >20,000 gallons	USD/1000 gallons	6.16	GBUC (2022)
Ecosystem services valuations: Habitat provisioning			
Willingness to pay for habitat conservation	USD/ household	26.20	Wang et al. (2021)
Ecosystem services valuations: Nature-based tourism			
Average tourism expenditure before hurricane events	USD/quarter	Depends on year and quarter	Bahamas Ministry of Tourism (2022)
Average tourism expenditure in 2021	USD/quarter	Depends on quarter	Bahamas Ministry of Tourism (2022)

S1. Achievable recharge volume from rainwater harvesting

The achievable recharge volume from rainwater harvesting schemes E_R [M^3T^{-1}] in wellfield 1,3 and 4 was calculated based on recommendations by the German institute for norms (DIN, 2002):

$$E_R = A_A \times e \times h_n \times h$$

with A_A, the catchment area [M^2], e the coefficient of yield [%] set to 0.8 for inclined hard roofs like on Grand Bahama, h_n the yearly rainfall amount [M] and h, the hydraulic filter efficiency [%] set to 0.9 for a typical filter value.

S2. Method to estimate the annual average tourism expenditure

The annual average tourism expenditure of the years before a hurricane event was calculated considering data from the years 2010 to 2015 and 2018. The total annual tourism expenditure of 2021 was estimated based on the data of the first quarter of 2021 and the averaged percentage of each quarter over multiple years (Bahamas Ministry of Tourism, 2022), as shown in Table S2.

Table S2. Applied tourism expenditure in tourism revenue projection (Bahamas Ministry of Tourism, 2022).

Period	Percentage	Average expenditure before hurricane events [USD]	Estimated expenditure of 2021 [USD]
First quarter of the year	27,9%	40,587,623	10,540,443
Second quarter of the year	30,1%	43,673,733	11,387,157
Third quarter of the year	22,1%	32,349,384	8,337,353
Fourth quarter of the year	19,9%	29,052,309	7,539,175
Full year	100%	145,663,049	37,804,128

S3. Risk assessment related to potential MAR scheme

Potential risks were identified for rooftop rainwater harvesting with drain trenches on Grand Bahama, based on a summary in Imig et al. (2022). Further, the risks were ranked according to the stage of MAR implementation into risks occurring in the planning phase, in the catchment of the water source, during MAR operation (infiltration, storage and recovery), or during distribution and final use (Table S3-S6). Qualitative risk scores were given using a risk matrix after Swierc et al. (2005) considering both likelihood and severity of consequences on a scale from 1 to 5 (Figure S1). Possible risk treatments were suggested by considering suggestions from DEEPWATER-CE (2020) and Nadebaum et al. (2004). The remaining risks after applying the mitigation strategies were evaluated with the risk score matrix again to determine the residual risk. Some risks occur in multiple phases, and if in the prior phase a treatment was suggested, the residual risk after treatment was used to continue with the risk in the next phase.

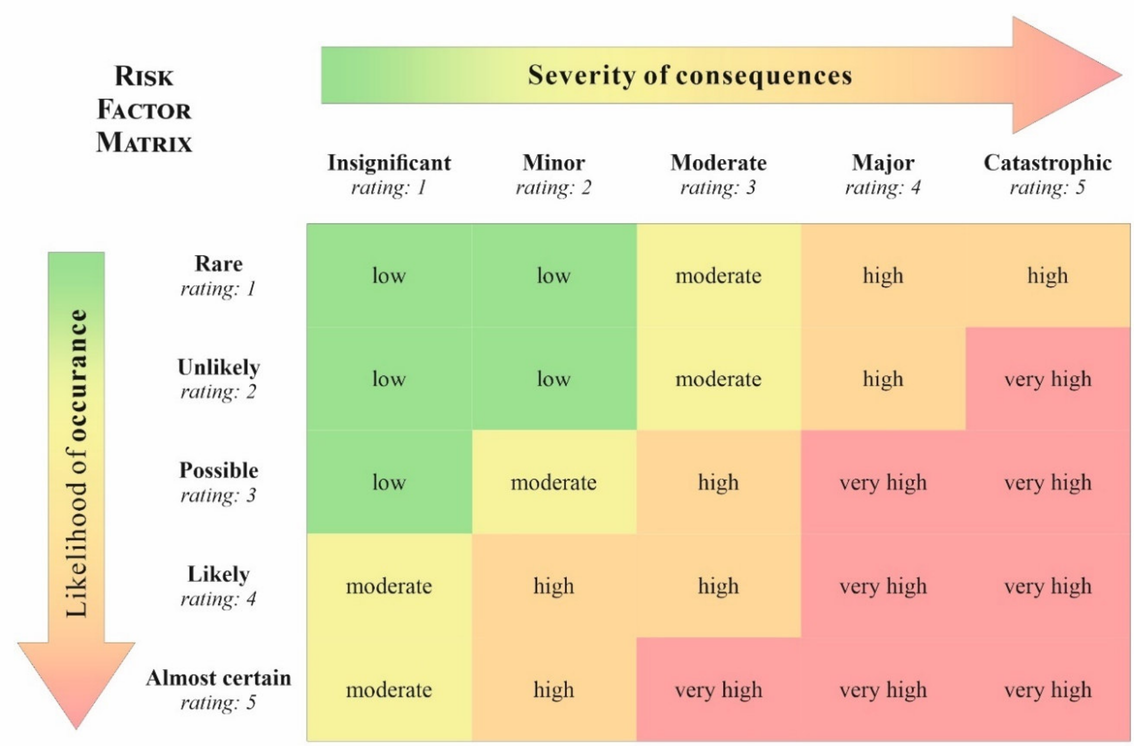

Figure S1.: Risk factor score matrix for qualitative risk assessment, relating the likelihood of hazards to the severity of consequences (Imig et al., 2022; after Swierc et al., 2005).

Table S3.: Identified, analysed, and evaluated risks in the MAR planning phase; H: human health risk, T: technical risk; L: Likelihood, C: Severity of consequences.

Planning Phase				
Type	Potential Risk	Score	Mitigation measure	Residual Score
H	Surface infiltration of saltwater or water with high pollutant loads into drain during storm event	Very high (L:5/C:3)	Sealing of storm drains at the top	Moderate (L:5/C:1)
H	Inflow of saltwater or water with high pollutant loads into the gutter during storm with very high surge	High (L:4/C:3)	MAR only in elevated areas	Moderate (L:1/C:3)
H	Inflow of saltwater or water with high pollutant loads into the gutter during storm with very high surge	High (L:4/C:3)	MAR only in elevated areas	Moderate (L:1/C:3)
T	Groundwater flooding due to mounding water table	High (L:3/C:3)	Leaving enough distance to groundwater table	Moderate (L:2/C:3)
H	Roof material deteriorating water quality	Moderate (L:4/C:1)	Study on water quality	
T	Increased carbonate dissolution causing to subsidence	Moderate (L:1/C:3)	-	Moderate (L:1/C:3)
H	Mobilization of toxic substances from carbonates	Low (L:1/C:2)	-	Low (L:1/C:2)

Table S4.: Identified, analysed, and evaluated risks during the runoff concentration phase in the catchment; H: human health risk, T: technical risk; L: Likelihood, C: Severity of consequences.

Catchment Phase				
Type	Potential Risk	Score	Mitigation measure	Residual Score
H	Surface infiltration of saltwater or water with high pollutant loads into drain during storm event	Moderate (L:5/C:1)	Adjustment of disinfection, dependent on monitoring	Low (L:2/C:1)
H	Inflow of saltwater or water with high pollutant loads into the gutter during storm with very high surge	Moderate (L:1/C:3)	Adjustment of disinfection, dependent on monitoring	Moderate (L:1/C:3)
H	Microbiological contamination and turbidity due to bird fecies, dead animals, leaf litter or dust on the roof	Moderate (L:3/C:2)	Adjustment of disinfection, dependent on monitoring	Low (L:2/C:2)
H	Roof material deteriorating water quality	Moderate (L:4/C:1)	Monitoring of water quality	Moderate (L:4/C:1)
H	Mobilization of toxic substances from carbonates	Low (L:1/C:2)	Monitoring of water quality	Low (L:1/C:2

Table S5.: Identified, analysed, and evaluated risks in the MAR operation phase; H: human health risk, T: technical risk; L: Likelihood, C: Severity of consequences.

Operation Phase				
Type	Potential Risk	Score	Mitigation measure	Residual Score
T	Increased carbonate dissolution causing subsidence	Moderate (L:1/C:3)	(Hydro)geochemical and geotechnical studies	Low (L:1/C:2)
T	Groundwater flooding due to mounding groundwater table	Moderate (L:2/C:3)	Decommissioning of MAR system during wet season, control borehole to notice high water level	Low (L:2/C:2)
T	Clogging of drain trench	Moderate (L:2/C:3)	-	Moderate (L:2/C:3)
T	Unplanned costs like cleaning of drain trench (No.13'); decommissioning of drain trench (No.7')	Moderate (L:2/C:3)	Account for economic flexibility in the budget	Low (L:2/C:2)

Table S6.: Identified, analysed, and evaluated risks in the MAR operation phase; H: human health risk, T: technical risk; L: Likelihood, C: Severity of consequences.

Distribution Phase				
Type	Potential Risk	Score	Mitigation measure	Residual Score
H	Biological contamination of water	High (L:2/C:4)	Adjust disinfection measure	Moderate (L:2/C:3)
H	Microbial or algae growth during storage	Moderate (L:2/C:3)	Adjust storage time or disinfect only after storage	Low (L:1/C:2)
T/H	Contamination with disinfection by-products	Moderate (L:2/C:3)	Use different disinfection measure	Low (L:1/C:2)

S4. Costs of reverse osmosis

A reverse osmosis system was installed in Grand Bahama and the published investment cost was $5 million (GBUC, 2021). This value was considered as a lumped sum of the measure's costs, but no detailed information on the types of costs was found. This lumped sum did not include operation costs. Therefore, the operation costs were estimated through a literature review on studies and publications describing similar projects (Abbasighadi, 2013; CDM, 2011; Sarica, 2018).

S5. Costs of Rooftop rainwater harvesting (RRWH)

Experts of the company Phoenix Engineer (M. Gomez, personal communication, April 14, 2022) provided the necessary information to estimate the investment and operation costs of the RRWH system.

The size of the gutter system was calculated by using the following information:

- the average length of the roof buildings, which was derived from the average roof area of the buildings in Wellfield 1 (221 m^2) and in Wellfields 3 and 4 (347 m^2);
- the assumption of a squared roof;
- planning the presence of four gutter sections per house.

The costs of the gutter system were estimated by using the following information:

- the fact that vinyl gutters have average lifespan of 25 years (Gutter professionals, 2017);
- the assumption that all buildings have one floor with an average height of 3 m;
- the average estimation of one soakaway excavation per building,
- the estimation of the total volume of gravel to be removed: corresponding to 23.8 m^3 for the buildings in Wellfield 1 and 37.4 m^3 for the buildings in Wellfields 3 and 4.

Table S7 describes the costs per unit used to estimate the operation costs, like the maintenance of the system or the service of experts to replace gutters.

Table S7. Basis for estimating investment and operation costs of the RRWH system.

Type of cost	Price	Unit	Comment
Project management and administration			
Experts in the installation of the system	190.00	$ / hour	16-hour installation per house, suggested by Phoenix Engineer
Preparation of the project			
Water quality analysis	160.00	$ / hour	Assumption of 40 hours
Implementation of works and equipping			
Gutter (vinyl)	15.00	$ / ft	Length based on the average size of roof
Distribution piping	10.50	$ / ft	Length based on average height of one floor house
Filter	161.29	$ / unit	Self-cleaning filter from (Rainy, 2023)
Excavation soakaway	4,500.00	$ / unit	One soakaway per house
Gravel	26.40	$ / ton	Stone 3/8''
Operation			
Maintenance of system	500.00	$ / month	
Experts in replacement of gutters	190.00	$ / hour	Vinyl gutters have a lifetime of 25 years
Regular water quality analysis	160.00	$ / hour	Assumption of two days per month

S6. Costs of reforestation

Jantawong et al. (2022) reported reforestation costs according to the initial stocking density. We combined these data with the number of trees in the reforestation area, information that was derived from the extent of the measure and from expert-based knowledge from Turks & Caicos Island Government (B. N. Manco, personal communication, April 1, 2022). As a result, we estimated that the reforestation would involve 1000 trees per hectare.

Table S8 displays the costs for the pre-planting phase, tree planting and operation. Tree production costs were assumed to be null, as the ongoing project "Establishment of a seedling nursery and replanting for forest recovery on Grand Bahama" would cover these costs by implementing a nursery for forest recovery (University of The Bahamas, 2021). We assumed two tree-planting events of the project (one for the first and one for the second year), where all saplings would be planted in the reforestation sites. For the maintenance costs, we assumed that weeding and fertilizer application would take place for two years, and that also tree-growth monitoring is needed for two years from planting.

Table S8. Basis for estimating investment and operation costs of the reforestation scenarios from Jantawong et al. (2022)

Type of cost	Year 1	Year 2	Unit
Pre-planting			
Site preparation	244.10	-	$ / ha
Pre-planting site survey	13.07	-	$ / ha
Tree planting			
Planting	2,346.20	1,218.59	$ / ha
Materials and equipment	253.80	129.03	$ / ha
Labour	874.00	546.56	$ / ha
Transportation	99.55	23.94	$ / ha
Operation			
Maintenance	1,398.36	693.97	$ / ha
Monitoring	54.19	31.04	$ / ha

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