**Supplementary material**

**Identifying suitable zones for integrated aquifer recharge and flood control in arid Qatar using GIS-based multi-criteria decision-making**

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**Table A1.** Examples of studies using GIS-based AHP for flood susceptibility mapping.

|  |  |  |  |
| --- | --- | --- | --- |
| **Study** | **Study area (Climate)** | **Selected criteria** | **Accuracy results** |
| Mahmoud and Gan (2018) | The Riyadh province and the Riyadh city (Arid) | **10 criteria:** flow accumulation, annual rainfall, slope, runoff, land use/cover, elevation, geology, soil type, distance from the drainage network, and drainage density | The results demonstrate a significant level of consistency between the flood susceptibility maps and flood records. |
| Abu El-Magd et al. (2019) | Awlad Toq-Sherq, Egypt (Arid and semi-arid) | **6 criteria:** elevation, slope, drainage network, lithology, topographic wetness index, and land use/land cover | A consistency index of 0.058 was computed, indicating a well-performing model. |
| Lin et al. (2019) | Zhengzhou city, China (Temperate and north subtropical monsoon climate) | **13 criteria:** topographic  standard deviation, land use/land cover, channel density, elevation, distance from the  drainage system, NDVI, slope, population density, gross domestic product, infrastructure of water conservancy projects, and medical service level, rainfall intensity, and rainfall frequency | A flood inventory map generated through the mapping 74 test sites, followed by plotting a receiver operating characteristic (ROC) curve was used for validation. The ROC shows an area under the curve (AUC) of 74.27%. |
| Costache and Tien Bui (2020) | The watershed of Suha river, Romania (Climate specific to mountainous regions situated in the  mid-latitude zone) | **8 criteria:** Slope angle, land use, profile curvature, plan curvature, convergence index, aspect, hydrological soil groups, and topographic position index | Validating samples revealed that the AHP model achieved a performance accuracy of 72.73% and an AUC value equal to 0.884. |
| Gudiyangada Nachappa et al. (2020) | The province of Salzburg, Austria (Continental climate with Alpine influences) | **11 criteria:** elevation, slope, aspect, topographic wetness index, stream power index, NDVI, geology, rainfall, land cover, distance to roads, and distance to drainage | The AUC technique as well as the relative flood density showed the accuracy of the AHP (AUC = 85.9%). |
| Souissi et al. (2020) | The Gabes region, Tunisia (Arid) | **8 criteria**: elevation, land use/land cover, lithology, rainfall intensity, drainage density, distance from the drainage network, slope, and groundwater depth | A histogram of susceptibility zones revealed that 74.51% of observed flood areas fall within the moderate to very high susceptibility class. |
| Akay (2021) | Gokirmak Basin, Turkey (Mediterranean) | **11 criteria:** elevation, slope, aspect, plan curvature, distance from stream, soil groups, topographic wetness index, sediment transport index, drainage density, elongation ratio, and stream order | The AHP was accurate at predicting flood susceptibility according to ROC analysis and SCAI variation. |
| Negese et al. (2022) | Dega Damot district, Ethiopia (majorly temperate, sub-humid highlands) | **11 criteria:** elevation, slope, flow accumulation, distance from rivers, annual rainfall, drainage density, topographic wetness index, land use/land cover, NDVI, soil type, and curvature | The flood susceptibility map was consistent with records of floods. Point data gathered from the main river/flood plains also validate the reliability of the model output. |
| Yilmaz (2022) | The Kastamonu province, Turkey (Semi-arid) | **11 criteria:** rainfall, slope, elevation, distance from stream, land use/land cover, lithology, curvature plan, curvature profile, topographic wetness index, stream power index, and normalized differences vegetation index | The accuracy of the results was tested using the ROC curves method. The AUC value for was calculated at 0.965. |

**Table A2.** Examples of studies using GIS-based AHP for groundwater recharge suitability mapping.

|  |  |  |  |
| --- | --- | --- | --- |
| **Study** | **Study area (Climate)** | **Selected criteria** | **Accuracy results** |
| Salar et al. (2018) | The Awaspi watershed, Iraq (Semi-arid) | **10 criteria:** slope, lithology, land use/land cover, altitude of groundwater table, rainfall, drainage density, geomorphology, lineament density, elevation, and topographic position index | Existing dams were positioned within suitability classes categorized as poor and moderate for groundwater recharge, which validates the method. |
| Al-Abadi et al. (2020) | Ali Al-Gharbi district, Iraq (Arid) | **8 criteria:** elevation, slope, lithology, soil, land cover, drainage density, aquifer’s saturated thickness, and groundwater depths | The use of the ROC curve showed a good accuracy in prediction of 76%. |
| Rajasekhar et al. (2020) | Southern part of the  Anantapur district, India (Semi-arid) | **7 criteria:** land use/land  cover, soil, geology, vadose zone, drainage density, slope, and runoff | The study's overall accuracy reached approximately 80–85%, demonstrating strong agreement with existing structures. |
| Zghibi et al. (2020) | The Korba aquifer, Tunisia (Semi-arid) | **8 criteria:** lithology, land use/cover, slope, geomorphology, lineament density, rainfall, drainage density, and soil type | ROC curve and monitoring of groundwater level at 25 shallow wells were used to validate the results, with a satisfactory accuracy of 75.6%. |
| Dar et al. (2021) | Kashmir Valley, India (Seasonal Mediterranean climate) | **8 criteria:** slope, soil texture, drainage density, land/land cover, lithology, geomorphology, lineament density, and rainfall | The results were validated, as the AUC was calculated to be 79.69%. |
| Abdulkerim et al. (2022) | Sude district, Oromia, Ethiopia (Subtropical highland climate or temperate oceanic climate with dry winters) | **8 criteria:** slope, soil, land use/land cover, geology, lineament density, rainfall, runoff depth, and drainage density | Validation of the groundwater recharge map was conducted using existing bore wells and hand-dug wells. |
| Mahdawi et al. (2022) | Kabul Aquifer System, Afghanistan (Arid and semi-arid) | **9 criteria:** slope, drainage density, rainfall, distance to fault, distance to river channel, lithology, ground water table, land cover, and soil texture | The locations of extraction wells overlap the potential recharge areas and the regions with high hydraulic conductivity values correspond to the high recharge zones. |
| Upwanshi et al. (2023) | Mulshi Taluka, Pune district, India (Tropical monsoon climate) | **11 criteria:** geomorphology, geology, slope, drainage density, rainfall, land use/land cover, lineament density, soil, NDVI, curvature, and topographic wetness index | Groundwater fluctuation data was employed to verify the accuracy of the results through ROC curve. The AUC score revealed an accuracy of 80.4%. |
| Al-Kakey et al. (2023) | Erbil basin, Iraq (Semi-arid) | **7 criteria:** topographic position index, geomorphology, lithology, land cover, slope, drainage-length density, and lineament-length density | The validation of the potential groundwater recharge zone map was based on static water level data, showing a satisfactory coefficient of determination of 0.73. |

A bar chart with different colored bars

Description automatically generated

**Fig. A1.** A representative chart of Saaty (2008)’s fundamental scale of absolute numbers.

**Table A3.** Pairwise comparison matrix for all criteria for flood susceptibility mapping.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Criteria \*** | **SWD** | **LULC** | **EL** | **SLO** | **LI** | **DD** | **RN** | **LD** | **SL** | **NDVI** |
| **SWD** | 1 | 2 | 2 | 2 | 3 | 4 | 4 | 4 | 6 | 6 |
| **LULC** | 1/2 | 1 | 2 | 2 | 3 | 4 | 4 | 4 | 5 | 6 |
| **EL** | 1/2 | 1/2 | 1 | 2 | 3 | 3 | 5 | 5 | 7 | 7 |
| **SLO** | 1/2 | 1/2 | 1/2 | 1 | 2 | 2 | 3 | 3 | 4 | 5 |
| **LI** | 1/3 | 1/3 | 1/3 | 1/2 | 1 | 2 | 3 | 3 | 4 | 4 |
| **DD** | 1/4 | 1/4 | 1/3 | 1/2 | 1/2 | 1 | 2 | 3 | 4 | 4 |
| **RN** | 1/4 | 1/4 | 1/5 | 1/3 | 1/3 | 1/2 | 1 | 4 | 4 | 4 |
| **LD** | 1/4 | 1/4 | 1/5 | 1/3 | 1/3 | 1/3 | 1/4 | 1 | 2 | 2 |
| **SL** | 1/6 | 1/5 | 1/7 | 1/4 | 1/4 | 1/4 | 1/4 | 1/2 | 1 | 4 |
| **NDVI** | 1/6 | 1/6 | 1/7 | 1/5 | 1/4 | 1/4 | 1/4 | 1/2 | 1/4 | 1 |
| **Totals** | **3.92** | **5.45** | **6.85** | **9.12** | **13.67** | **17.33** | **22.75** | **28** | **37.25** | **43** |

**\*** **SWD**, stormwater drainage system density; **LULC**, land use / land cover; **EL**, elevation; **SLO**, slope; **LI**, lithology; **DD**, drainage density; **RN**, rainfall; **LD**, lineament density; **SL**, soil type; and **NDVI**, Normalized Difference Vegetation Index.

**Table A4.** Pairwise comparison matrix for all criteria for groundwater recharge zones mapping.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Criteria \*** | **LI** | **LULC** | **SLO** | **EL** | **LD** | **RN** | **DD** | **SL** | **NDVI** | **SWD** |
| **LI** | 1 | 2 | 4 | 4 | 6 | 7 | 7 | 8 | 9 | 9 |
| **LULC** | 1/2 | 1 | 2 | 4 | 5 | 5 | 7 | 8 | 8 | 9 |
| **SLO** | 1/4 | 1/2 | 1 | 2 | 3 | 4 | 6 | 8 | 8 | 9 |
| **EL** | 1/4 | 1/4 | 1/2 | 1 | 2 | 3 | 5 | 7 | 7 | 9 |
| **LD** | 1/6 | 1/5 | 1/3 | 1/2 | 1 | 2 | 3 | 4 | 4 | 9 |
| **RN** | 1/7 | 1/5 | 1/4 | 1/3 | 1/2 | 1 | 2 | 3 | 3 | 5 |
| **DD** | 1/7 | 1/7 | 1/6 | 1/5 | 1/3 | 1/2 | 1 | 2 | 2 | 3 |
| **SL** | 1/8 | 1/8 | 1/8 | 1/7 | 1/4 | 1/3 | 1/2 | 1 | 1 | 3 |
| **NDVI** | 1/9 | 1/8 | 1/8 | 1/7 | 1/4 | 1/3 | 1/2 | 1 | 1 | 2 |
| **SWD** | 1/9 | 1/9 | 1/9 | 1/9 | 1/9 | 1/5 | 1/3 | 1/3 | 1/2 | 1 |
| **Totals** | **2.80** | **4.65** | **8.61** | **12.43** | **18.44** | **23.37** | **32.33** | **42.33** | **43.50** | **59.00** |

**\*** **LI**, lithology; **LULC**, land use / land cover; **SLO**, slope; **EL**, elevation; **LD**, lineament density; **RN**, rainfall; **DD**, drainage density; **SL**, soil type; **NDVI**, Normalized Difference Vegetation Index; and **SWD**, stormwater drainage system density.

**Table A5.** Normalized pairwise comparison matrix and factors’ weights influencing flooding.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Criteria \*** | **SWD** | **LULC** | **EL** | **SLO** | **LI** | **DD** | **RN** | **LD** | **SL** | **NDVI** | **Eigenvector values** | **Influence (%)** |
| **SWD** | 0.26 | 0.37 | 0.29 | 0.22 | 0.22 | 0.23 | 0.18 | 0.14 | 0.16 | 0.14 | 0.22 | 22.03 |
| **LULC** | 0.13 | 0.18 | 0.29 | 0.22 | 0.22 | 0.23 | 0.18 | 0.14 | 0.13 | 0.14 | 0.19 | 18.65 |
| **EL** | 0.13 | 0.09 | 0.15 | 0.22 | 0.22 | 0.17 | 0.22 | 0.18 | 0.19 | 0.16 | 0.17 | 17.26 |
| **SLO** | 0.13 | 0.09 | 0.07 | 0.11 | 0.15 | 0.12 | 0.13 | 0.11 | 0.11 | 0.12 | 0.11 | 11.26 |
| **LI** | 0.09 | 0.06 | 0.05 | 0.05 | 0.07 | 0.12 | 0.13 | 0.11 | 0.11 | 0.09 | 0.09 | 8.78 |
| **DD** | 0.06 | 0.05 | 0.05 | 0.05 | 0.04 | 0.06 | 0.09 | 0.11 | 0.11 | 0.09 | 0.07 | 7.03 |
| **RN** | 0.06 | 0.05 | 0.03 | 0.04 | 0.02 | 0.03 | 0.04 | 0.14 | 0.11 | 0.09 | 0.06 | 6.16 |
| **LD** | 0.06 | 0.05 | 0.03 | 0.04 | 0.02 | 0.02 | 0.01 | 0.04 | 0.05 | 0.05 | 0.04 | 3.66 |
| **SL** | 0.04 | 0.04 | 0.02 | 0.03 | 0.02 | 0.01 | 0.01 | 0.02 | 0.03 | 0.09 | 0.03 | 3.10 |
| **NDVI** | 0.04 | 0.03 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | 0.02 | 0.01 | 0.02 | 0.02 | 2.07 |
| **Totals** | **1.00** | **1.00** | **1.00** | **1.00** | **1.00** | **1.00** | **1.00** | **1.00** | **1.00** | **1.00** | **1.00** | **100.00** |

**\*** **SWD**, stormwater drainage system density; **LULC**, land use / land cover; **EL**, elevation; **SLO**, slope; **LI**, lithology; **DD**, drainage density; **RN**, rainfall; **LD**, lineament density; **SL**, soil type; and **NDVI**, Normalized Difference Vegetation Index.

**Table A6.** Normalized pairwise comparison matrix and factors’ weights influencing groundwater recharge.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Criteria \*** | **LI** | **LULC** | **SLO** | **EL** | **LD** | **RN** | **DD** | **SL** | **NDVI** | **SWD** | **Eigenvector values** | **Influence (%)** |
| **LI** | 0.35 | 0.43 | 0.39 | 0.32 | 0.33 | 0.30 | 0.24 | 0.21 | 0.21 | 0.16 | 0.3 | 29.63 |
| **LULC** | 0.18 | 0.22 | 0.26 | 0.32 | 0.27 | 0.21 | 0.21 | 0.18 | 0.18 | 0.16 | 0.22 | 21.75 |
| **SLO** | 0.12 | 0.11 | 0.13 | 0.16 | 0.16 | 0.17 | 0.18 | 0.18 | 0.18 | 0.16 | 0.15 | 15.18 |
| **EL** | 0.09 | 0.05 | 0.07 | 0.08 | 0.11 | 0.13 | 0.15 | 0.16 | 0.16 | 0.16 | 0.12 | 11.52 |
| **LD** | 0.06 | 0.04 | 0.04 | 0.04 | 0.05 | 0.09 | 0.09 | 0.09 | 0.09 | 0.16 | 0.08 | 7.53 |
| **RN** | 0.05 | 0.04 | 0.03 | 0.03 | 0.03 | 0.04 | 0.06 | 0.07 | 0.07 | 0.09 | 0.05 | 5.06 |
| **DD** | 0.04 | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 | 0.05 | 0.05 | 0.05 | 0.03 | 3.31 |
| **SL** | 0.04 | 0.03 | 0.02 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.03 | 0.02 | 2.4 |
| **NDVI** | 0.04 | 0.03 | 0.02 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.03 | 0.02 | 2.16 |
| **SWD** | 0.04 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 1.46 |
| **Totals** | **1.00** | **1.00** | **1.00** | **1.00** | **1.00** | **1.00** | **1.00** | **1.00** | **1.00** | **1.00** | **1.00** | **100.00** |

**\*** **LI**, lithology; **LULC**, land use / land cover; **SLO**, slope; **EL**, elevation; **LD**, lineament density; **RN**, rainfall; **DD**, drainage density; **SL**, soil type; **NDVI**, Normalized Difference Vegetation Index; and **SWD**, stormwater drainage system density.

**Table A7.** Calculation of the principal eigenvalue for flood susceptibility and groundwater recharge mapping.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Criteria \*** | **Totals (1)** | | **Eigenvector values (2)** | | **Eigenvalues (12)** | |
| **FS \*\***  **(Table A3)** | **GR\*\*\***  **(Table A4)** | **FS**  **(Table A5)** | **GR**  **(Table A6)** | **FS** | **GR** |
| **EL** | 6.85 | 12.43 | 0.17 | 0.12 | 1.16 | 1.49 |
| **SLO** | 9.12 | 8.61 | 0.11 | 0.15 | 1.00 | 1.29 |
| **LD** | 28.00 | 18.44 | 0.04 | 0.08 | 1.12 | 1.48 |
| **DD** | 17.33 | 32.33 | 0.07 | 0.03 | 1.21 | 0.97 |
| **RN** | 22.75 | 23.37 | 0.06 | 0.05 | 1.37 | 1.17 |
| **LI** | 13.67 | 2.80 | 0.09 | 0.30 | 1.23 | 0.84 |
| **SL** | 37.25 | 42.33 | 0.03 | 0.02 | 1.12 | 0.85 |
| **NDVI** | 43.00 | 43.50 | 0.02 | 0.02 | 0.86 | 0.87 |
| **LULC** | 5.45 | 4.65 | 0.19 | 0.22 | 1.04 | 1.02 |
| **SWD** | 3.92 | 59.00 | 0.22 | 0.01 | 0.86 | 0.59 |
| **Principal eigenvalue ()** |  | |  | | **10.97** | **10.57** |

**\* EL**, elevation; **SLO**, slope; **LD**, lineament density; **DD**, drainage density; **RN**, rainfall; **LI**, lithology; **SL**, soil type; and **NDVI**, Normalized Difference Vegetation Index; **LULC**, land use / land cover; and **SWD**, stormwater drainage system density.

**\*\* FS**, flood susceptibility

**\*\*\* GR**, groundwater recharge potential

**Table A9.** Reported flood events in Qatar in literature and news.

|  |  |  |
| --- | --- | --- |
| **Flood event** | **Affected areas** | **Reference** |
| 1995 | - Some streets in Doha | Membery (1997); Al Mamoon and Rahman (2017) |
|  |  |  |
| 2013 | - The Northern parts of the country  - Certain parts of Doha city that were not equipped to handle unexpected water surges | News of the South (2013) |
|  |  |  |
| 2015 | - Parts of Qatar, including Doha | FloodList (2015) |
|  |  |  |
| 2018 | - Abu Hamour (a district in Al Rayyan)  - Doha | FloodList (2018) |

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