

Estimating Groundwater Recharge in the Delta of Wadi El-Arish aquifer, North Sinai, Egypt, using WetSpass-M model

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Abstract - Groundwater is the main freshwater reserve of arid and semi-arid regions, and its recharge is difficult to estimate. This study applies the spatially distributed WetSpass-M water balance model to estimate rainfall-derived recharge in the Delta of Wadi El-Arish aquifer, North Sinai, Egypt. The model was run on a 30 m grid with twelve monthly climatological inputs (1984-2019) for precipitation, temperature and wind speed, soil texture from the Harmonized World Soil Database, three land-use classes, default soil and runoff parameters, and literature-based parameters for olive orchards. Simulated January recharge at six observation wells was about 0.057 mm/month at four wells on bare sand and 0.0014 and 0.0005 mm/month at the other two, showing that recharge is controlled by land use, soil and slope. These rates are roughly 9 to 1,100 times lower than the lowest recharge of an earlier calibrated flow model of the aquifer, so the model as configured does not reproduce the magnitude of the reference recharge and its results are preliminary. The water-level surface of the reference model was on average 6.1 m shallower than the depths observed in 2016, with a correlation of 0.96, consistent with the reported decline in water levels. The results are consistent with a very small rain-fed recharge relative to abstraction, but calibration, sensitivity analysis and evaluation against independent recharge estimates are needed before the model is used for prediction.

Key Words: WetSpass-M, groundwater recharge, Wadi El-Arish, arid coastal aquifer, model evaluation

1. INTRODUCTION

Groundwater along Mediterranean coastal zones typically exists under phreatic (unconfined) conditions, forming thin freshwater lenses that float above underlying saline water and are replenished through rainfall infiltration [1]. Egypt, as a semi-arid country, is particularly exposed to the combined pressures of climate change, groundwater overexploitation, and large-scale development projects along its northern coast; given its growing dependence on groundwater as a vital alternative water resource, these pressures substantially heighten the region's water security vulnerability. In arid and semi-arid coastal settings such as the Al-Arish aquifer, where recharge is already constrained by low annual rainfall and high evaporative demand, even modest changes in the magnitude or timing of precipitation could have

disproportionately large effects on groundwater availability.

Wadi El-Arish constitutes the largest drainage basin in the Sinai Peninsula, and its aquifer has attracted sustained Egyptian government interest for water resource development projects. Numerous studies have therefore examined the aquifer from a range of perspectives. EL-Alfy [2] classified the aquifer's groundwater and characterized the geochemical processes governing its chemistry using GIS-based methods. Abdelaziz and Bakr [3] applied an inverse groundwater flow model (GMS) with recharge from rainfall infiltration, return flow from imported Nile water, and domestic water use, and found a clear decline in groundwater levels indicating that abstraction exceeds natural recharge, which places the water balance in a critical state. Abdel Zaher et al. [4] identified favorable groundwater potential zones in the southern Wadi El-Arish basin, within the Wadi Abu Tareifiya and southern Wadi El-Azariq sub-basins, and estimated runoff volumes of 4.19–59.30 million m³ with the HEC-1 hydrologic model. With a focus on the vulnerability of the basin, Mohamed and El-Raey [5] developed a composite flash-flood vulnerability index from hydro-climatic and physical parameters, and found that urban areas, loamy sand, sand dunes and low-lying flat terrain were the most susceptible to flooding, with 42% of the basin classified as low vulnerability, 45% moderate, and 13% high.

Despite this body of work, research on the Wadi El-Arish aquifer has concentrated on hydrochemical characterization, historical groundwater flow, potential zones, and flash-flood risk. None of these studies has estimated the rainfall-driven recharge of the aquifer with a spatially distributed water balance model, although recharge is the quantity that ultimately sustains the aquifer and the input needed by any later assessment of abstraction or climate scenarios. Such an estimate requires a physically based model that resolves how land use, soil and slope partition rainfall between interception, runoff, evapotranspiration and recharge. WetSpass, an acronym for "Water and Energy Transfer between Soil, Plants, and Atmosphere under quasi-Steady State", is a spatially distributed, GIS-based water balance model first developed by Batelaan and De Smedt [6], [7]. It partitions each grid cell into vegetated, bare soil, impervious, and open water fractions, solves an independent water balance for each, and recombines them into a cell-level recharge estimate. Its

extension to monthly resolution, WetSpas-M [8], better represents intra-annual recharge variability, which matters where recharge is concentrated in a short wet season, as along the Mediterranean coast.

Although developed for temperate European catchments, WetSpas has since been applied in arid, semi-arid and data-scarce environments, including the Gaza Strip [9], the Nile Delta [10], other African basins [11], and the Birki watershed of northern Ethiopia, where Meresa and Taye [12] estimated about 1.12 million m³ of annual recharge over 45 km², equivalent to a sustainable extraction rate of about 0.17 m³/d/ha. In Sinai, Soliman et al. [13] calibrated WetSpas against isotope-derived recharge in the El-Qaa plain of South Sinai, and Soliman et al. [14] coupled WetSpas with MODFLOW and CORDEX climate projections there, projecting recharge declines of about 35–75% and water-table drops of 7–8 m by 2071–2100. No comparable application exists for the Wadi El-Arish aquifer. The present study applies WetSpas-M to estimate rainfall-derived recharge in the Delta of Wadi El-Arish and evaluates the result against the recharge and water levels of the calibrated flow model of Abdelaziz and Bakr [3]. It also states the assumptions made and the further evaluation needed before the model can be used for prediction. Section 2 describes the study area, Section 3 the model, data and evaluation approach, Section 4 the results, and Section 5 the conclusions.

2. STUDY AREA

2.1 Location and general description

Wadi El-Arish is located in North Sinai, Egypt, and constitutes the largest drainage basin in the Sinai Peninsula. The study area lies between longitudes 33°35' E and 34°14' E and latitudes 30°47' N and 31°12' N, as shown in Fig. 1. The Delta of Wadi El-Arish relies on groundwater as its principal source of water for drinking, agricultural, industrial, and other uses. Across much of this coastal aquifer, the groundwater table now sits below mean sea level, indicating that freshwater abstraction has exceeded natural recharge; the aquifer is currently sustained by lateral inflow from adjacent aquifers, depletion of aquifer storage, and return flow from domestic wastewater [3].

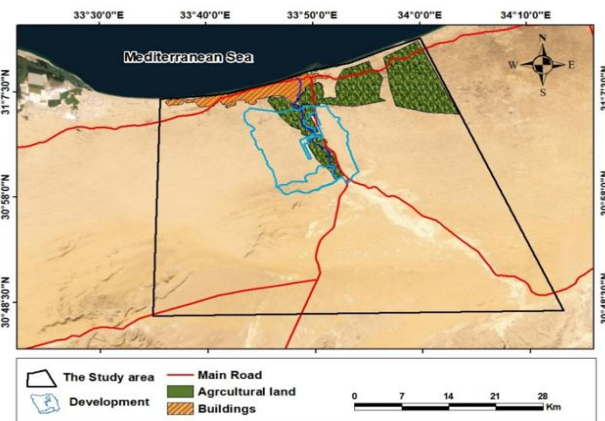


Fig -1: Location of the study area.

2.2 Climate

The study area has an arid to semi-arid climate, with hot summers, cold and rainy winters, and a high evaporation rate. Mean annual rainfall ranges from 60 to 80 mm, and daily mean evaporation reaches 4 mm/day. Average summer temperatures range from 25°C to 43°C, and winter temperatures from 3°C to 10°C.

2.3 Geology and hydrogeology

The Delta of Wadi El-Arish sustains heavy pumping for irrigation and is intensively cultivated with olives, date palms, and vegetables [15]. North Sinai comprises sedimentary rocks ranging in age from Triassic to Quaternary [16], [17], [15]. The Quaternary deposits are the principal water-bearing formations in the Delta of Wadi El-Arish and consist of sand dunes, old beach sand, and Kurkar, with a thickness of approximately 80 to 100 m [18], [19]. The sand dune deposits are widely distributed along the coastal plain, overlie the old beach sand, and are locally interbedded with clay and gravel layers; their thickness ranges between 20 and 40 m.

2.4 Soil characteristics

The soils of the Wadi El-Arish watershed are spatially heterogeneous and closely tied to the underlying geomorphological units. A morphometric and remote-sensing-based characterization of Wadi El-Arish classified the basin into nine geomorphological units and reported that wadi deposits (approximately 2,617 km²) have very gentle slopes, deep soil profiles exceeding 120 cm, and loamy sand to gravelly sand texture, that sand sheets are sand-dominated, and that alluvial plain, terrace and footslope deposits range from loamy sand to very gravelly sand, with salinity generally increasing toward the lower-lying depositional units [20].

An independent hydrogeophysical assessment of north-central Sinai describes the El-Arish basin soils as predominantly yellowish-brown, consistent with loamy sand to sandy loam textures, and distinct from the coarser gravelly sands and sand dunes of adjacent zones [21]. At the coastal fringe, an environmental soil study of the north Sinai coastal zone reports considerably greater textural variability, from clay to coarse sand within single profiles, and links fine-textured soils and elevated soluble salts to seawater seepage in low-lying coastal locations [22]. This coastal-to-inland gradient is consistent with the earlier soil genesis and classification study of Sinai's coastal plain [23].

Collectively, these studies indicate loamy sand to sandy loam along the wadi corridor and its agricultural periphery, coarser sand and gravelly sand in the surrounding sand-sheet desert, and finer, more clay-influenced textures in the low-lying coastal fringe. The soil map used in the model (Fig. 2D; Section 3.3.2) comes from a global database with a resolution of about 1 km. It shows sand over most of the domain, silt loam along the wadi corridor, and sandy loam in the south-west, which differs in detail from the local descriptions above. This difference is a limitation of the input data (Section 4.4), and it means that soil texture is represented as broad zones rather than as local variability.

3. MATERIALS AND METHODS

3.1 The WetSpa model

The model used in this study is WetSpa, an acronym for "Water and Energy Transfer between Soil, Plants, and Atmosphere under quasi-Steady State" [6], [7]. It relies on both physical and hydro-meteorological input datasets. WetSpa computes the total water balance of each raster cell by decomposing it into independent balances for the vegetated, bare-soil, open-water, and impervious components of the cell. This captures the heterogeneity of land use within a cell, which depends on the raster resolution. Within each component, the hydrological processes are modelled in a cascading sequence: following a rainfall event they are assumed to occur in a defined order, which is necessary for quantifying them at a seasonal time scale, and the magnitude of each process is bounded by the physical and hydro-meteorological constraints of the study area [6]. WetSpa-M applies the same scheme at a monthly time step [8].

Equations (1)–(3) combine the components of the vegetated, bare-soil, open-water, and impervious surfaces into the total water balance of a raster cell, where ET_{raster} , S_{raster} and R_{raster} are the cell's total evapotranspiration, surface runoff, and groundwater recharge, and the subscripts v, s, o and i denote the vegetated, bare-soil, open-water and impervious components, with area fractions a_v , a_s , a_o and a_i . Precipitation is the starting point of the water balance of each component, and interception, surface runoff, evapotranspiration and recharge follow in sequential order.

$$ET_{raster} = a_v ET_v + a_s ET_s + a_o ET_o + a_i ET_i \quad (1)$$

$$S_{raster} = a_v S_v + a_s S_s + a_o S_o + a_i S_i \quad (2)$$

$$R_{raster} = a_v R_v + a_s R_s + a_o R_o + a_i R_i \quad (3)$$

3.2 Data sources and preparation

Hydrological models operating within a GIS environment, such as WetSpa, require all input layers to share a consistent resolution and spatial domain. In accordance with the WetSpa handbook, the model is populated beginning with the DEM (Fig. 2A) and the derived slope map (Fig. 2B), with all other layers at the same 30 m × 30 m resolution. The digital elevation model (Fig. 2A) rises from north to south: elevations below 50 m characterize the northern coastal strip and the wadi channel, most of the interior lies between 50 and 100 m, higher ground (100–150 m) occurs to the east and in the south-western corner, and a prominent feature in the south-west exceeds 200 m. The slope map (Fig. 2B) shows predominantly gentle terrain, mostly 1–5%; slopes above 10% are confined to the flanks of the elevated feature and the south-western corner, and the wadi channel has the lowest gradients (<1%). Three land-use classes were delineated (Fig. 2C): bare soil/sand sheet, which dominates the domain; olive orchards, concentrated in the northern-central sector along the wadi corridor; and buildings/urban land, forming a narrow strip along the northern coast that corresponds to the El-Arish urban area. Soil texture (Fig. 2D) was derived from the Harmonized World Soil Database v2.0 [24] and reclassified to the WetSpa-M soil scheme. All layers were resampled to the common 30 m grid.

Monthly climatological means for 1984–2019 were computed for each meteorological variable, which gives twelve monthly inputs representing one average year. Precipitation was taken from GPCC at 0.25°. Because the study area is much smaller than the source grid cell, the precipitation field is effectively uniform over the domain, and it was resampled to the 30 m grid by bilinear interpolation. Monthly mean, maximum and minimum temperature and wind speed at 2 m were taken from NASA POWER at 15 grid points, averaged by calendar month over the 35 years, interpolated to the DEM grid by inverse distance weighting, and masked to the study area. Potential evapotranspiration was calculated with the Hargreaves method from these temperatures and the extraterrestrial radiation at each point. Snow cover and irrigation inputs were set to zero, because snow does not occur and irrigation is not modelled explicitly. Groundwater depth was supplied as one static map for all months collected from WRRI. Table 1 summarizes the data.

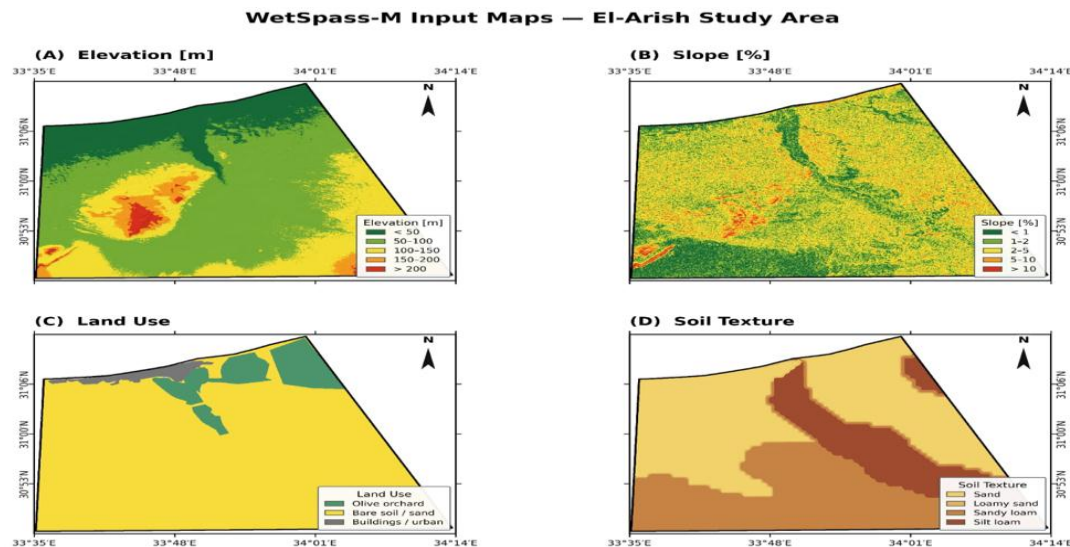


Fig -2: WetSpaas-M spatial input layers for the study area: (A) elevation, (B) slope, (C) land use, and (D) soil texture, all at 30 m × 30 m resolution.

Table -1: Summary of the meteorological and observation data.

Data type	Dataset	Temporal resolution	Spatial resolution	Period	Variable
Gridded observation	GPCC	Monthly	0.25°	1984–2019	Precipitation
Reanalysis	NASA POWER	Monthly	15 grid points	1984–2019	Temperature (mean, max, min), wind speed
Ground observation	Al-Arish (WRII) wells	–	Points	1988	Depth to water, EC

3.3 Model parameterization

WetSpaas requires three parameter lookup tables, Landuse.tbl, Soil.tbl and Runoff_Coefficient.tbl, which link each land-use and soil class to the physical parameters governing interception, evapotranspiration and runoff. Where the built-in defaults of the software were applicable they were adopted; where the dominant land-use class, olive cultivation, was not represented among the defaults, its parameters were derived from the published olive ecophysiology literature.

3.3.1 Land use

The land-use map (Fig. 2C) has three classes: olive orchard, bare soil/sand sheet, and buildings/urban. Since olive is not among the default vegetation classes, its parameters were set individually: the vegetated area fraction (0.45) and leaf area index (1.8) reflect the low ground cover of traditional, non-intensive Mediterranean orchards, where the canopy does not close between and beneath trees; the root depth (1.2 m) reflects the deep, drought-adapted rooting of olive under rainfed conditions; and the minimum stomatal resistance (200 s/m), above the generic FAO-56 reference of 100 s/m, reflects stomatal closure under water stress. The other olive parameters follow the default orchard class. The bare soil class uses the

default values of the excavation class, and the buildings/urban class uses those of the default city-center class with area fractions of 0.15 bare and 0.85 impervious. Table 2 lists the parameters used.

Table -2: Land-use parameters used in Landuse.tbl.

Parameter	1 Olive orchard	2 Bare soil / sheet	3 Buildings / urban
RUNOFF_VEG	forest	bare soil	grass
VEG_AREA (fraction)	0.45	0	0
BARE_AREA (fraction)	0.55	1	0.15
IMP_AREA (fraction)	0	0	0.85
OPENW_AREA (fraction)	0	0	0
ROOT_DEPTH (m)	1.2	0.05	0.3
LAI	1.8	0	2
MIN_STOM (s/m)	200	110	100
VEG_HEIGHT (m)	4.0	0.001	0.12

Parameter	1 Olive orchard	2 Bare soil / sand sheet	3 Buildings / urban
nManing	0.05	0.09	0.03
LandFactor	0.4	0.222	0.667
AerodynResistance	49.8	426.67	212.01

3.3.2 Soil

The soil texture map (Fig. 2D) comes from the Harmonized World Soil Database v2.0 [24], which reports texture in the USDA classification. Because the WetSpa-M Soil.tbl uses the same 12-class USDA scheme, the four classes present were assigned directly to their default codes (Table 3): sand (Class 1), loamy sand (Class 2), sandy loam (Class 3) and silt loam (Class 4). Sand dominates the domain, silt loam occupies the wadi corridor and a small area in the north-east, sandy loam is found in the south-west, and loamy sand occurs in narrow transition zones. Cells without a valid class after resampling were assigned to sand. All hydraulic parameters were kept at the default values for these classes. Since the source data have a resolution of about 1 km, resampling to 30 m preserves the class boundaries but adds no finer detail.

Table -3: Soil.tbl classes applied (WetSpa-M default values; classes 1–4 of the 12-class default table).

Parameter	1 Sand	2 Loamy sand	3 Sandy loam	4 Silt loam
Field capacity	0.12	0.15	0.21	0.29
Wilting point	0.05	0.07	0.09	0.10
Plant available water	0.07	0.08	0.12	0.19
Residual water content	0.02	0.035	0.041	0.015
A1	0.51	0.47	0.44	0.40
Evapo-depth	0.05	0.05	0.05	0.05
Tension height	0.07	0.09	0.15	0.21
P_Frac summer	0.09	0.09	0.09	0.26
P_Frac winter	0.01	0.01	0.01	0.07
Teta	0.136	0.176	0.266	0.408

3.3.3 Runoff coefficients

Surface runoff in WetSpa-M is computed from runoff coefficients defined for each combination of surface type (vegetated, bare, impervious), soil class and slope class. In the study area these combinations comprise the four soil classes, the slope classes, and the vegetated, bare and impervious fractions of the three land-use classes. Each land-use class was linked to a runoff vegetation category through the RUNOFF_VEG field: olive orchard to forest,

following the default orchard class, and bare soil to bare soil. The buildings/urban class was linked to grass, as in the default urban classes, which has no effect because its vegetated fraction is zero. All coefficients were kept at the defaults supplied with WetSpa-M, which provides defaults for the standard combinations and recommends changing them only where site evidence justifies it.

3.4 Model evaluation approach

No field measurements of recharge exist for the study area, and the model was not calibrated by adjusting parameters; its parameters are the defaults or literature values described above. It is therefore evaluated against the results of Abdelaziz and Bakr [3] in two ways. First, the recharge simulated at the wells matched by coordinates between the WRRI records and the model grid was extracted from the recharge raster and compared, after conversion to a common unit, with the range of recharge calibrated in their model. This comparison concerns magnitude and pattern and not exact agreement, because their recharge is a calibrated, zone-based parameter of a flow model that also contains non-rainfall sources. Second, the depth to water given by the calibrated water levels of their model was compared with the depths observed by the WRRI at the same wells, to show how far the reference still represents the observed water table. WetSpa-M does not simulate groundwater heads, so this second comparison does not test the model itself.

For the depth comparison the residual is the reference depth minus the observed depth. The statistics computed are the mean error (ME), mean absolute error (MAE), root-mean-square error (RMSE), RMSE normalized by the observed range (NRMSE), percent bias (PBIAS = $100 \Sigma(S - O) / \Sigma O$), the correlation coefficient (r), and the Nash-Sutcliffe efficiency, $NSE = 1 - \Sigma(S - O)^2 / \Sigma(O - \bar{O})^2$, where S and O are the reference and observed values and $\bar{O}$ is the observed mean [25]. An NSE above 0.40 is regarded as acceptable for water-table depth [26], and an NRMSE of 10% or less is the customary criterion for calibrated groundwater-flow models [27], [28].

4. RESULTS AND DISCUSSION

4.1 Simulated recharge at the observation wells

Table 4 lists the recharge simulated by WetSpa-M for January at the six wells whose coordinates could be matched between the WRRI records and the model grid (N1, N2, N9, R18, R20 and R26). Four of the wells (N1, N2, R18 and R26) have almost identical values, between 0.0568 and 0.0576 mm/month (mean 0.0573; coefficient of variation 0.6%), whereas N9 (0.00137 mm/month) and R20 (0.00046 mm/month) are roughly 40 and 120 times lower. The spatial distribution of the January recharge is shown in Fig. 3.

Table -4: January recharge simulated by WetSpaas-M at the matched observation wells.

Well	Latitude (°N)	Longitude (°E)	Recharge (mm/month)	Equivalent (10^{-6} m/day)
N1	31.1283	33.8403	0.05728	1.85
N2	31.1111	33.8525	0.05762	1.86
N9	31.1481	33.8583	0.00137	0.044
R18	31.1203	33.8444	0.05679	1.83
R20	31.1175	33.9519	0.00046	0.015
R26	31.1272	33.8372	0.05749	1.85

The near-identical values at four wells follow from the structure of the model. Because precipitation, temperature and wind speed are effectively uniform over this small domain (Section 3.2), the spatial variation of simulated recharge is controlled almost entirely by the land-use, soil and slope classes, and wells within the same combination of classes return the same recharge. The much lower values at N9 and R20 therefore indicate a different combination of classes at those locations.

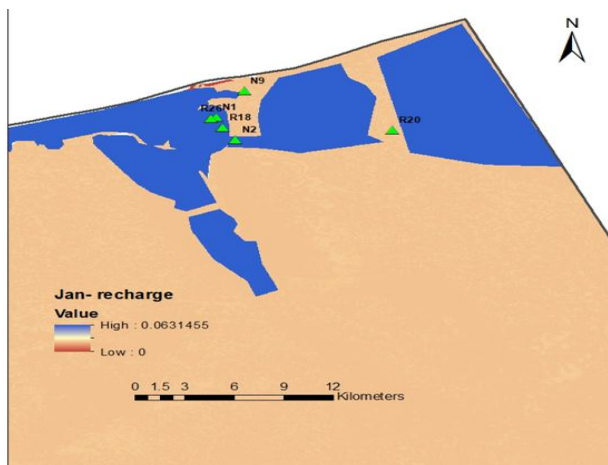


Fig -3: Recharge simulated by WetSpaas-M for January (mm/month).

4.2 Comparison with the recharge reported by Abdelaziz and Bakr [3]

Abdelaziz and Bakr [3] built a groundwater flow model of the Delta of Wadi El-Arish in GMS and used PEST with the pilot-point method to estimate hydraulic conductivity and recharge simultaneously. Recharge was parameterized in zones defined from surface geology, vegetation density, general land use and a Landsat image, and the model was calibrated against water levels for 1988. Their calibrated recharge ranges from 1.62×10^{-5} to 3.50×10^{-3} m/day. Their conclusions, that groundwater levels are declining and that abstraction exceeds natural recharge, which depends mainly on annual rainfall, are the reference for this study.

The January recharge at N1, N2, R18 and R26, 0.057 mm/month, is equivalent to about 1.9×10^{-6} m/day (Table 4), and at N9 and R20 to 4.4×10^{-8} and 1.5×10^{-8} m/day. All of these values lie below the lowest value in the legend of Abdelaziz and Bakr [3], 1.62×10^{-5} m/day, which is about 0.5 mm per month or 6 mm/yr: the difference is a factor of about 9 at the four wells and about 370 and 1,100 at N9 and R20. January is one of the wettest months, so the mean rate over the year should not be much above these values; even if all twelve months equalled January, the annual recharge would be below 0.7 mm, about 1% of the 60–80 mm mean annual rainfall. The lowest recharge of Abdelaziz and Bakr [3] corresponds to 7–10% of annual rainfall, and their highest value, 3.5×10^{-3} m/day, to more than 1,200 mm/yr, or 16 to 21 times the annual rainfall. Such rates cannot come from rainfall alone and must include the additional sources of their model, namely return flow from imported Nile water and from domestic water use, which a rainfall-driven model such as WetSpaas-M does not contain.

The simulated recharge therefore does not reproduce the magnitude of the reference recharge, even in the rain-fed parts of the domain. Three factors probably contribute. First, the reference recharge is a calibrated lumped parameter of a flow model, which must also supply the flux needed to reproduce heads under abstraction, lateral inflow and storage change, so it can exceed the rainfall-derived recharge and is uncertain and non-unique [29]. Second, mean monthly forcing averaged over 35 years removes the few intense events that produce most of the recharge in arid regions [30]. Third, the soil, runoff and olive parameters are defaults or literature values that were not calibrated, and other WetSpaas applications show that results are sensitive to such parameters [31], [32]. At the same time, a very low recharge on bare sand is physically consistent with the climate: with 60–80 mm of rain per year and evaporation of about 4 mm/day, almost all rainfall is returned to the atmosphere.

4.3 Depth to water: reference surface versus observations

WetSpaas-M computes recharge as the residual of the cell water balance [7], [8] and does not simulate groundwater heads, so the comparison in this section does not test the model. Its purpose is to establish how well the water-level surface of the reference model, calibrated to 1988 conditions, still describes the observed water table. The depths were extracted from the groundwater-level surface derived from the calibrated levels of Abdelaziz and Bakr [3]. Table 5 compares them with the depths observed by the WRRI in February 2016 at the six wells, and Table 6 gives the statistics defined in Section 3.4.

Table -5: Depth to water from the reference surface [3] and observed depth (February 2016).

Well	Observed depth (m)	Reference-surface depth (m)	Residual, reference – observed (m)
N1	20.18	14.26	-5.92
N2	28.43	17.67	-10.76
N9	27.90	25.71	-2.19
R18	40.40	31.01	-9.39
R20	48.53	45.99	-2.54
R26	19.25	13.62	-5.63
Mean	30.78	24.71	-6.07

Table -6: Goodness-of-fit statistics for depth to water (n = 6).

Statistic	Value	Reference value or interpretation
Number of wells (n)	6	One measurement date (February 2016)
Mean error (ME)	-6.07 m	Ideal value 0; negative means the reference depth is smaller than observed
Mean absolute error (MAE)	6.07 m	Equal to ME : all residuals have the same sign
Root-mean-square error (RMSE)	6.86 m	–
Normalized RMSE (RMSE / observed range of 29.28 m)	23.4%	Customary criterion $\leq 10\%$ [27], [28]
Percent bias (PBIAS)	-19.7%	Negative: reference depths smaller than observed
Correlation coefficient (r)	0.961	Pattern among wells is preserved
Coefficient of determination (R^2)	0.923	–
Nash–Sutcliffe efficiency (NSE)	0.577	> 0.40 is acceptable for water-table depth [26]

Statistic	Value	Reference value or interpretation
NSE after removing the mean bias	0.909	Most of the misfit is a systematic offset
RMSE after removing the mean bias	3.18 m	Scatter around the offset

All six depths given by the reference surface are shallower than observed (residuals between -2.2 and -10.8 m), so the water table of the reference is consistently higher than the one measured in 2016. The mean error (-6.07 m) equals the mean absolute error, which confirms that the difference is one-sided, and the RMSE of 6.86 m is 23.4% of the observed range of 29.3 m. At the same time the reference surface preserves the relative differences among wells: the correlation is 0.96 ($R^2 = 0.92$) and the NSE of 0.58 exceeds the 0.40 regarded as acceptable for water-table depth. When the mean bias is removed the NSE rises to 0.91 and the RMSE falls to 3.18 m, so most of the misfit is a systematic offset and not a difference in spatial pattern.

The one-sided offset is what would be expected if the water table has fallen since 1988, as Abdelaziz and Bakr [3] report from abstraction exceeding recharge. Taken at face value, it corresponds to a fall of about 6 m, or about 0.2 m/yr over the 28 years between the reference surface and the observations. Part of the offset may, however, come from a vertical difference between the DEM and the surveyed wellhead elevations, from the interpolation of the surface, or from the small number of wells, so the value should be treated as an indication. The result also shows that the reference levels describe the spatial pattern of depth adequately but not its absolute value, which limits their use as a benchmark for a 1984–2019 climatology.

4.4 Model assumptions and limitations

The model was simplified in several ways to keep the set-up tractable with the data available. These assumptions are listed in Table 7 with their implications, because they bound how far the results can be interpreted. Parameters were taken from the WetSpa-M defaults or the literature (Section 3.3), so the model is not calibrated, and the comparison with Abdelaziz and Bakr [3] is an evaluation, not a calibration.

Table -7: Assumptions and limitations of the WetSpa-M application.

Assumption or limitation	Implication for the results
One climatological year: the 12 monthly inputs are 1984–2019 averages, run as a quasi-steady state.	Interannual variability and individual extreme events are averaged out. Recharge in arid regions is often concentrated in a few intense events and beneath ephemeral channels [30], so mean-monthly forcing may underestimate event-driven recharge.

Assumption or limitation	Implication for the results
Spatially uniform meteorology: GPCP precipitation (0.25°) is effectively a single value over the domain; temperature and wind come from 15 NASA POWER points interpolated by inverse distance weighting; all layers were resampled to 30 m.	Resampling harmonizes the grids but adds no real spatial detail. Recharge differences arise only from land use, soil, slope and groundwater depth; coastal and orographic gradients are not represented.
Potential evapotranspiration (from the Hargreaves method); wind speed at 2 m used without height adjustment.	The PET method affects actual evapotranspiration and therefore recharge; one method was used and no alternative was tested.
Land use reduced to three classes with identical parameters in all 12 months (evergreen olive).	Olive parameters (LAI, root depth, stomatal resistance, height) come from the literature, not from field measurement, and one class represents orchards of different age, density and irrigation.
Soil texture from HWSD v2.0 (about 1 km), four classes with default hydraulic parameters; cells without a valid class assigned to sand.	Soil boundaries are broad, they differ in detail from local descriptions (Section 2.4), and local textural variability is not resolved.
Runoff coefficients kept at the WetSpa-M defaults.	The coefficients are not calibrated to the site, so runoff, and hence recharge, in wadi channels and steeper cells may deviate from local behaviour.
Groundwater depth is a single static map for all months.	Seasonal fluctuation and the cone of depression around pumping wells are not represented, and any DEM error propagates into the derived depth.
Recharge from irrigation return flow, imported Nile water and domestic wastewater is not represented (snow and irrigation inputs set to zero).	Simulated recharge is natural, rainfall-derived recharge only, and is smaller than the total recharge in the flow model of Abdelaziz and Bakr [3], which includes these sources.
WetSpa-M yields recharge only: no groundwater flow, abstraction, lateral inflow or seawater intrusion.	Heads and storage change cannot be simulated, so the model cannot be evaluated against observed levels.
Only January recharge, at six wells, was compared with the reference.	Annual and seasonal recharge are not evaluated, and six points give little statistical power.
The reference is one calibrated model [3] for a different period.	The reference is itself a model output, not an independent measurement of recharge, and it is uncertain and non-unique.
No sensitivity or uncertainty analysis was carried out.	Other WetSpa applications show strong sensitivity to the intensity coefficient and to land and soil factors [32] and to vegetation parameters such as crop height [31], so the uncertainty of the present recharge is unknown.

4.5 Discussion

The results show that, in this setting, recharge is determined mainly by surface properties. With uniform forcing the model separates the wells into two groups: bare sandy surfaces, where recharge is small but measurable, and locations with higher evapotranspiration or water retention, where recharge is almost nil. Recharge in arid and semi-arid regions is generally a small and highly variable fraction of precipitation and depends strongly on soil, vegetation and surface conditions [30]. For comparison, WetSpa gave a recharge of 7.4% of a mean annual precipitation of 573 mm in the Birki watershed of northern Ethiopia [12]; with 60–80 mm of rainfall and high evaporation, a much smaller fraction is expected in the Delta of Wadi El-Arish, and the simulated values are consistent with this. They are also consistent with the conclusion of Abdelaziz and Bakr [3] that natural, rainfall-dependent recharge is small relative to abstraction.

The magnitude of the simulated recharge is, however, 9 to 1,100 times lower than the lowest recharge of the reference model, and this study cannot decide whether the reference overestimates rain-fed recharge, because it must compensate for other fluxes, or whether the present configuration underestimates it, because of the climatological forcing and the uncalibrated parameters. Other WetSpa applications have been evaluated against an independent estimate of recharge. Armanuos et al. [10] calibrated WetSpa for the Nile Delta against recharge calculated from the water balance and obtained R^2 of 0.99 and 0.94 with RMSE of 4.86 and 9.39 mm for 1991 and 2000, and an overall RMSE of 8.83 mm and R^2 of 0.88 for six years, four of which were used only for validation. Amen and Calvache [32] compared WetSpa-M recharge in the Motril-Salobreña coastal aquifer, Spain, with recharge from the water-table fluctuation method and reported R^2 of about 0.86, a mean error of 1.1 mm/month

and a mean absolute error of 2.5 mm/month. Soliman et al. [13], in the El-Qaa plain of South Sinai, calibrated WetSpa against recharge derived from $\delta^{18}\text{O}$ and $\delta^2\text{H}$ isotopes and validated it with MODFLOW. In each case the reference is an independent estimate of recharge, whereas here it is the calibrated recharge of another model; the present comparison is therefore a weaker test.

The most useful next step is to calibrate the sensitive parameters, above all the intensity coefficient and the land and soil factors [32], against an independent estimate of recharge and not against the flow model's recharge, and then to couple the result with a MODFLOW model so that heads are simulated and the comparison with observed levels becomes a direct test [13], [14]. Soliman et al. [14] used such a coupling with CORDEX-based climate ensembles in the northern El-Qaa plain and projected recharge reductions of nearly 35 to 75% during 2071–2100 for the moderate and severe ensembles. The same route is open for the Wadi El-Arish aquifer once the present model has been calibrated.

4.6 Further evaluation

The results are a first check and are not sufficient to certify the model. Further work should: (1) simulate all twelve months and the annual total, and compare them with the reference for all wells and zones; (2) extend the water-level comparison to all wells and all WRII dates for 2016–2026, and report the NSE, PBIAS, RMSE and normalized RMSE for each date [33], [26]; (3) compare the simulated recharge with independent estimates such as the water-table fluctuation method, the chloride mass balance or environmental isotopes [29], [13], [32]; (4) carry out a sensitivity and uncertainty analysis of the global and local parameters, particularly the intensity coefficient, the land and soil factors and the olive vegetation parameters [31], [32]; (5) replace the climatological year by a transient series and add irrigation return flow and imported water; and (6) couple the recharge to a MODFLOW model so that heads are simulated directly. The calibrated model can then be forced with climate-perturbed inputs.

5. CONCLUSIONS

WetSpa-M was applied to the Delta of Wadi El-Arish on a 30 m grid with twelve monthly climatological inputs, default soil and runoff parameters, and literature-based parameters for olive orchards. The main findings are as follows.

1. January recharge at six observation wells was about 0.057 mm/month at four wells on bare sand and 0.0014 and 0.0005 mm/month at two wells, roughly 40 and 120 times lower. With uniform meteorological forcing, recharge is controlled by land use, soil and slope.

2. These rates are about 9 to 1,100 times lower than the lowest recharge of the calibrated flow model of Abdelaziz and Bakr [3], whose highest values include return flow from imported water. The model as configured does not reproduce the magnitude of the reference recharge, so it is neither calibrated nor validated, and its results are preliminary.
3. The reference water-level surface was on average 6.1 m shallower than the depths observed in February 2016 (normalized RMSE 23%, PBIAS –19.7%) but preserved the spatial pattern ($r = 0.96$, NSE = 0.58), which is consistent with the decline in levels reported by Abdelaziz and Bakr [3]. This comparison does not test WetSpa-M, which does not simulate heads.
4. The very small simulated rain-fed recharge is consistent with the finding that abstraction exceeds natural recharge in the Delta of Wadi El-Arish and with the climate of the area.
5. The simplifications adopted (a climatological year, uniform meteorology, default parameters, a static groundwater-depth map, no irrigation return flow) limit the interpretation and are listed in Table 7.
6. Calibration of the sensitive parameters against independent recharge estimates, sensitivity analysis, evaluation of all months, more wells and dates, and coupling with a groundwater flow model are needed before the model is used for prediction or for climate scenarios.

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