Supplementary Information for

Long-term Hydro-economic Analysis Tool for Evaluating Global Groundwater Supply and Cost: Superwell v1.0

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This Supplementary Information (SI) document presents additional details related to Superwell's inputs and outputs to support the documentation in the main text.

1 Geo-processed Hydrogeological Conditions

The World Hydrological Classification (WHY class) categorizes aquifers into classes that are easy (30), medium (10), or hard (20) for well installation, reflecting the aquifer's hydrocomplexity and directly influencing installation cost rates based on these classifications.

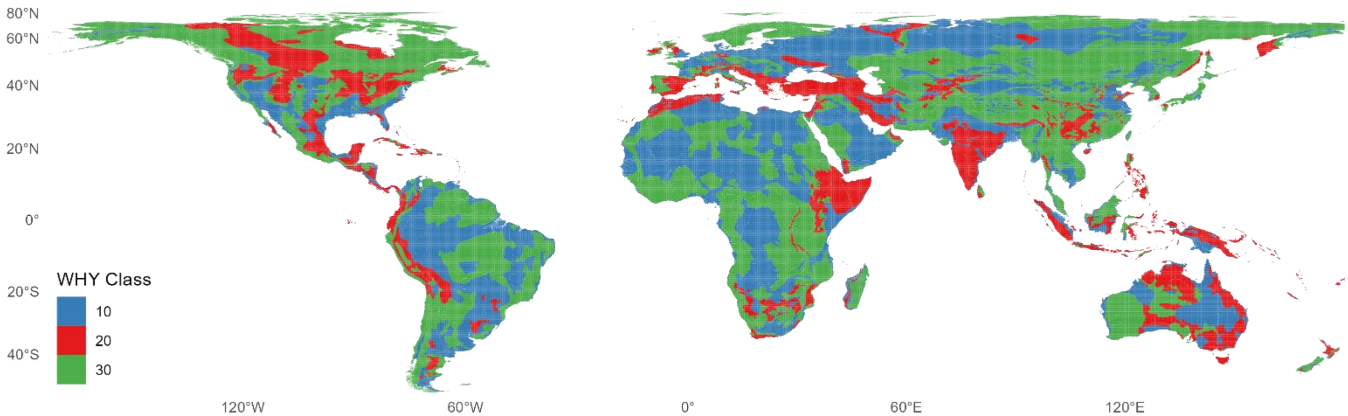


Figure 1: WHYMap aquifer classes based on Richts et al., (2011)

Grid area shows intersections of spatial boundaries (countries, basins, WHY class) with rectilinear grid of 0.5 degree (roughly 50 km by 50 km) to keep homogeneous grid cells.

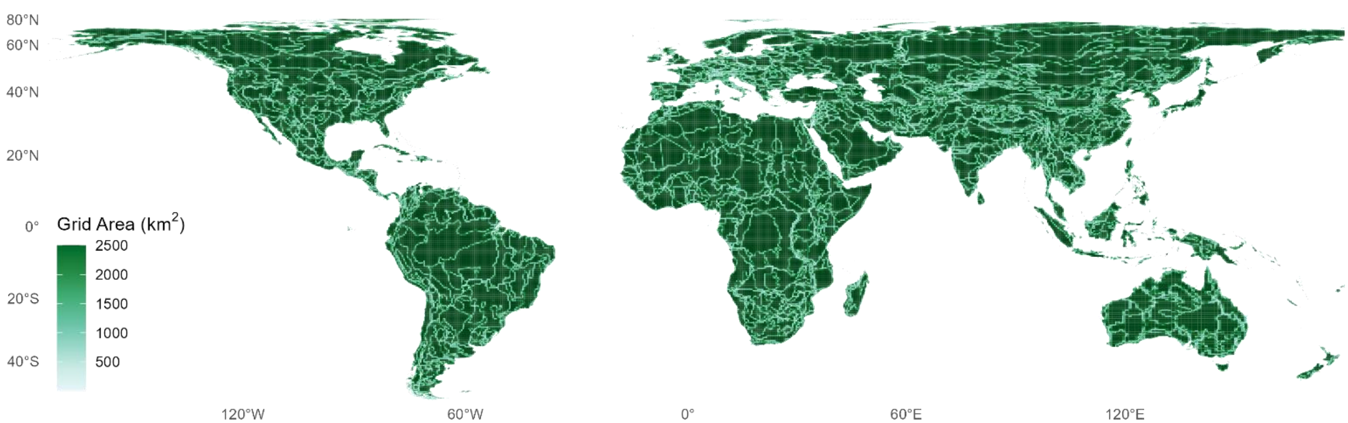


Figure 2: Area of grid cells in km^2 discretized for superwell

Table 1: Descriptive statistics of geo-processed aquifer conditions across all grid cells globally (count = 106,432) used as input conditions for superwell

	Porosity (-)	Permeability (m^2)	Aquifer Thickness (m)	Depth to Water (m)	Grid Area (km^2)
Mean	0.138106	-13.765	329.8149	24.16211	1200.8
Standard Deviation	0.059178	0.796782	250.5558	22.40557	1028.4
Minimum	0.01	-16.5	37	0	0.0
1st Quartile (25%)	0.099375	-14.2286	200	7.222222	92.3
Median	0.141707	-13.7333	266.8706	17.22222	1045.3
3rd Quartile (75%)	0.19	-13.1714	376.2083	35.13571	2486.0
Maximum	0.28	-10.9	4665	196.5556	2500.7

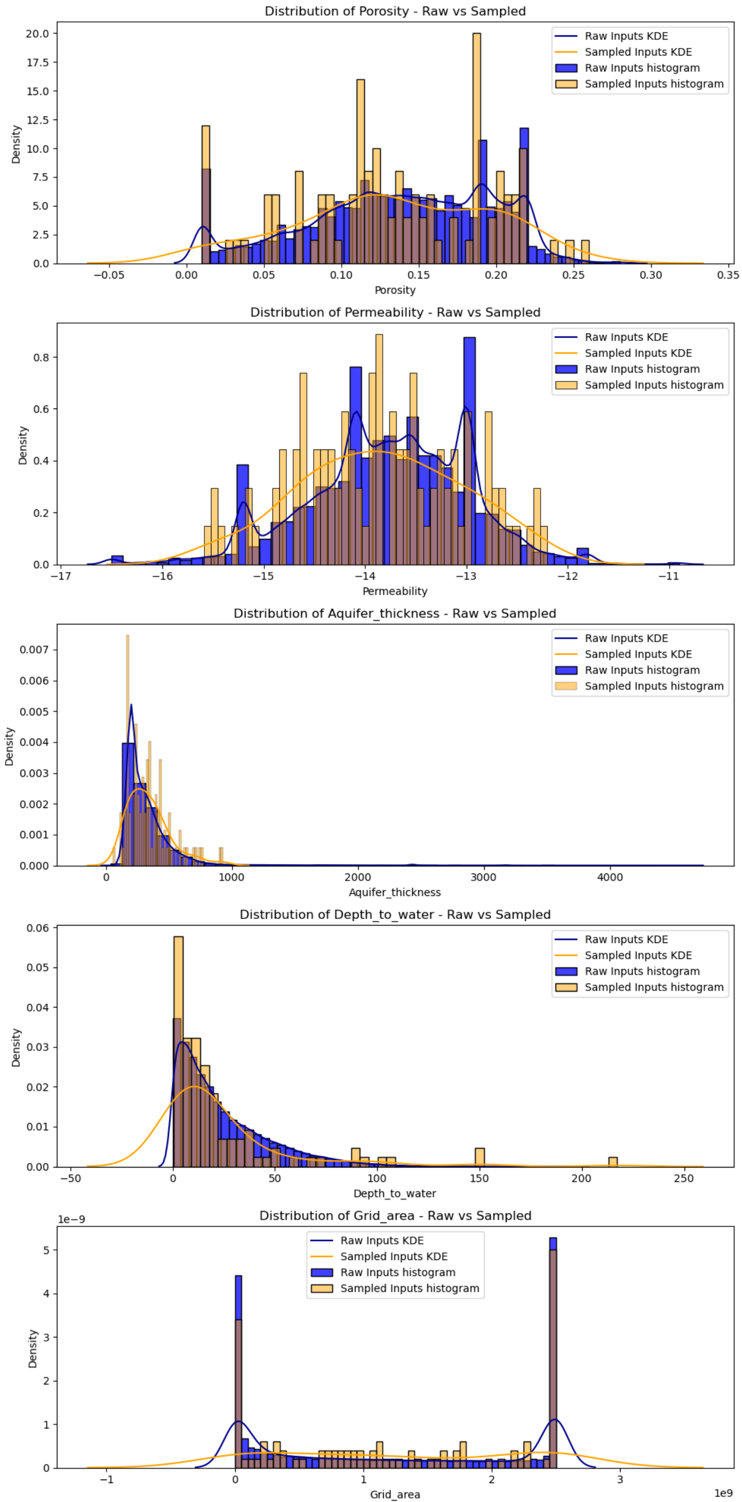


Figure 3: Kernal density estimates of aquifer properties used as inputs to *Superwell*

2 Dynamics for a Single Grid Cell

This example has been created to demonstrate superwell dynamics using a single grid cell and a single scenario of moderate depletion (25%) and low ponded depth (0.3m). In this example, wells are deepened in year 16 (Figure 4d) to maintain the initial pumping rate (Figure 6a). In year 48, the drawdown constraint is violated so the pumping rate (Figure 6a) is reduced because the deepening in year 16 extended the well to the total depth of the aquifer and further deepening is not possible. Groundwater pumping ceases after year 51 because the depletion limit of 25% is reached in year 51. Deepening in year 16 increases the total well length (Figure 4d) and the aquifer saturated thickness intersected by the well (Figure 4e), which also increases the Transmissivity (Figure 5b). The increased Transmissivity due to deepening reduces the drawdown (Figure 6d) as the higher Transmissivity results in less drawdown at the well pumping rate compared to before the deepening. When the well yield is reduced in year 48, the well area served and total number of wells in the grid cell are increased so each well still meets the annual ponded depth target.

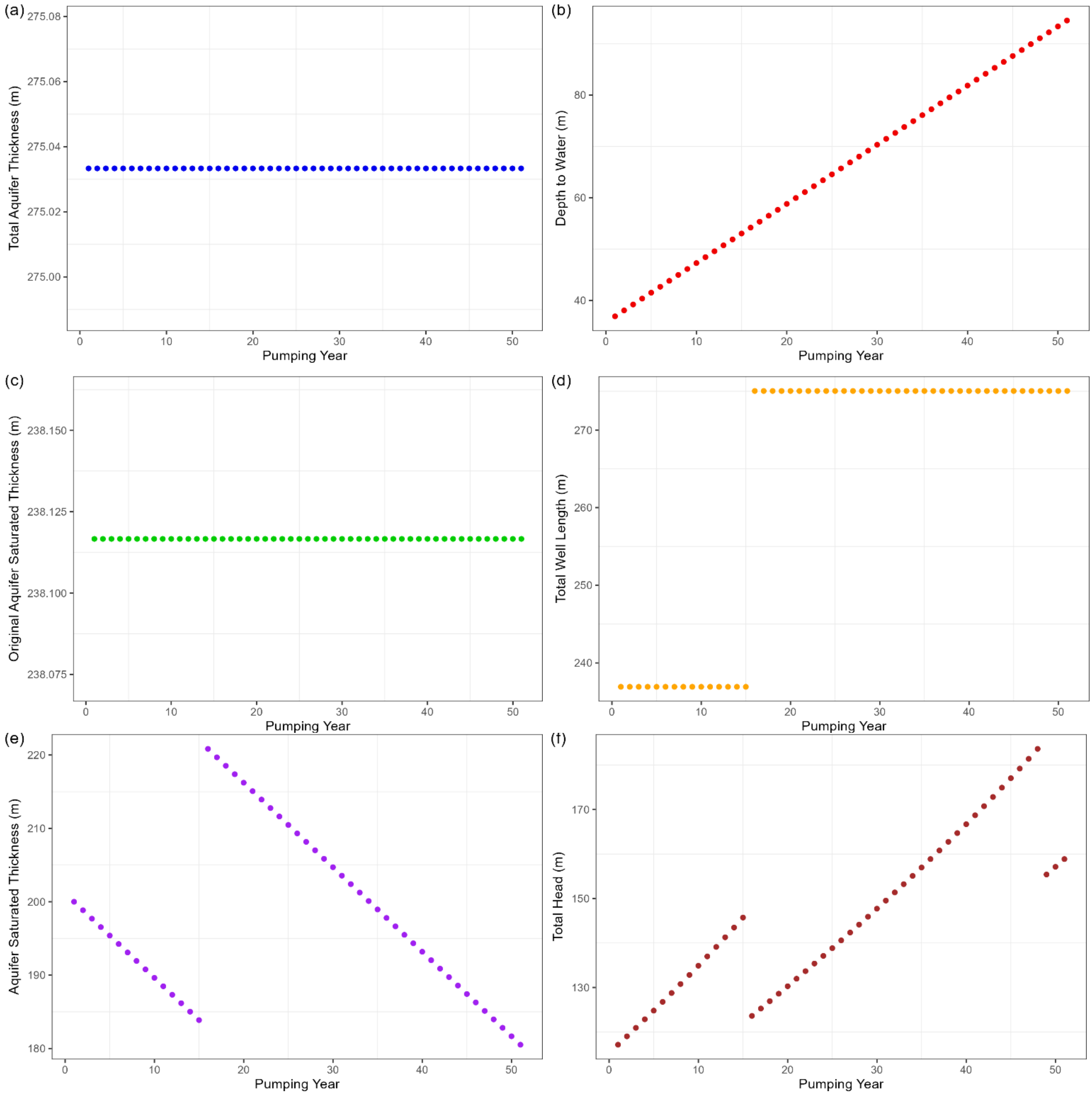


Figure 4: Aquifer Depths and Thicknesses: (a) Total Aquifer Thickness (m), (b) Depth to Water (m) reflecting changes in groundwater levels due to pumping, (c) Original Aquifer Saturated Thickness (m) showing initial saturated aquifer thickness in first year of pumping, (d) Total Well Length (m) indicating well infrastructure depth, (e) Aquifer Saturated Thickness (m) showing changing thickness in response to changing well depth and (f) Total Head (m) demonstrating the hydrostatic and structural responses of the aquifer system to the changes in well yield and well depth.

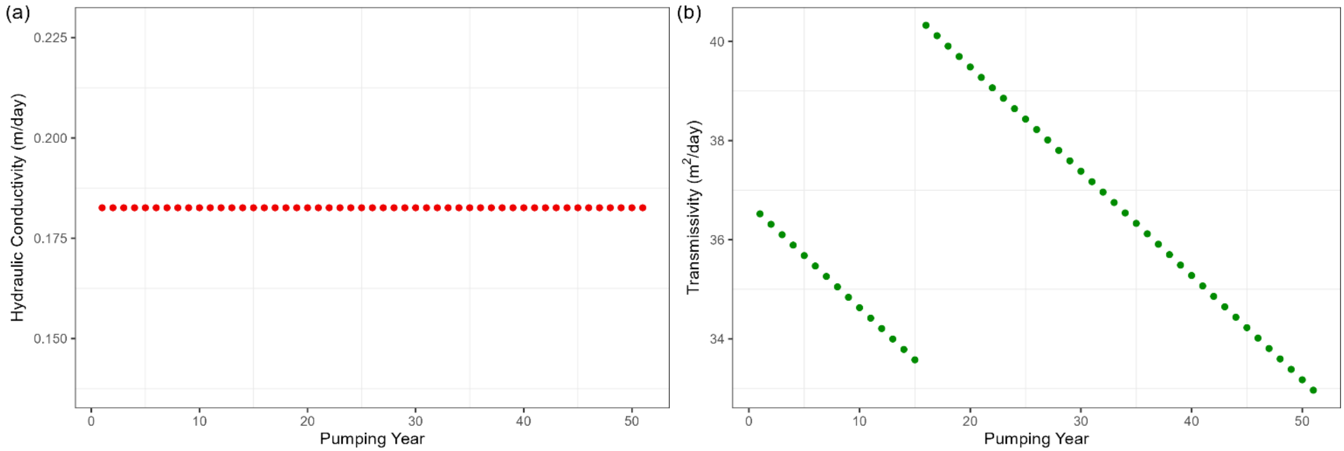


Figure 5: Aquifer hydraulic properties: (a) Transmissivity ($T = Kb$; m^2/day) and (b) hydraulic conductivity (K; m/day) showing the changing T in response to changing saturated aquifer thickness (b; m)

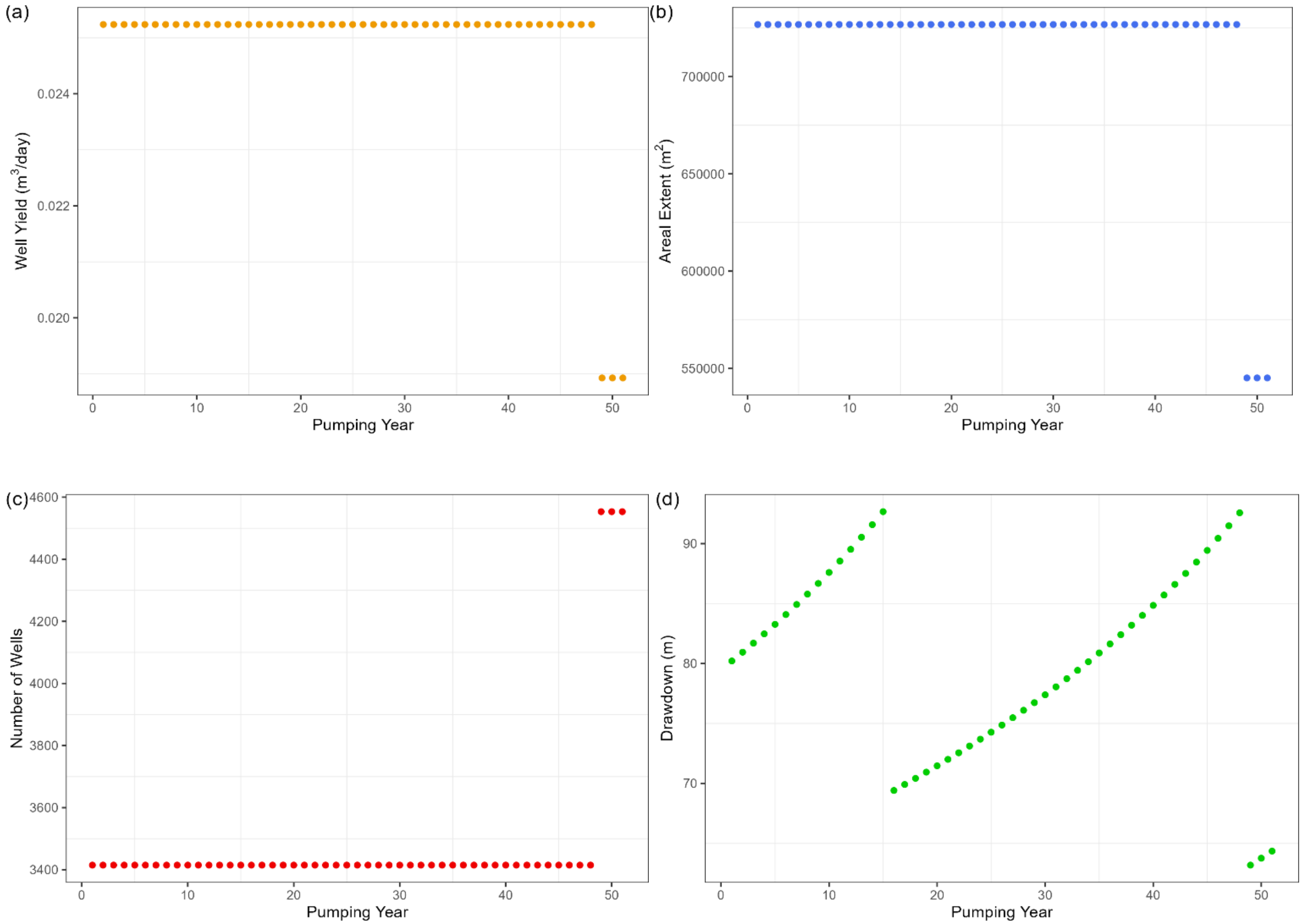


Figure 6: Well hydraulics: (a) Well Yield (m³/day; *Q*) showing the volume of water extracted per day (specified from a pre-defined array of possible pumping rate. *Q* reduces if the aquifer depth is not able to support pumping volumes), (b) Areal Extent (m²) indicating the spatial coverage of pumping from a well in a grid cell, (c) Number of Wells in a grid cell, and (d) Drawdown (m) illustrating the impact of pumping on groundwater levels near the well head.

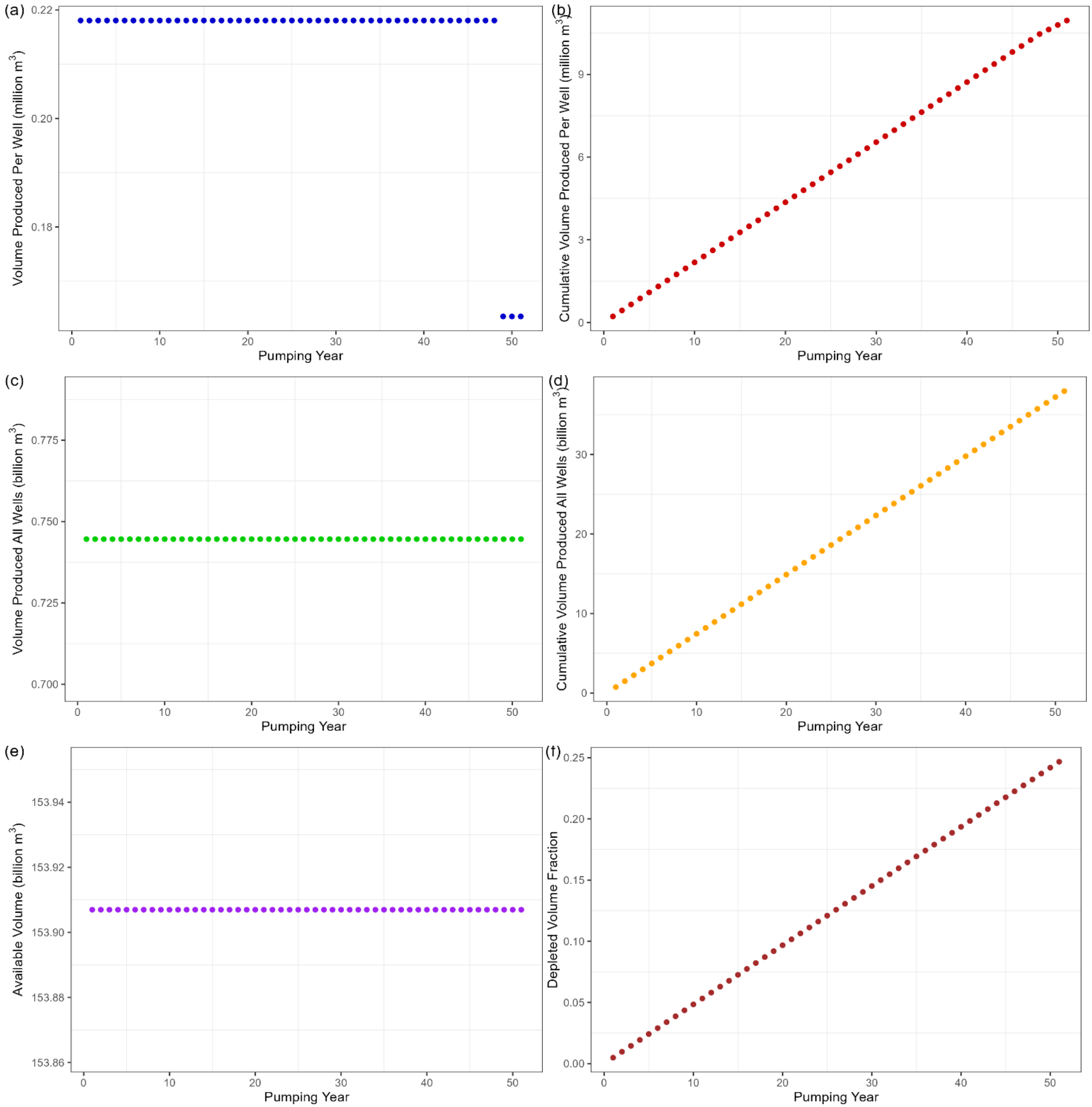


Figure 7: Groundwater volumes (extraction and availability): (a) Volume produced per well (million m³) and (b) Cumulative volume produced per well (million m³) showing individual well productivity over time in this grid cell, (c) Total volume produced by all wells (billion m³) and (d) Cumulative volume produced by all wells (billion m³) showing the total groundwater extraction, with (e) Available volume (billion m³) calculated using aquifer properties, and (f) Depleted Volume Fraction indicating the ratio between resource availability and depletion over time (until the depletion limits are met, in this case 25%).

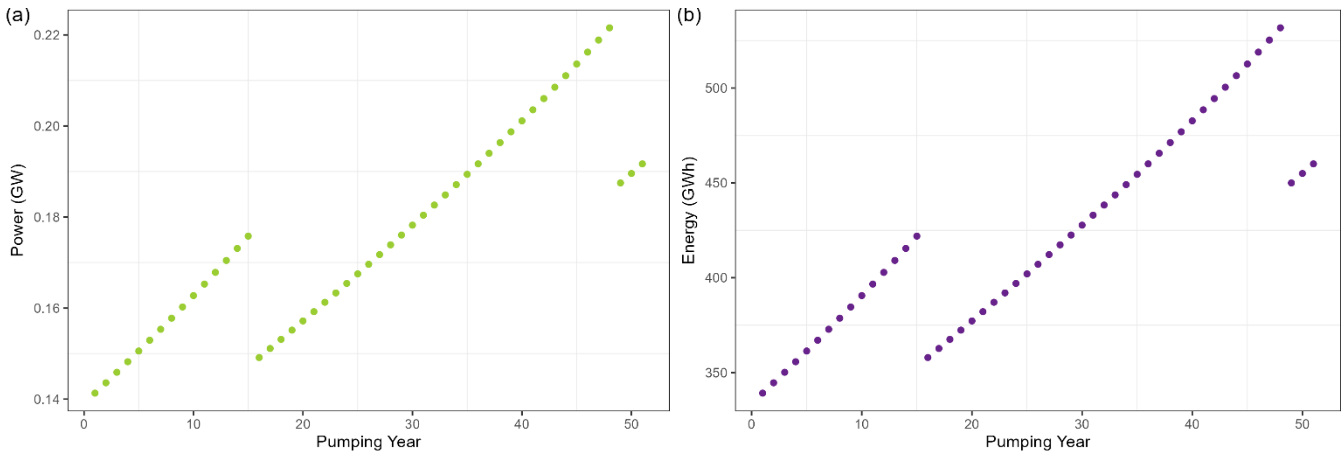


Figure 8: Energy and power to pump groundwater: (a) Power (GW) and (b) Energy (GWh) showing the energy requirements associated with groundwater extraction.

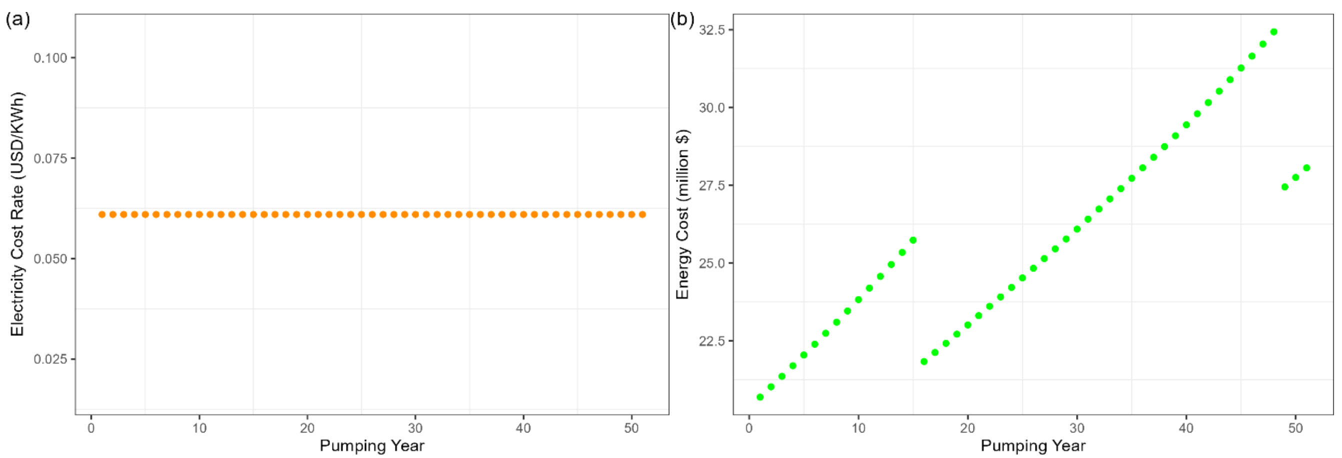


Figure 9: Energy costs: (a) Energy Cost Rate (USD/KWh) representing electricity cost rate in this grid cell and (b) Energy Cost (million $)

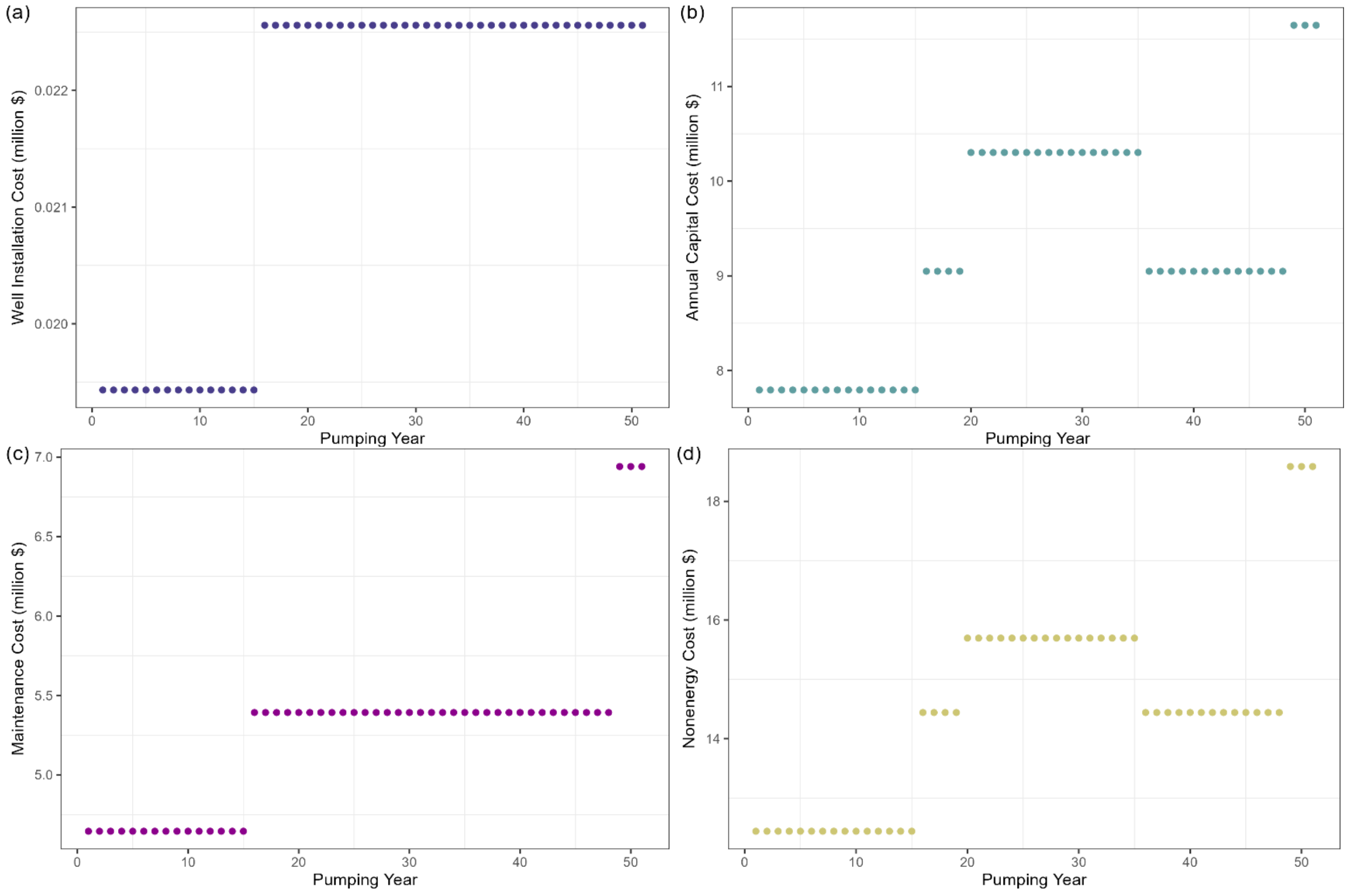


Figure 10: Nonenergy cost and its components: (a) Well Installation Cost (million $), (b) Annual Capital Cost (million $), (c) Maintenance Cost (million $), and (d) Nonenergy Cost (million $) covering various non-energy cost components associated with infrastructure requirements of pumping groundwater.

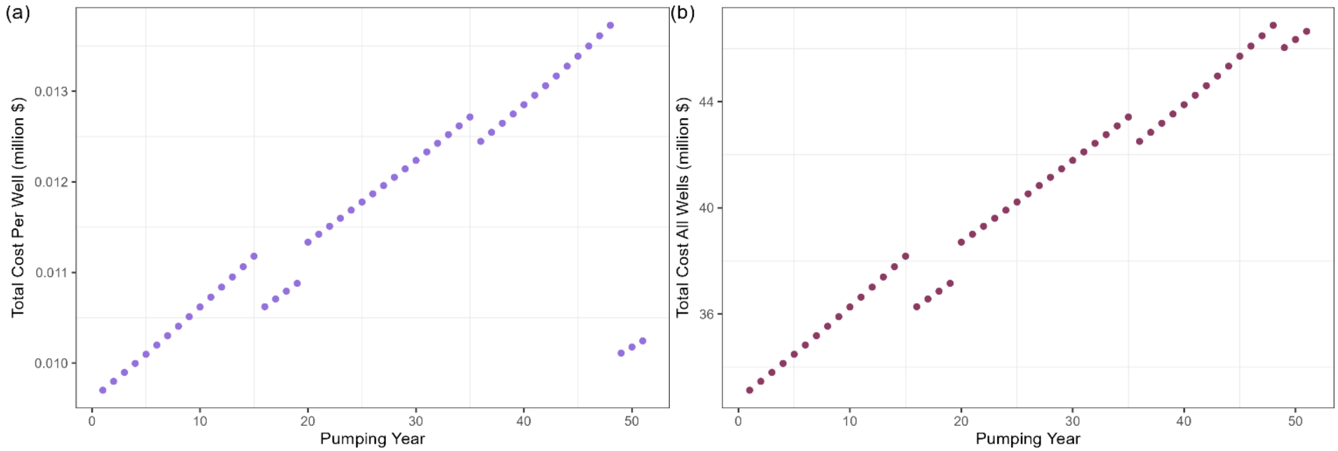


Figure 11: Total costs of groundwater extraction: (a) Total Cost Per Well (million \$) and (b) Total Cost All Wells (million \$) in this grid cell showing the overall cost burden of groundwater extraction for this grid cell in a moderate extraction scenario

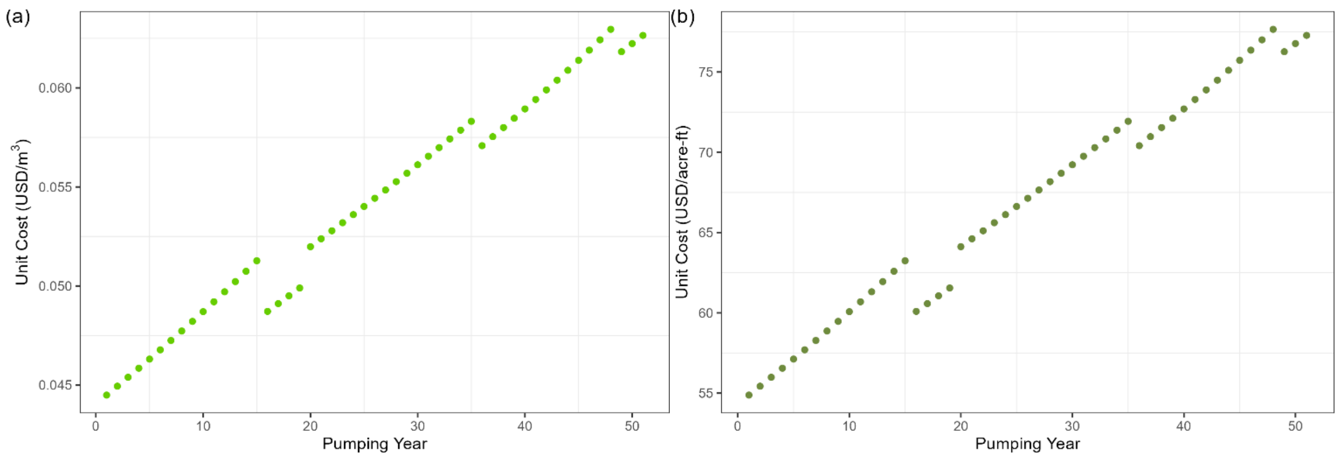


Figure 12: Unit costs of groundwater supply: (a) Unit Cost (USD/m³) and (b) Unit Cost (USD/acre-ft) providing insight into the cost-effectiveness and productivity of this grid cell ($unit\ cost\ =\ total\ volume\ produced\ /\ total\ cost\ of\ production$).

3 Processing and Results Maps

This section provides spatial details on a 0.5-degree gridded resolution using global maps of key inputs and outputs of superwell in a moderate depletion (25%) and low ponded depth target scenario (0.3m).

3.1 Hydraulics

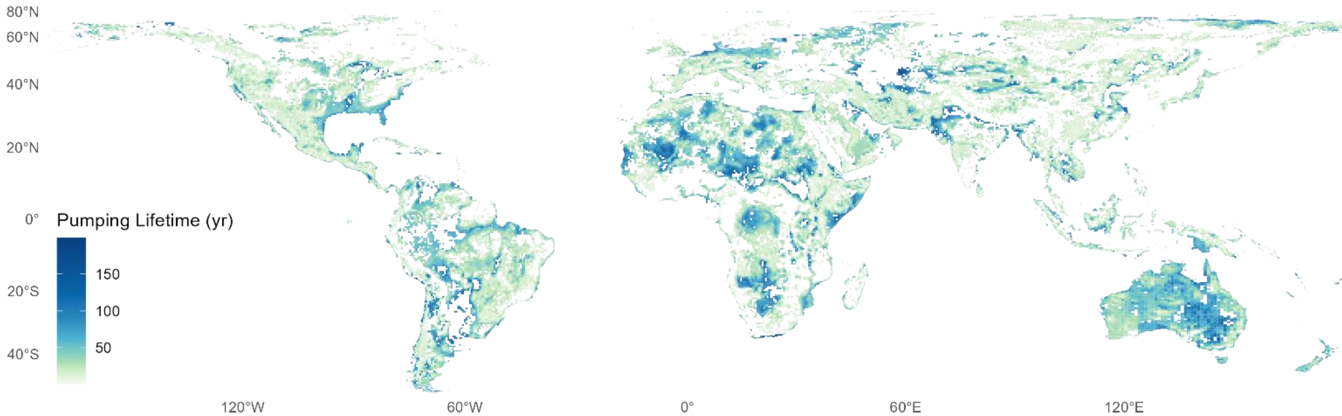


Figure 13: Pumping lifetime (year)

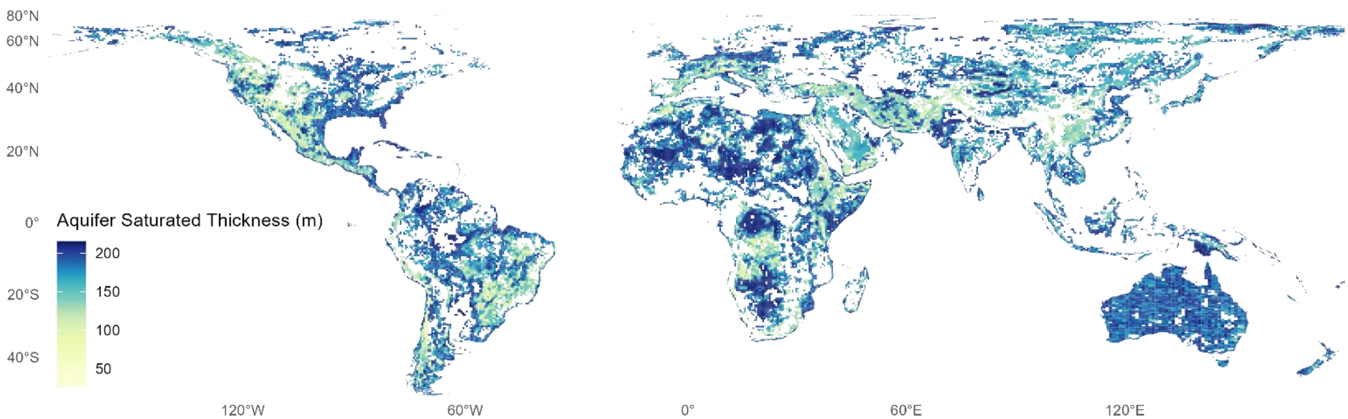


Figure 14: Aquifer saturated thickness (m)

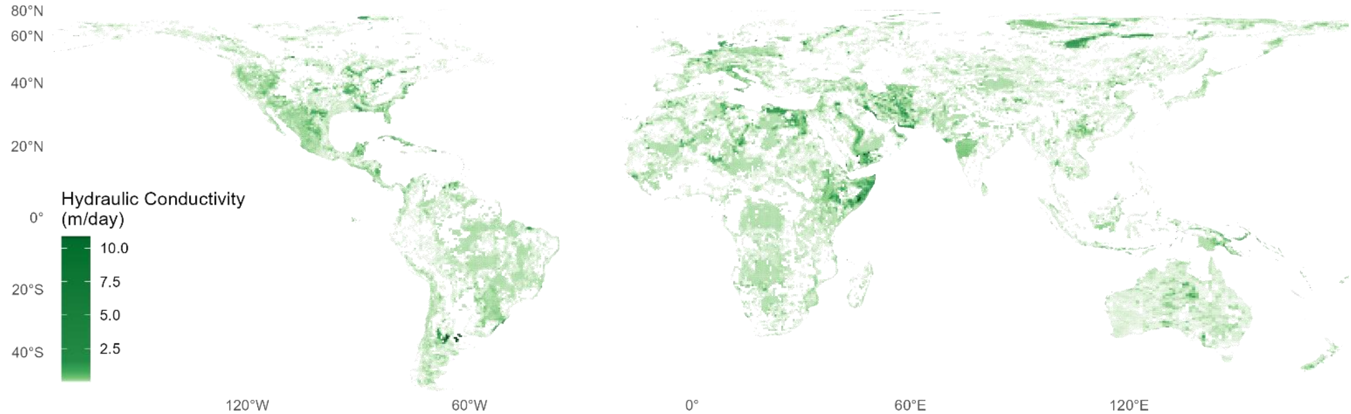


Figure 15: Hydraulic conductivity (m/day)

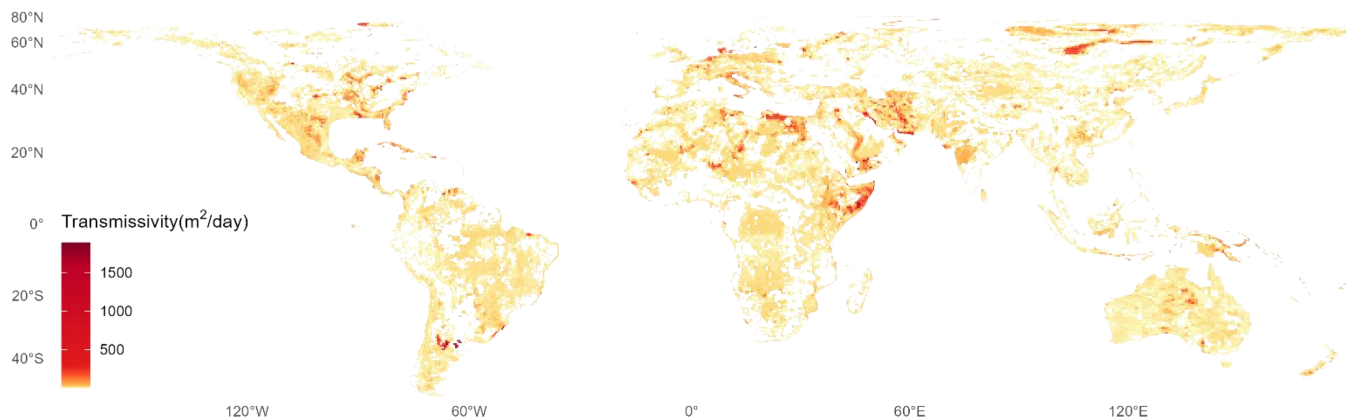


Figure 16: Transmissivity (m^2/day) averaged over all pumping years

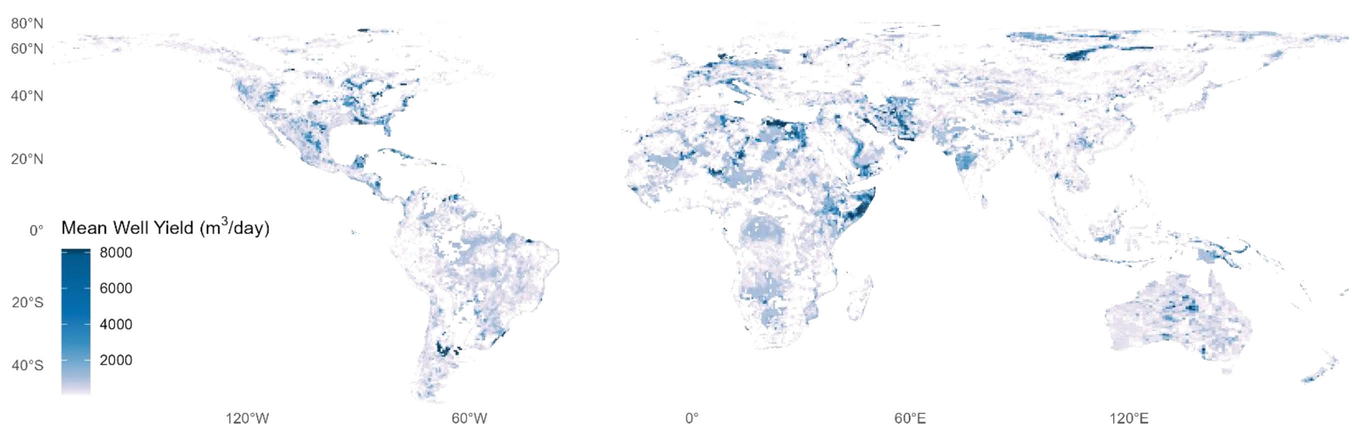


Figure 17: Well yield (m^3/day) averaged over pumping lifetime

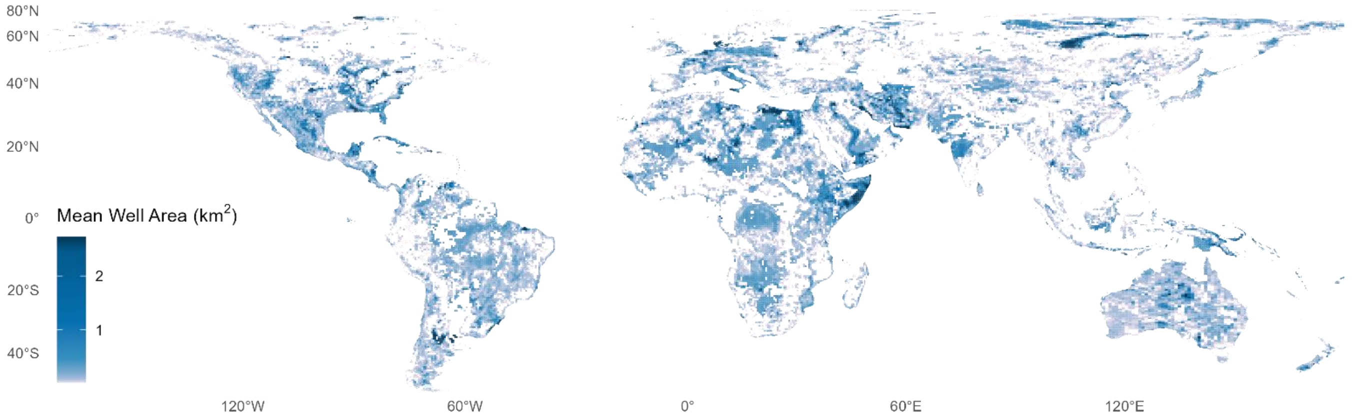


Figure 18: Well area (km^2) averaged over pumping lifetime

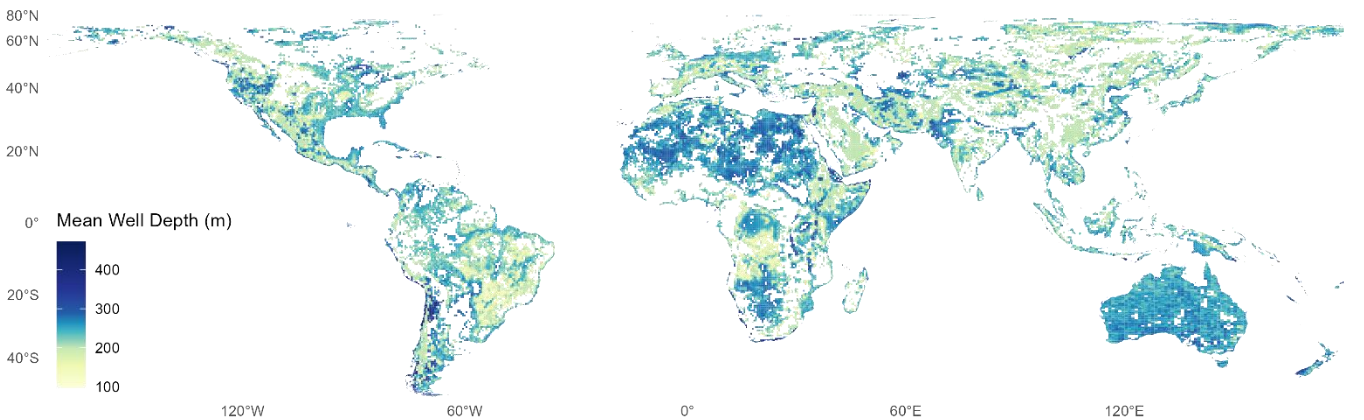


Figure 19: Total well length (well depth; m) averaged over pumping lifetime

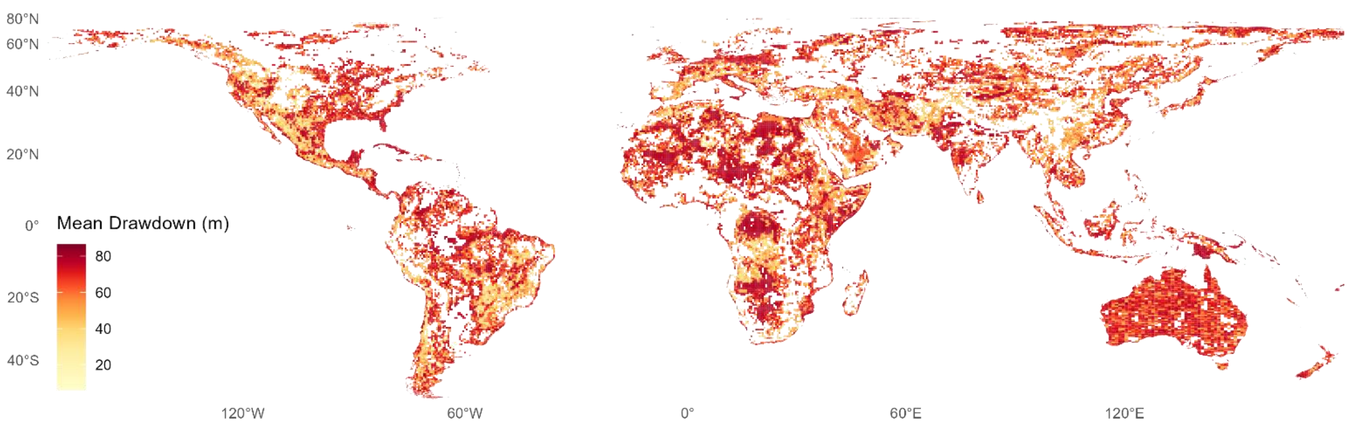


Figure 20: Drawdown (m) averaged over pumping lifetime

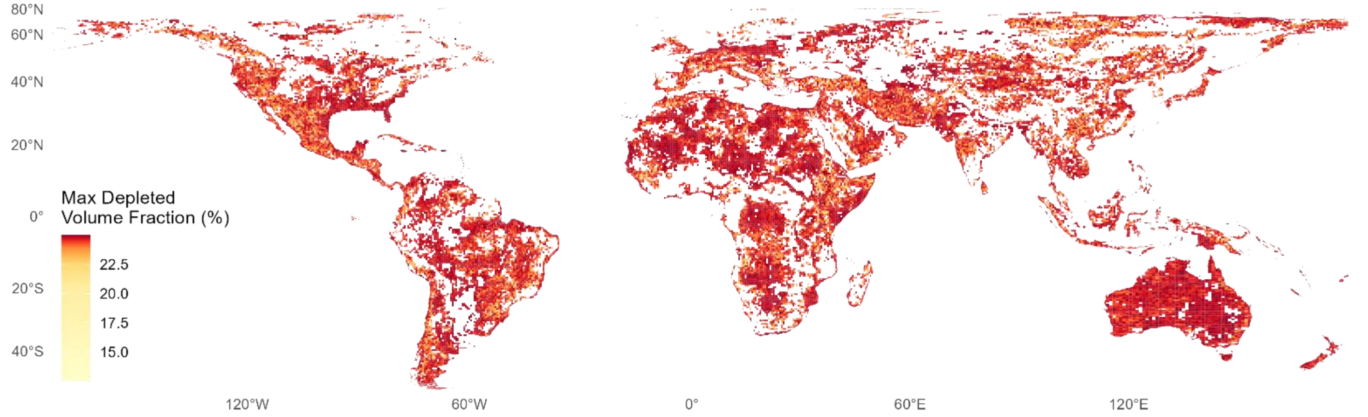


Figure 21: Maximum fraction of depleted volume i.e., volume produced over available volume, also referred to as depletion limit

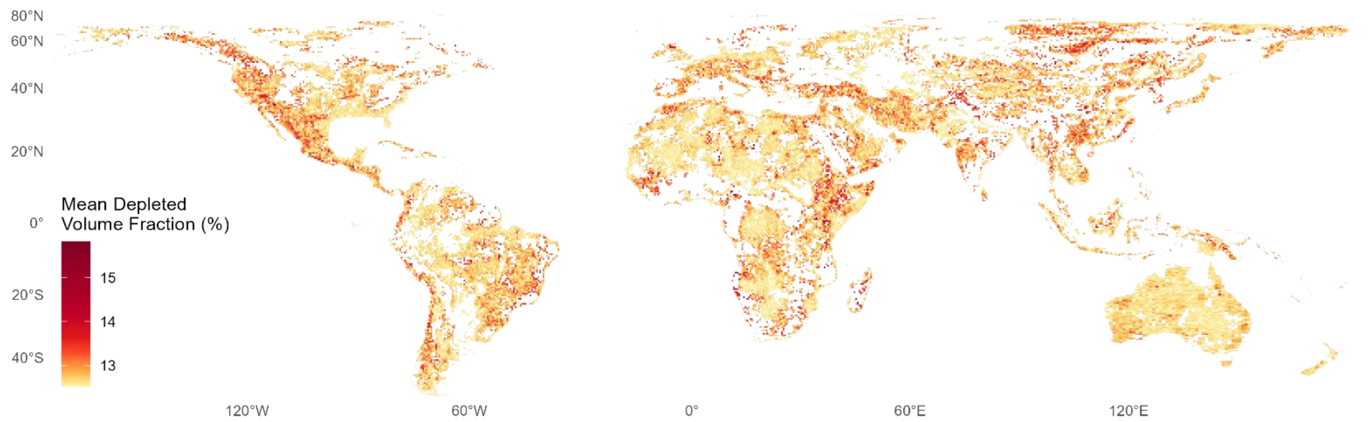


Figure 22: Mean fraction of depleted volume i.e., volume produced over available volume, averaged over pumping lifetime

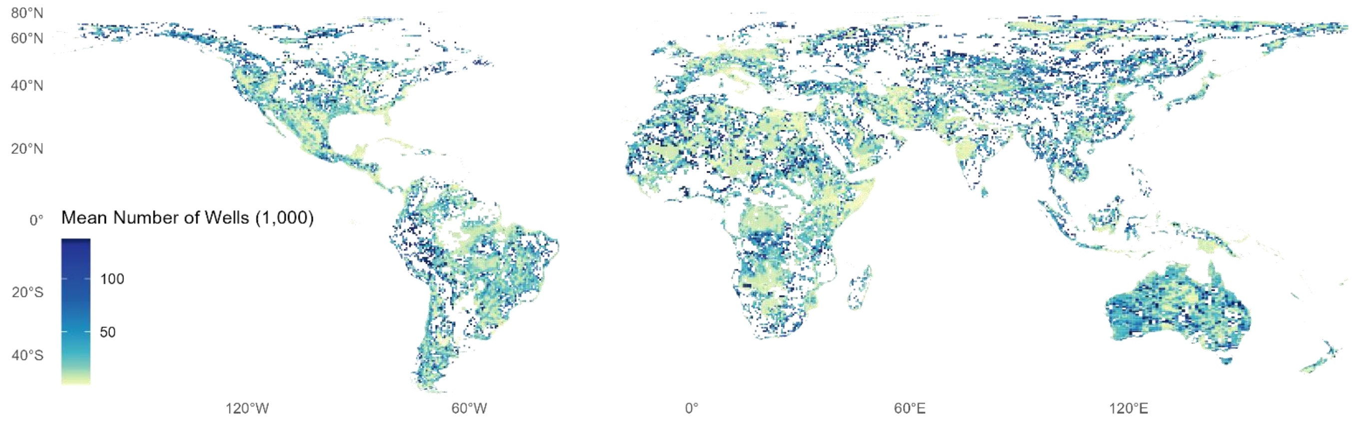


Figure 23: Number of well in a grid cells (x1000)

3.2 Costs

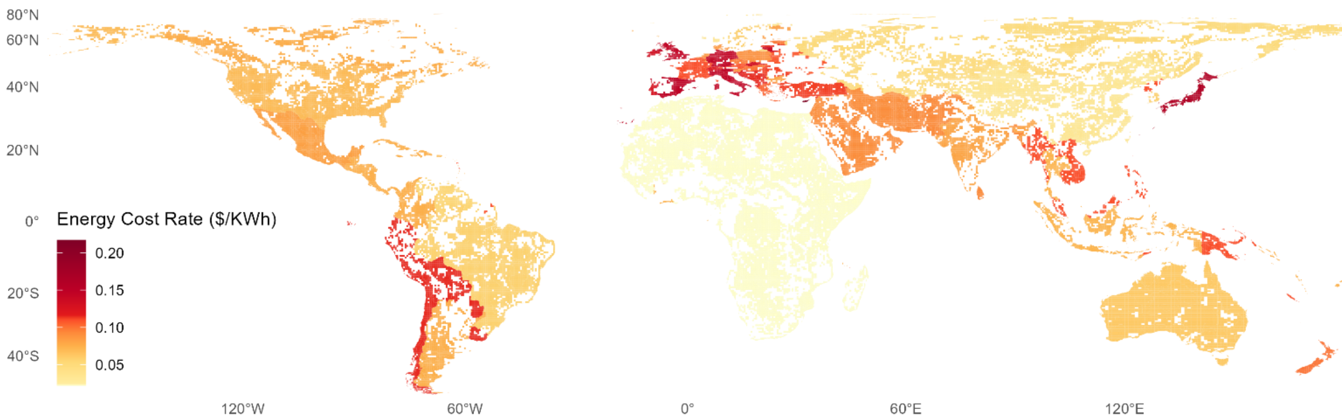


Figure 24: Electricity cost rate (2016 USD/KWh) for 172 countries downscaled to all grid cells. 0.074 (USD/KWh) is assumed to fill missing grid cells.

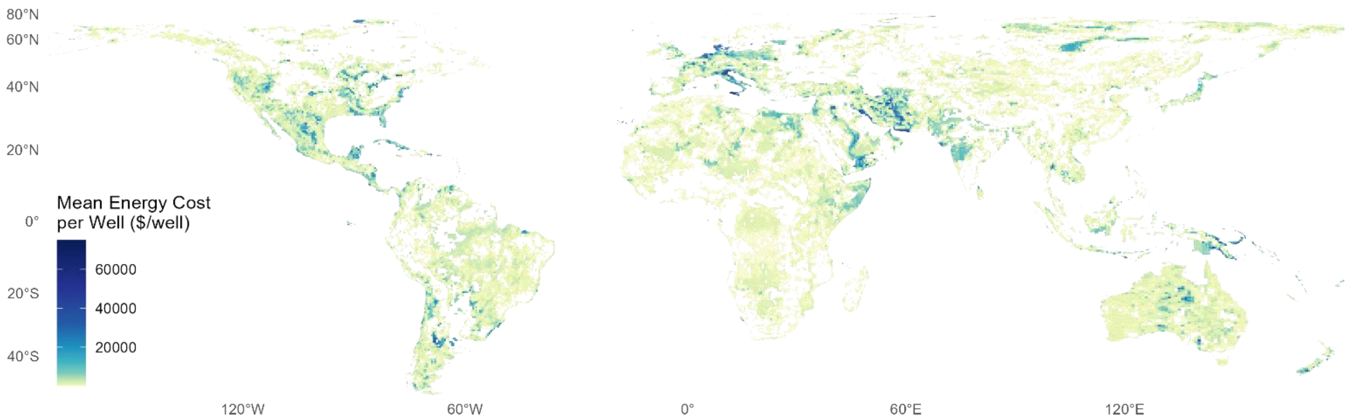


Figure 25: Energy cost per well (USD/well)

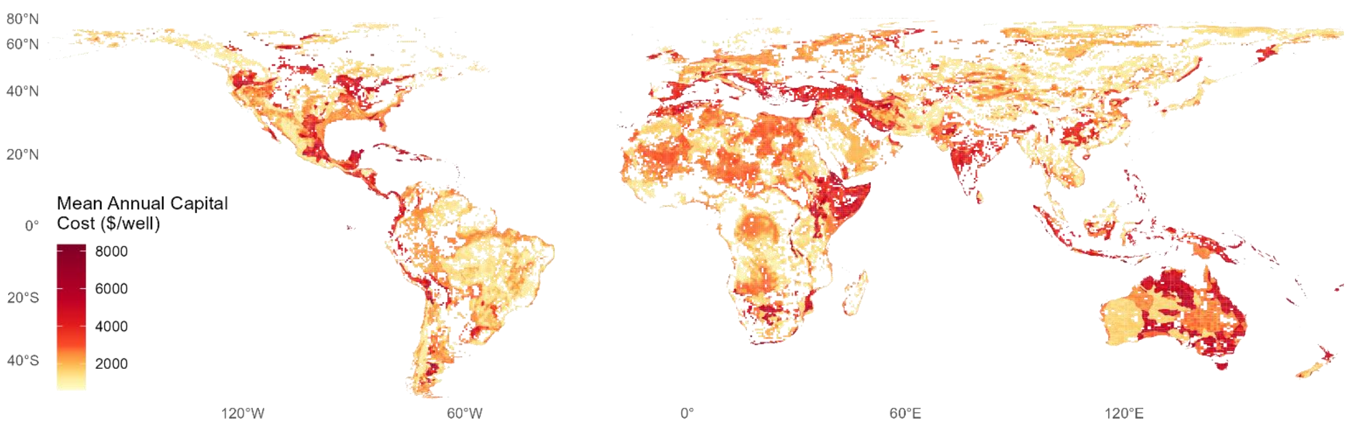


Figure 26: Annual capital cost per well (USD/well) averaged over pumping lifetime

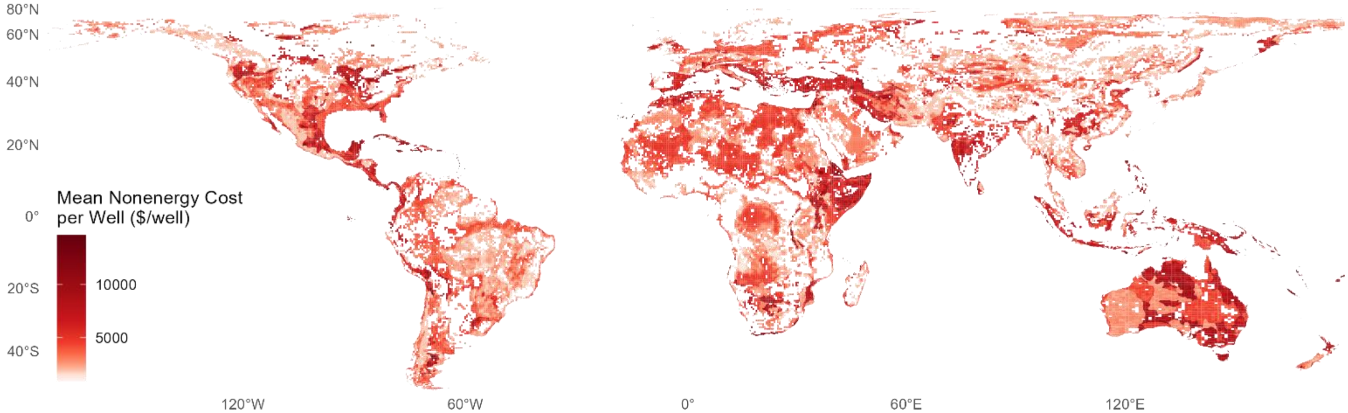


Figure 27: Non-energy cost per well (USD/well) averaged over pumping lifetime

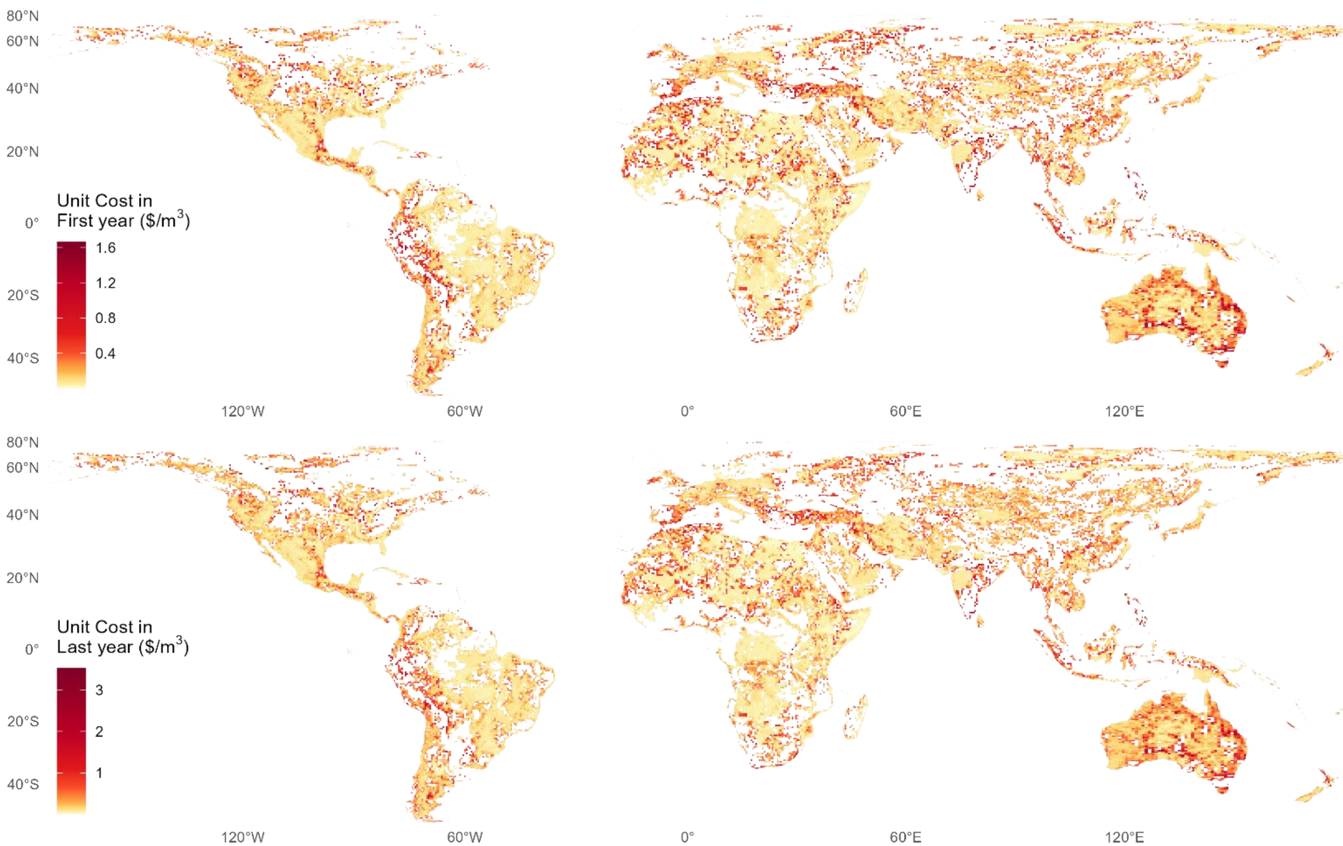


Figure 28: Unit cost (USD/m^3) in first and last year of pumping

4 Timeseries of Key Global Variables

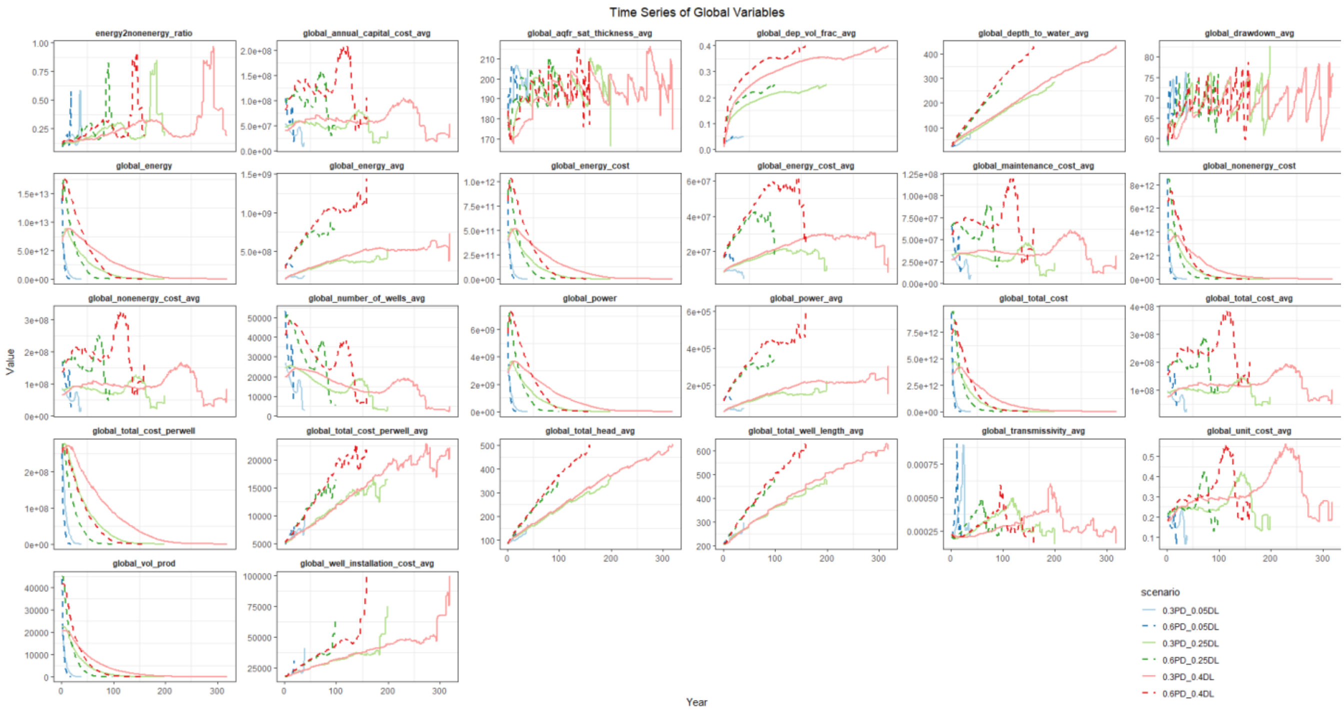


Figure 29: Timeseries of all key global variables produced by superwell across six scenarios (DL = Depletion limit, PD = Ponded depth). Note some plots have log scale on x-axis. Global average implies a mean across all grid points in a given year of pumping simulation.

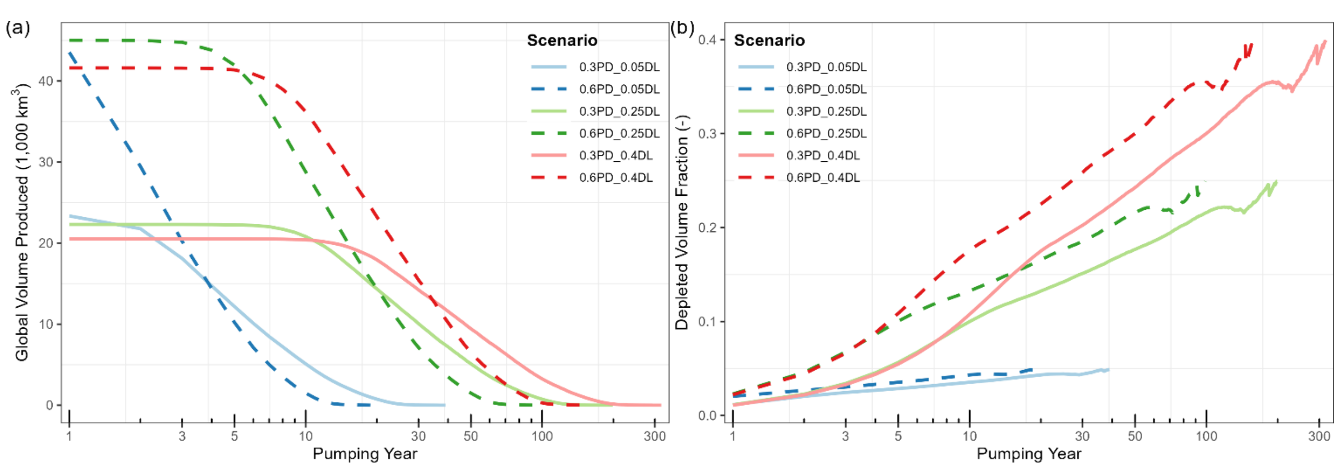


Figure 30: Global pumping volume characteristics: (a) Global volume pumped (1000 km^3) and (b) depletion volumes fraction representing volume pumped over available volume globally in a year of pumping. Note the log-scale on x-axis

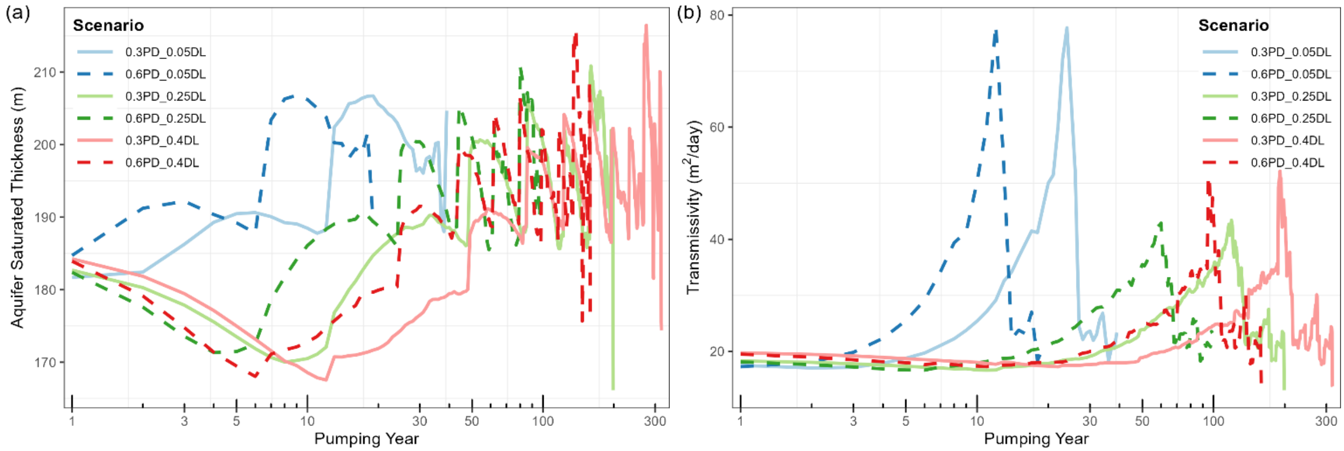


Figure 31: Aquifer characterises: (a) saturated aquifer thickness (m) and (b) transmissivity (m²/day) that get updated as wells are deepened over time. Note the log-scale on x-axis

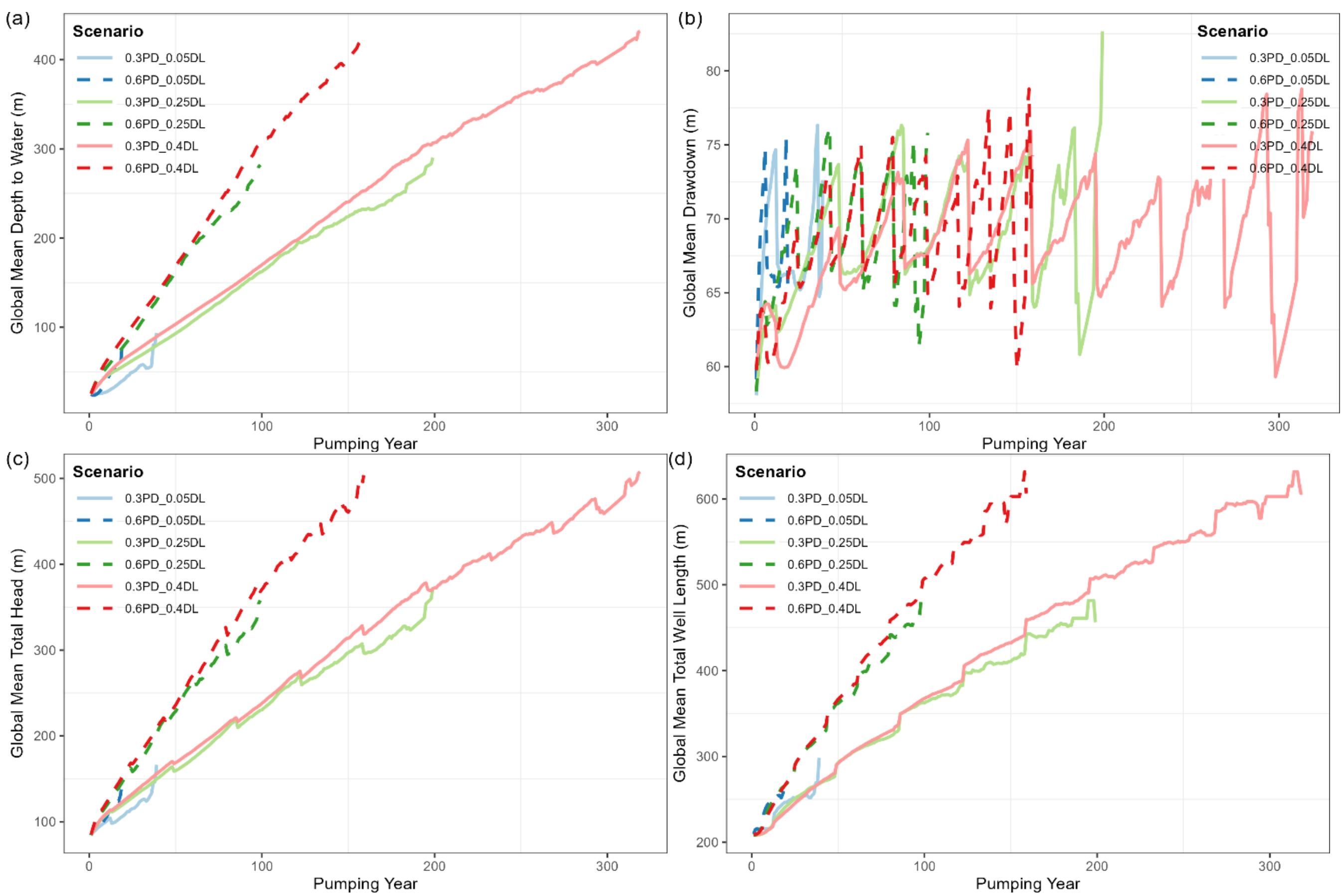


Figure 32: Depth characteristics averaged across all grid cells in a model pumping year: (a) Global mean depth to water (m), indicating the average depth from the surface to the groundwater level. (b) Global mean drawdown (m), representing the average

decline in groundwater level due to pumping. (c) Global mean total head (m), the average hydraulic head or energy per unit weight of water. (d) Global mean total well length (m), indicating the average length of all wells across all grid cells.

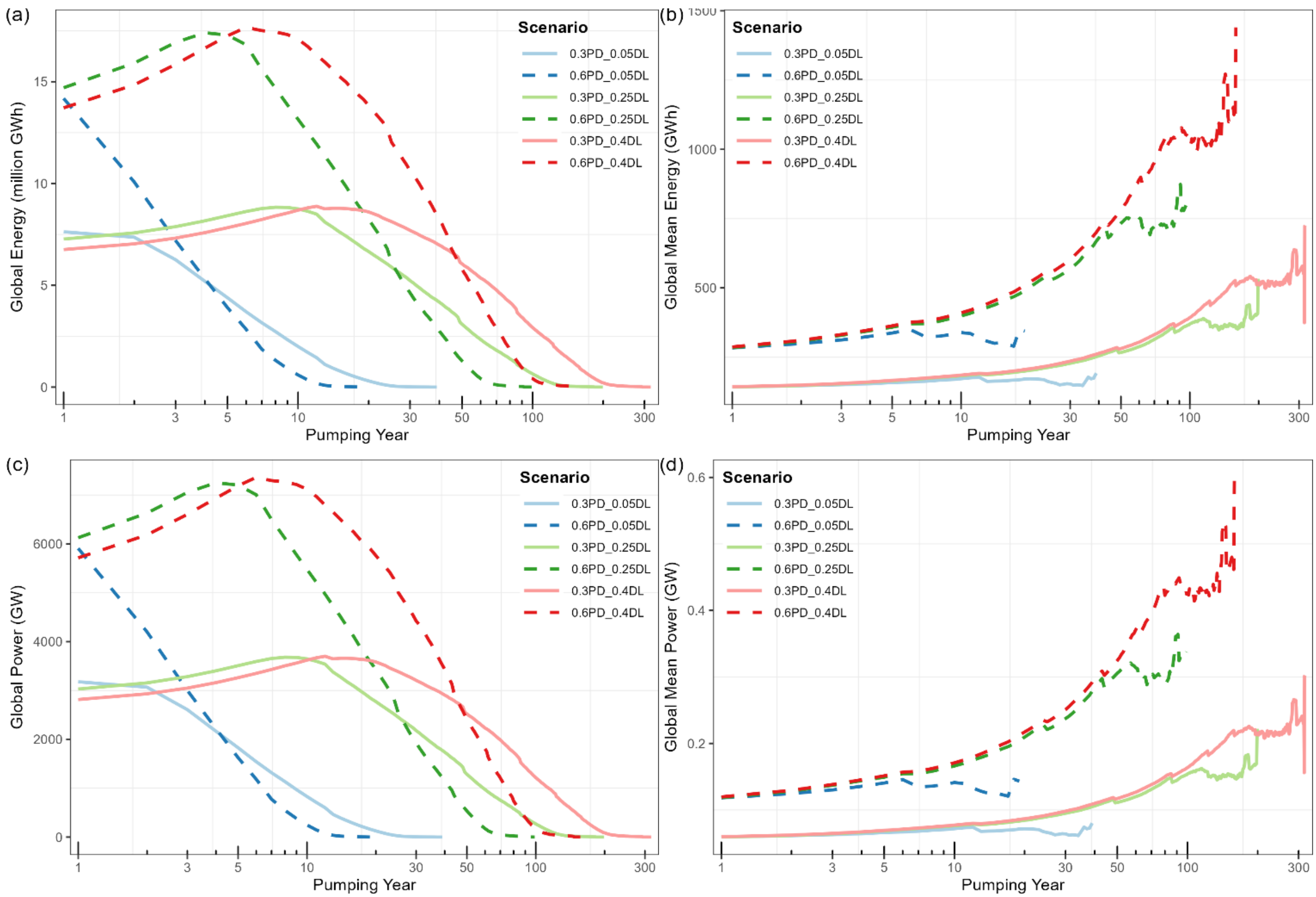


Figure 33: Energy and power requirements for pumping groundwater in all grid cells in a model pumping year: (a) Total energy used globally to pump groundwater (million GWh); (b) Global mean energy (GWh) representing the average energy used across all grid cells; (c) Total power required to pump groundwater globally; and (d) Global mean power (GW) indicating the average power used across all grid cells. Note the log-scale on x-axis

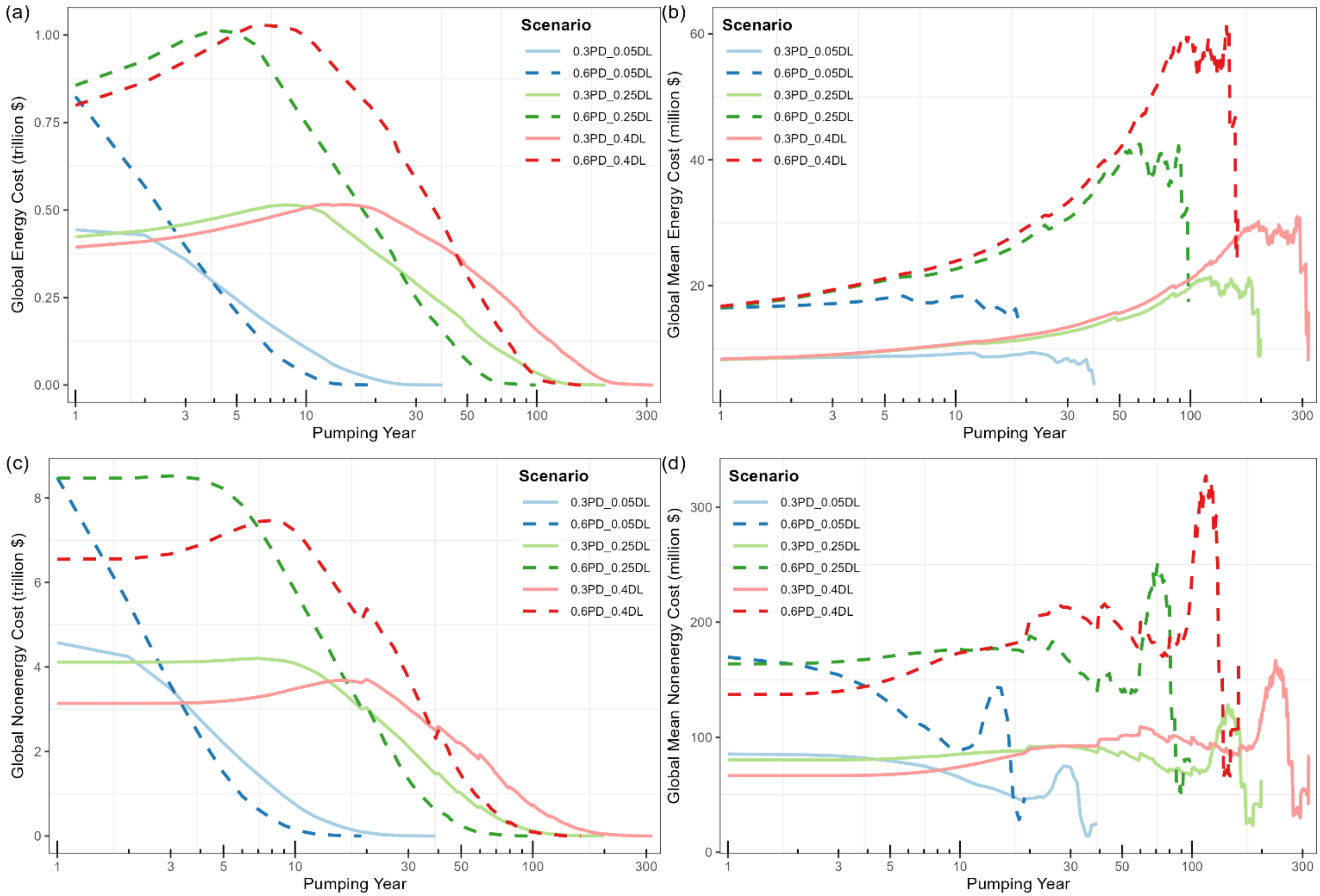
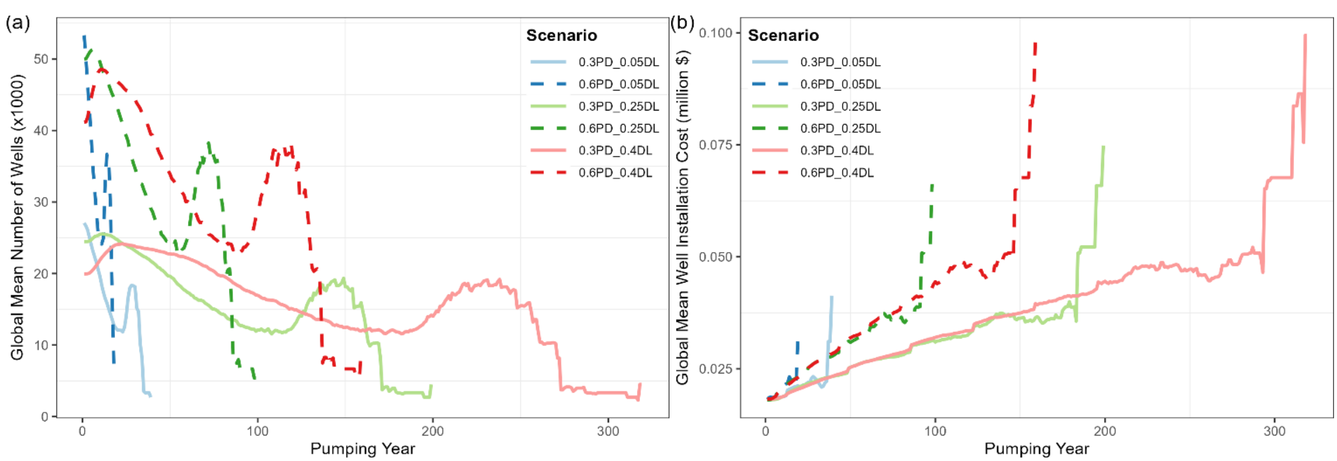


Figure 34: Global energy and nonenergy costs in all grid cells: (a) Total energy cost globally (trillion USD); (b) Global mean energy cost, representing the average cost of energy (million USD) across all grid cells; (c) Total nonenergy cost globally (trillion USD), representing the total of all costs associated with groundwater extraction excluding energy costs of pumping; (d) Global mean nonenergy cost (million USD), indicating the average nonenergy cost across all grid cells. Note the log-scale on x-axis



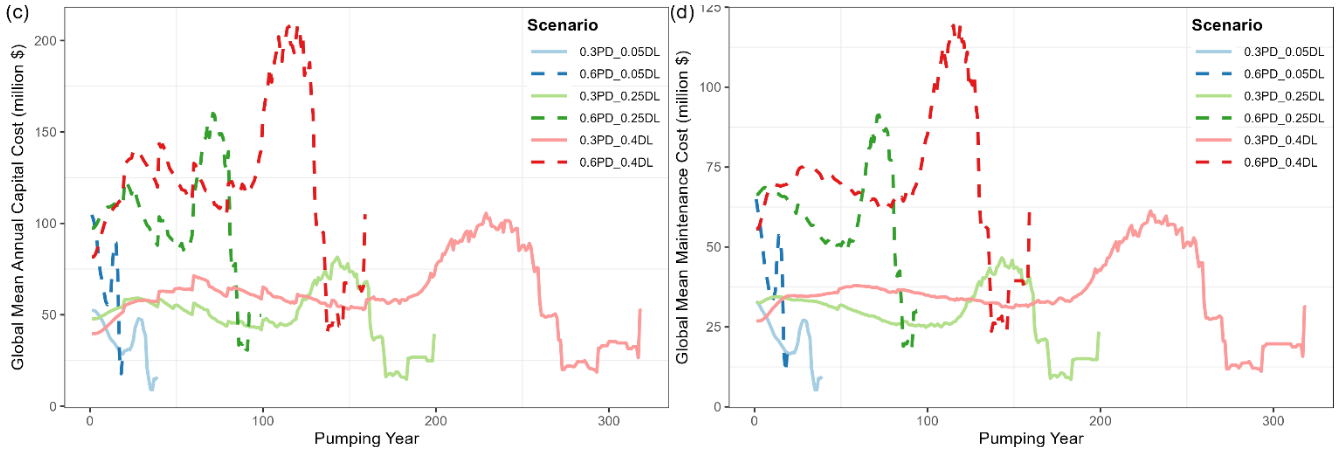
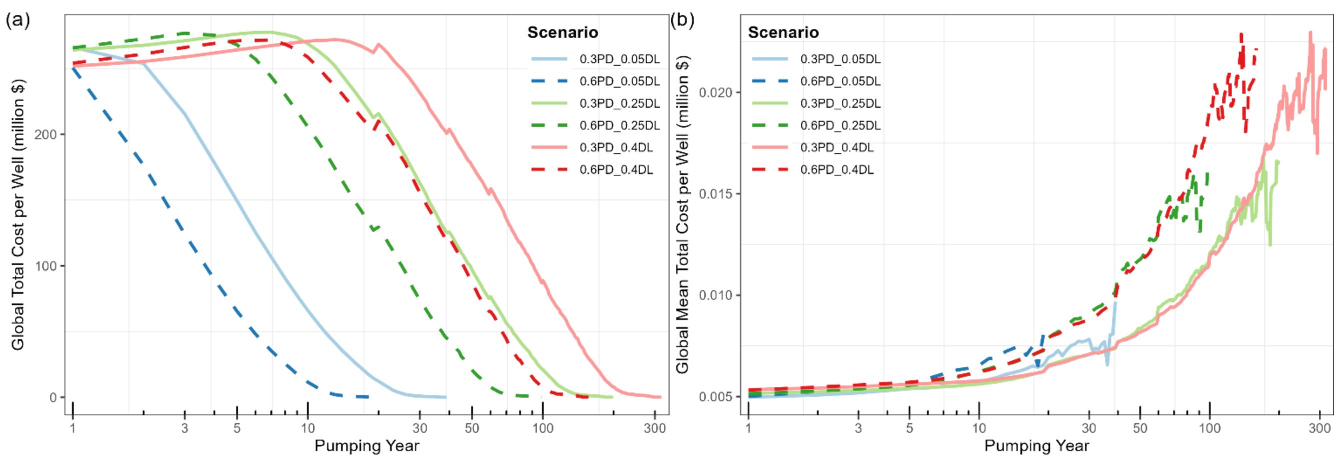


Figure 35: Nonenergy costs components across averaged across all grid cells in a pumping year: (a) Global mean number of wells required to meet pumping targets (1000s); (b) Global average cost of installing a groundwater well (million USD); (c) Global mean annual capital cost (million USD), representing the average annual cost of capital investments in groundwater infrastructure; (d) Global average cost of maintaining groundwater wells (million USD).



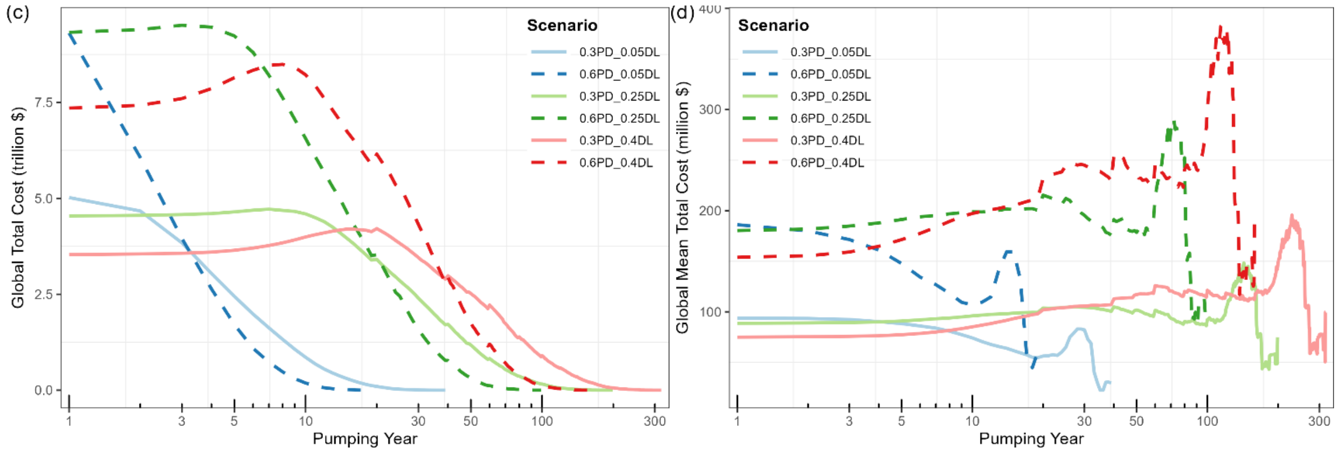


Figure 36: Global total and mean costs for groundwater extraction globally: (a) Sum of total cost globally per each well (million USD); (b) Global mean total cost per well (million USD), reflecting the average expenditure incurred for each well across all grid cells in a model pumping year; (c) Total cost of groundwater extraction globally (trillion USD); and (d) Global mean total cost (million USD), denoting the average cost of groundwater extraction across all grid cells. Note the log-scale on x-axis

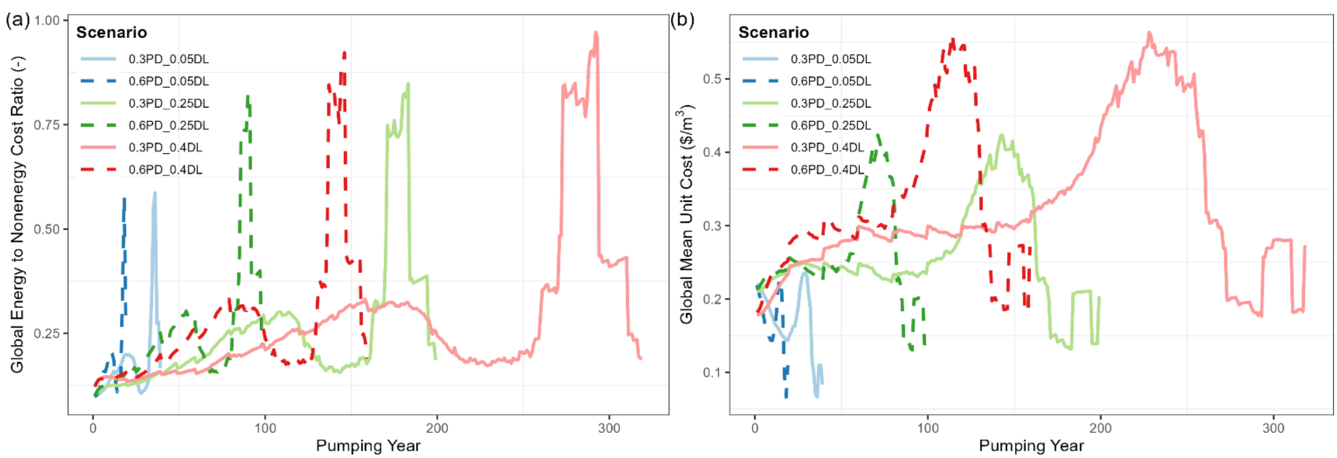


Figure 37: Cost ratios: (a) Ratio of total energy costs to nonenergy costs ratio globally; and (b) Global mean unit cost (USD/m^3) calculated using a ratio of total cost of groundwater extraction over total volume extraction across all grid cells in a model pumping year, indicating the average cost of extracting a cubic meter of groundwater, in USD/m^3.

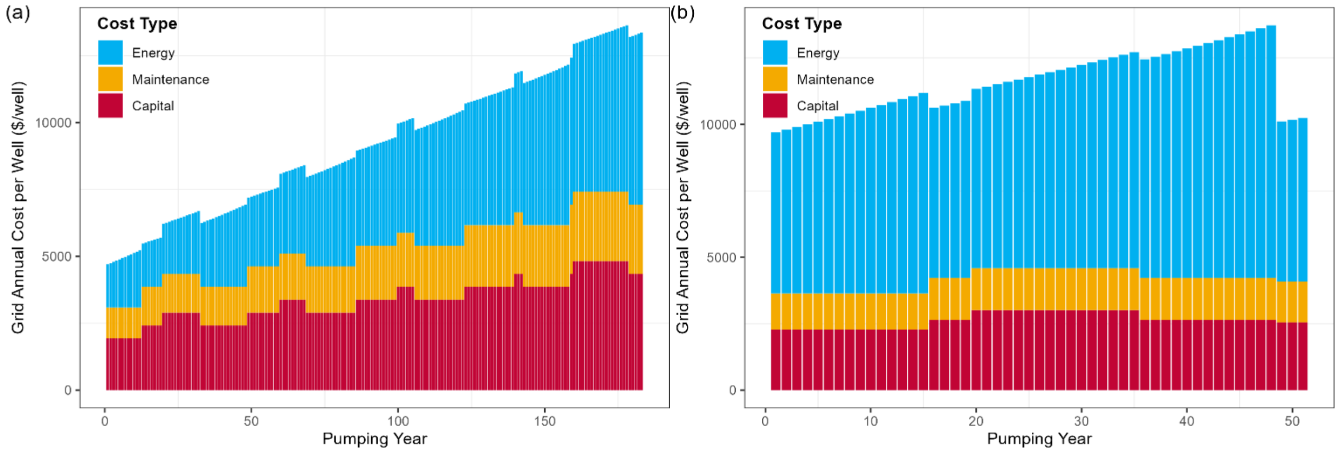


Figure 38: All cost components stacked over each other for (a) global (all grid cells) and (b) a single grid cell.

5 Correlations

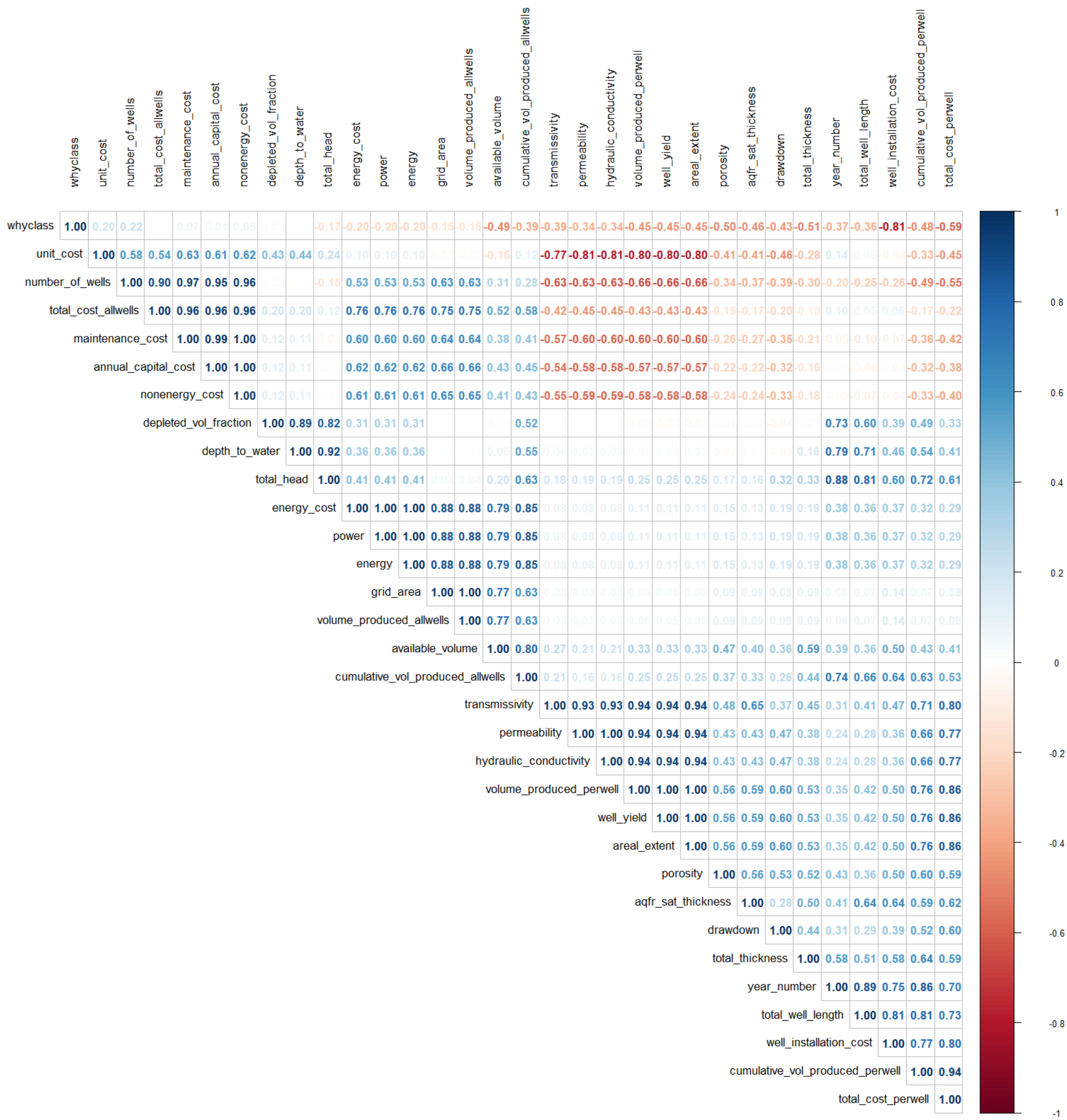


Figure 39: Spearman correlation matrix of all inputs and outputs of superwell model

6 References

Richts, A., Struckmeier, W. F., & Zaepke, M. (2011). WHYMAP and the Groundwater Resources Map of the World 1:25,000,000. In J. A. A. Jones (Ed.), *Sustaining Groundwater Resources: A Critical Element in the Global Water Crisis* (pp. 159-173). Springer Netherlands. https://doi.org/10.1007/978-90-481-3426-7_10