Ecosystem Service: Groundwater Recharge Service, a Regulating Service

# 1. Introduction

## 1.1 Definition of Groundwater Recharge Ecosystem Service

Groundwater recharge broadly describes the replenishment of water to a groundwater flow system (Winter 2000). IT is a part of the hydrological regulation process. There are two mains ways about how groundwater recharge service contributes to human well-being: (i) provision of water resources for human use (drinking, irrigation, and industrial use) and (ii) regulating the levels of groundwater table, which make the access to groundwater resources easier and more reliable.

## 1.2 Previous literature

The studies that valuing groundwater recharge service per se is not many. Most of the previous GEP studies do not isolate groundwater recharge service as a distinct service, but they view the service as a part of the broader categories of hydrological services such as water provisioning service. Therefore, the value of groundwater recharge service is implicitly included in the value of these broader categories. For example, Ouyang et al. (2020) implicitly accounted for the groundwater recharge as part of water provisioning and flood regulation services. Such a treatment of groundwater recharge service can be found in other studies as well (e.g., Deng et al. (2025); Joshi et al. (2025); Pacetti et al. (2024)).

As a studies that explicitly value groundwater recharge service per se, Acharya and Barbier (2000) studies quantify the value of groundwater recharge as a regulating service in the context of agricultural production in wetlands in northern Nigeria. They link the crop yields from recharge-supported irrigation to ecosystem value of groundwater recharge. Based on hypothetical scenarios of groundwater recharge rates, they estimate the value of groundwater recharge as a welfare change for irrigation-dependent agricultural producers in the region. Another study by Brauman, Freyberg, and Daily (2015) estimates the value of groundwater recharge regulating service as a pumping cost for water extraction saved owing to natural groundwater recharge associated with different land use types in Kona, Hawaii. They estimate the monetary value of the groundwater recharge service attributed to a specific land cover scenario as the difference in pumping costs for water before and after the land-use change.

## 1.3 Research Question

The previous GEP literature does not provide a standalone estimate for groundwater recharge service, rather the value of the service is accounted primarily as a provisioning service, focusing on its contribution to current water supply. Meanwhile, there are some agricultural economics and hydrology studies that focus on valuing groundwater recharge service as a regulating service.

To fill this gap, I estimate the value of groundwater recharge service as a regulating service, focusing on its role in stabilizing aquifer levels. From the perspective of human well-being, this regulating service is important because it helps maintain (or slow) the long-term decline of groundwater levels, thereby avoiding increased pumping costs to extract groundwater and the need for investment in alternative water supply sources or infrastructure adaptation (e.g., drilling deeper wells, more energy-intensive pumping system, or building reservoirs). To quantify this service, I pose the following question: *“If the recharge didn’t happen, what would it cost to deliver the same amount of water to people or systems that currently benefit from it?”*.

For example, groundwater table would decrease in the absence of groundwater recharge regulating service. This would lead to the following two consequences to people (Acharya and Barbier 2000): (i) increased pumping costs to extract groundwater as the groundwater table declines below a certain level, (ii) the need for investment in alternative water supply sources or infrastructure adaptation if the groundwater table declines beyond the maximum depth that can be pumped.

This framing aligns with the idea of the replacement cost approach. The saving in pumping costs associated with the groundwater recharge service has been used as a measure of the value of groundwater recharge in the literature (e.g., Acharya and Barbier (2000), Brauman, Freyberg, and Daily (2015)). This allows for estimating the gross ecosystem product (GEP) of recharge based on the costs that would be incurred to replicate its function artificially or offset the consequences of its absence.

# 2. Methods

I will conduct the analysis on a watershed scale. The watershed is a common scale for hydrological analysis because it is a natural hydrological unit that collects precipitation and drains it into a common outlet, such as a river or lake. The first step of my analysis is to prepare which watersheds to analyze. To this end, I use two datasets: one is the major groundwater basin boundary dataset obtained from Niazi et al. (2024), and the other is the watershed boundary data from HydroBASINS v1 (Level 6) (Lehner and Grill 2013). Specifically, I identified the watersheds that overlap with major groundwater basins. In total, 7,722 watersheds are selected for the analysis.

**insert a figure here**

Due to the lack of data on actual measurement of natural groundwater recharge rate globally, I will use the InVEST Seasonal Water Yield (SWY) model to estimate the amount of groundwater recharge provided from natural ecosystems. I use one of the key outputs of the SWY model called local recharge, which is the amount of net rainfall that infiltrates into soil beyond the root zone.

The valuation of groundwater recharge regulating service is done in the following ways: First, I estimate natural groundwater recharge rate per year for each watershed , () which is derived from the InVEST SWY model. Next, I derive the unit cost of pumping groundwater from the aquifer to the surface as a function of the depth of the water table. The total cost of pumping groundwater consists of three components (Naggar 2003); (i) capital cost of the pumping system, (ii) operation and maintenance cost, and (iii) energy cost which is a function of the depth of the water table. Since I will derive the value of groundwater recharge service as a difference in pumping costs with and without groundwater recharge, the capital cost and operation and maintenance cost of the pumping system, which is assumed to be constant regardless of the depth of the water table, will cancel out in the difference. Thus, all the information I need to proceed the analysis is the marginal cost of pumping water as a function of the depth of the water table. To this end, I will rely on the engineering formula to approximate it (Naggar 2003). The energy cost of pumping a unit volume of water is given by the following formula:

, where is the cost of pumping water (in ) which is a function of the lift height (in ), given that the specific weight of water (approximately ), the pumping efficiency (dimensionless, typically between 0.6 and 0.9), and the energy price (in ). The factor is used to convert energy from joules to kilowatt-hours (), as electricity prices are typically expressed in units of kilowatt-hours (USD/kWh). The energy cost of pumping water is a linear function of the lift height .

Then the total energy cost required to pump of water is given by:

Finally, based on the estimated groundwater recharge rate and the marginal cost function, I will estimate the GEP of groundwater recharge. Suppose that is the status quo water table depth in the presence of groundwater recharge. I will assume is the average depth of the water table in the watershed in the last x years (e.g., 10 years). Let be the water table depth in the absence of groundwater recharge. is obtained by subtracting the estimated groundwater recharge rate from (i.e., ). Then the value of groundwater recharge service in the watershed is estimated as the pumping cost saved due to the groundwater recharge service, which is given by the difference in pumping costs with and without groundwater recharge:

, where of water is pumped from the aquifer in watershed in that year.

# 3. Data

The InVEST SWY model requires the following data inputs: (i) Monthly precipitation (raster data), (ii) Monthly reference evapotranspiration (raster data), (iii) Digital elevation model (raster data), (iv) Land use/land cove (raster data), (v) Soil hydrologic group, and (vi) Biophysical table (.csv file). All of these data are publicly available. The data sources are summarized in Table X. The data on energy price is obtained from IEA (2019).

## 3.1 Estimate Groundwater Recharge Rate with InVEST SWY Model

In this section, I describe the data I use to estimate groundwater recharge rate with the InVEST SWY model. In the following section, I will outline the data required for running the InVEST SWY model in the bold section. Also, I provide the source of each dataset and briefly describe how the input data is prepared for the InVEST SWY model. For more details on the data preparation and how I calibrate the model parameters to the local conditions of each watershed, please see the section of Processing Steps and Calibration.

### 3.1.1 Data Inputs for InVEST SWY Model

* **Watershed Boundary (AOI) Data**
  + HydroBASINS v1 (Level 6) watershed boundary data (Lehner and Grill 2013)
  + Major aquifer boundary data from (Niazi et al. 2024)
* **Land Use/Land Cover Data**
  + LULC data is obtained from European Space Agency Climate Change Initiative land cover at 300m resolution
* **Biophysical Table Data**
  + Curve number values from GCN250 dataset (Jaafar, Ahmad, and El Beyrouthy 2019)
  + Global data of monthly crop evapotranspiration coefficient (Kc) is not available. I calculate it using the reflectance-based Kc (NDVI-Kc methods). The NDVI data is obtained from monthly data on MODIS/Terra Vegetation Indices with 0.05 degree resolution (Didan 2021). See the section of Processing Steps and Calibration for details on the NDVI-Kc methods.
* **Digital Elevation Model (DEM)**
  + Void-filled DEM data with 15 arc-seconds resolution is obtained from HydroSHEDS v1.1 (Lehner, Verdin, and Jarvis 2008).
* **Monthly precipitation and reference evapotranspiration data**
  + Daily precipitation and reference evapotranspiration data is obtained AgERA5 dataset (version 2.0) from Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (Copernicus Climate Change Servic 2020). This is gridded weather datasets with 0.1 degree resolution. For each grid cell, I calculate the monthly mean precipitation and reference evapotranspiration values.
* **Monthly Rain Events Table by Climate Zone**
  + A Rain event table is a table that contains the number of monthly rain events () for each watershed. By default, the InVEST SWY model only requires rain event table for entire watershed. However, given the spatial variation of the rainfall events, I prepare the rain event table for each climate zone within each watershed. Climate zone data is obtained from the Köppen-Geiger classification map for the period 1991-2020 downloaded from GloH2O (**Beck.etal2023?**). For each watershed, I calculate the number of monthly rain events () for each climate zone using the daily precipitation data.
* **Monthly Alpha Table**
  + Following the description in the InVEST SWY model documentation, the monthly alpha table is prepared by calculating the ratio of the previous month’s precipitation to the total precipitation for each watershed (i.e., ).
* **Soil Hydrologic Group**
  + HYSOGs250m dataset (Ross et al. 2018) is used to define the soil hydrologic groups (HSGs) for each watershed. This dataset provides the global hydrologic soil groups at 250m resolution.
* **Threshold Flow Accumulation value**
  + I derived the threshold flow accumulation value for each watershed based on the global layer of streams (HydroRIVERS v1) and a flow accumulation map. Both datasets are obtained from HydroSHEDS dataset (Lehner and Grill 2013).
* **Beta\_i Parameter**
  + For each watershed, Beta\_i Parameter is calculated from the DEM data and the flow accumulation map of that watershed. See the section of Processing Steps and Calibration for details on how to calculate the Beta\_i parameter.
* **Gamma Parameter**
  + Using the soil hydrologic group data, I set the Gamma parameter for each watershed. See the section of Processing Steps and Calibration for details on how to calculate the Gamma parameter for each watershed.

## 3.2 Calibrating the Model Parameters

In this section, I describe how I calibrate the model parameters of the SWY model to the local conditions of each watershed. The InVEST SWY model requires several parameters to be calibrated for each watershed, including the threshold flow accumulation value, the biophysical table data, Beta\_i and Gamma parameters. Although it is common to use the default values for these parameters, I calibrate them to better represent the local conditions of each watershed.

### 3.2.1 Threshold Flow Accumulation Value

Using the flow accumulation map and the global layer of streams, I computed the threshold flow accumulation value for each watershed. The threshold flow accumulation value is the minimum number of upstream cells that contribute to a stream cell. I extracted the flow accumulation value along the streams in the watershed and used the 25th percentile of the flow accumulation values as the threshold value. 25th percentile is used to avoid the outliers in the flow accumulation values.

### 3.2.2 Biophysical Table Preparation

Biophysical table data for the InVEST SWY model requires soil-group specific curve numbers and monthly crop evapotranspiration coefficient (Kc) values for each land use/land cover (LULC) class. There is no single numbers for the curve number and Kc values for global scale. To account for the heterogeneity of the curve number and Kc values across regions, I calibrate the biophysical table data for each watershed.

For watershed-specific curve numbers, I use the GCN250 dataset (Jaafar, Ahmad, and El Beyrouthy 2019). GCN250 dataset provides the gridded data of curve numbers for global scale at 250m resolution. Using the GCN250 dataset, the map of soil hydrologic groups (HYSOGs250m), and the LULC data for the watershed, I calculated the mean values of curve numbers for each soil group and LULC class.

Global Kc values are not available nor there is no consensus on the Kc values for each of the various land use/land cover classes. However, it is safe to assume that the Kc values for some land use/land cover classes are constant and similar across months and regions. For example, the Kc values for evergreen forests, grasslands, and wetlands are generally constant throughout the year.

Therefore, I use constant Kc value for land use/land cover classes including including evergreen forest, deciduous forest, shrublands, urban, bare ground, snow/ice, and open water. These constant Kc values are borrowed from the previous studies (Allen et al. 1998; Liu et al. 2017). Meanwhile, for the other land use/land cover classes such as rainfed or irrigated cropland and deciduous forests, the Kc values vary by month. For these classes, I calculate the monthly Kc values using the reflectance-based Kc (NDVI-Kc methods). This reflectance-based Kc method is widely used in the previous studies to estimate the Kc values for various land use/land cover classes (e.g., Bausch (1995); Choudhury et al. (1994); Glenn, Nagler, and Huete (2010); (**Kamble.etal2023?**); (**Rayes-Gonzalez.etal2015?**)). Following the previous studies, I calculate the monthly Kc values for each LULC class using the NDVI-Kc methods. The monthly NDVI data is obtained from the MODIS/Terra Vegetation Indices with 0.05 degree resolution (Didan 2021).

With NDVI data, Kc value is calculated using the following equation (Bausch 1995):

### 3.2.3 Beta\_i and Gamma Parameters

Another parameter that needs to be calibrated for each watershed is the Beta\_i and Gamma parameters. The Beta\_i parameter in the SWY model represents the fraction of upgradient water subsidy that is available for evapotranspiration at a given location. Following the description in the InVEST SWY model documentation, Beta\_i parameter is calculated as the topographic wetness index (TWI):

, where is upstream contributing area (i.e. A = flow accumulation cell area, in ) and is the slope in radians. is calculated from the flow accumulation map. The slope is calculated from the DEM data using the terrain function in the terra R package. After deriving TWI for each grid cell of the DEM data, I calculate the mean TWI value within each watershed. This mean TWI value is used as the watershed-specific Beta\_i parameter for each watershed in the SWY model to represent the average topographic subsidy available to each watershed.

The Gamma parameter controls how much of the water recharge is made available to the downgradient pixels. Gamma = 0 means that no water moves downgradient from the pixel, while Gamma = 1 means that all local recharge becomes available to downgradient pixels. This parameter is set to 1 by default in the SWY model. However, I set the Gamma parameter for each watershed based on the soil hydrologic group raster data, which is one of the input data for the SWY model as described above. This raster dataset classifies each grid cell into one of four USDA-defined hydrologic soil groups: A (group 1), B (2), C (3), and D (4). As the group number increases, soils become more impermeable, with Group A having the highest infiltration rates and Group D having the lowest.

Given this gradient in lateral subsurface connectively, I assigned following Gamma values to each group: 0.95 for Group A, 0.85 for Group B, 0.75 for Group C, and 0.55 for Group D. Then, for each watershed, I calculated an area-weighted average of these Gamma values based on the fractional coverage of each soil group. The resulting watershed-specific Gamma values are used as input to the SWY model to better represent spatial differences in subsurface flow connectivity.

# 4. Limitations and Future Work

While I use the cost of pumping water from the aquifer to the surface as a proxy for the value of groundwater recharge service, the decreasing water table can also lead to other adverse economic consequences in other forms. For example, the declining water table decreases the well yield (i.e., the amount of water that can be pumped from a well per unit time). In the context of agricultural production that depends on irrigation, this can lead to reduce crop yields, as farmers may not be able to satisfy the water demand of their crops in a timely manner. The loss of productivity and the consequential income loss is not captured in the current analysis.

# 5. References

Acharya, Gayatri, and Edward B. Barbier. 2000. “Valuing Groundwater Recharge Through Agricultural Production in the Hadejia-Nguru Wetlands in Northern Nigeria.” *Agricultural Economics* 22 (3): 247–59. <https://doi.org/10.1111/j.1574-0862.2000.tb00073.x>.

Allen, Richard G, Luis S Pereira, Dirk Raes, and Martin Smith. 1998. “Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements-FAO Irrigation and Drainage Paper 56.” *Fao, Rome* 300 (9): D05109.

Bausch, Walter C. 1995. “Remote Sensing of Crop Coefficients for Improving the Irrigation Scheduling of Corn.” *Agricultural Water Management* 27 (1): 55–68. <https://doi.org/10.1016/0378-3774(95)01125-3>.

Brauman, Kate A., David L. Freyberg, and Gretchen C. Daily. 2015. “Impacts of Land-Use Change on Groundwater Supply: Ecosystem Services Assessment in Kona, Hawaii.” *Journal of Water Resources Planning and Management* 141 (12): A4014001. <https://doi.org/10.1061/(ASCE)WR.1943-5452.0000495>.

Choudhury, Bhaskar J, Nizam U Ahmed, Sherwood B Idso, Robert J Reginato, and Craig S. T Daughtry. 1994. “Relations Between Evaporation Coefficients and Vegetation Indices Studied by Model Simulations.” *Remote Sensing of Environment* 50 (1): 1–17. <https://doi.org/10.1016/0034-4257(94)90090-6>.

Copernicus Climate Change Servic. 2020. “Agrometeorological Indicators from 1979 to Present Derived from Reanalysis.” Copernicus Climate Change Service (C3S) Climate Data Store (CDS). <https://doi.org/10.24381/cds.6c68c9bb>.

Deng, Haoyu, Chengmin Li, Tong Chen, Yulan Song, and Jian Cao. 2025. “Valuing the Ecological Products of Wetlands and Strategies for Implementation: A Case Study of Weishui Wetland in Songzi City, Hubei Province.” *Polish Journal of Environmental Studies* 34 (3): 2627–45.

Didan, Kamel. 2021. “MODIS/Terra Vegetation Indices Monthly L3 Global 0.05Deg CMG V061.” NASA Land Processes Distributed Active Archive Center. <https://doi.org/10.5067/MODIS/MOD13C2.061>.

Glenn, Edward P., Pamela L. Nagler, and Alfredo R. Huete. 2010. “Vegetation Index Methods for Estimating Evapotranspiration by Remote Sensing.” *Surveys in Geophysics* 31 (6): 531–55. <https://doi.org/10.1007/s10712-010-9102-2>.

IEA. 2019. “Energy Prices and Taxes.” *IEA, Paris* 2019 (1).

Jaafar, Hadi H., Farah A. Ahmad, and Naji El Beyrouthy. 2019. “GCN250, New Global Gridded Curve Numbers for Hydrologic Modeling and Design.” *Scientific Data* 6 (1): 145. <https://doi.org/10.1038/s41597-019-0155-x>.

Joshi, Anil Prakash, Shivam Joshi, Ramesh Kumar Sudhanshu, Durgesh Pant, Sushil Rai, Atul Rawat, and Himani Purohit. 2025. “Deciphering Uttarakhand’s Human Efforts Towards the Ecology Through Gross Environment Product (GEP) Calculations.” *Environmental and Sustainability Indicators* 25: 100578.

Lehner, Bernhard, and Günther Grill. 2013. “Global River Hydrography and Network Routing: Baseline Data and New Approaches to Study the World’s Large River Systems.” *Hydrological Processes* 27 (15): 2171–86. <https://doi.org/10.1002/hyp.9740>.

Lehner, Bernhard, Kristine Verdin, and Andy Jarvis. 2008. “New Global Hydrography Derived From Spaceborne Elevation Data.” *Eos, Transactions American Geophysical Union* 89 (10): 93–94. <https://doi.org/10.1029/2008eo100001>.

Liu, Chunwei, Ge Sun, Steven G. McNulty, Asko Noormets, and Yuan Fang. 2017. “Environmental Controls on Seasonal Ecosystem Evapotranspiration/Potential Evapotranspiration Ratio as Determined by the Global Eddy Flux Measurements.” *Hydrology and Earth System Sciences* 21 (1): 311–22. <https://doi.org/10.5194/hess-21-311-2017>.

Naggar, Osman Mohammed. 2003. “Analysis of Groundwater Production Cost.” In *Seventh International Water Technology Conference, Cairo*, 1–3. Citeseer.

Niazi, Hassan, David Watson, Mohamad Hejazi, Catherine Yonkofski, Stephen Ferencz, Chris Vernon, Neal Graham, Thomas Wild, and Jim Yoon. 2024. “Global Geo-processed Data of Aquifer Properties by 0.5 Grid, Country and Water Basins.” MultiSector Dynamics - Living, Intuitive, Value-adding, Environment. <https://doi.org/10.57931/2307831>.

Ouyang, Zhiyun, Changsu Song, Hua Zheng, Stephen Polasky, Yi Xiao, Ian J. Bateman, Jianguo Liu, et al. 2020. “Using Gross Ecosystem Product (GEP) to Value Nature in Decision Making.” *Proceedings of the National Academy of Sciences* 117 (25): 14593–601. <https://doi.org/10.1073/pnas.1911439117>.

Pacetti, Tommaso, Marco Lompi, Giovanna Panza, Alessandro Bosso, Marco Monaci, Giovanni Pasini, and Riccardo Santolini. 2024. “Gross Ecosystem Product as a Measure of Natural Capital Value: An Italian Experience.” *Earth Systems and Environment*, October. <https://doi.org/10.1007/s41748-024-00492-z>.

Ross, C. Wade, Lara Prihodko, Julius Anchang, Sanath Kumar, Wenjie Ji, and Niall P. Hanan. 2018. “HYSOGs250m, Global Gridded Hydrologic Soil Groups for Curve-Number-Based Runoff Modeling.” *Scientific Data* 5 (1): 180091. <https://doi.org/10.1038/sdata.2018.91>.

Winter, Thomas C. 2000. *Ground Water and Surface Water: A Single Resource*. DIANE Publishing.