Ecosystem Service: Groundwater Recharge Service, a Regulating Service

# 1. Introduction

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.

In the past GEP studies, groundwater recharge service is often treated as a part of broader categories of hydrological services such as water provisioning service or flood regulation service. 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., Pacetti et al. (2024); Deng et al. (2025); Joshi et al. (2025)). Meanwhile, there are some studies some agricultural economics and hydrology studies that focus on valuing groundwater recharge service as a regulating service. Acharya and Barbier (2000) is one of a few studies that explicitly value groundwater recharge service per se. They quantify the value of groundwater recharge as a regulating service focusing on its role in 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. This study aims to provide a global-scale assessment of the value of groundwater recharge service as a regulating service. Specifically, I focus on the role of groundwater recharge in stabilizing aquifer levels, which has received limited attention in the previous GEP studies. This regulating service of groundwater recharge is important from the perspective of human well-being, as it helps maintain (or slow) the long-term decline of groundwater levels, thereby avoiding increased pumping costs to extract groundwater and circumventing 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 the value of groundwater recharge regulating 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?”*. 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

This section describes the methods used to estimate the GEP of groundwater recharge service as a regulating service. To derive the cost savings in pumping water due to groundwater recharge, I need information on the unit cost of pumping groundwater to the surface. Given the lack of such data globally, I rely on the engineering formula to approximate it (Naggar 2003). The energy cost of pumping a unit volume of water (in ) is given by the following equation[[1]](#footnote-21):

, where is the total head (in ), is the specific weight of water (approximately )[[2]](#footnote-22), is the pumping efficiency (a value between 0 and 1), and is the energy price (in ). The pumping efficiency means how much of the energy is actually consumed for lifting water. Although it is likely that pumping efficiency varies by region depending on the type of pumping system used, there is no global information on regional values of pumping efficiency. Here, I assume a uniform pumping efficiency of based on FAO’s reference value for pumping efficiency of motor driven pumps (Phocaides 2007). 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). Given a price of electricity price in , the energy cost of pumping water is described as a linear function of the total head .

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

Let be the total head when recharging does not occur, and be the total head when recharging occurs. Total head is the sum of the vertical distance from pump to static water level (i.e., depth to static water table, ) and the additional head loss due to friction in the pipes (i.e., drawdown and friction loss, ). Assuming that the friction loss is constant regardless of the pumping (i.e., and ), the difference in total costs to pump of water in the presence and absence of groundwater recharge is given by:

, where is the change in the depth to the water table due to groundwater recharge. The necessary information to compute the cost savings in pumping water associated with groundwater recharge includes (i) the change in the depth to the water table due to groundwater recharge (), (ii) the volume of water pumped (), and (iii) the coefficient , which depends on the energy price (). For the volume of water pumped (), I use the country-level groundwater withdrawal data for all sectors downloaded from FAO-AQUASTAT Core Database (FAO 2019). The country-level price of electricity is obtained from the International Energy Agency (IEA) report (IEA 2019). To estimate , I use the InVEST Seasonal Water Yield (SWY) model. The next section describes the data sources for the SWY model and the calculation of some key watershed-specific parameters for the SWY model.

# 3. Data for InVEST SWY Model Inputs and Parameters

Due to the lack of data on actual measurement of natural groundwater recharge rate globally in 2019, 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. The local recharge in the SWY model indicates the amount of net rainfall that infiltrates into the soil beyond the root zone. Given that it is the amount of water that is not used by evapotranspiration and runs off as surface water, it is a reasonable proxy for the amount of water that percolates down to the groundwater system, thus representing the natural groundwater recharge rate. Although it is possible that some portion of the local recharge may be lost through lateral subsurface flow before reaching the groundwater system, there is no global data on such information. Thus, for simplicity, I assume that all water classified as local recharge in the SWY model eventually contributes to groundwater recharge.

I conduct the analysis on a watershed scale, which 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. I restrict the analysis to watersheds that intersect regions with observed groundwater dependence for human use (e.g., domestic, agricultural, and industrial uses). To identify these watersheds, I use the global estimates of groundwater withdrawal for agricultural, domestic, and industrial sectors developed by Nazari, Reinecke, and Moosdorf (2025). I overlay the groundwater raster with HydroBASINS v1 Level 6 watershed boundaries (Lehner and Grill 2013), and select only those watersheds that intersect at least 20 percent of grid cells with strictly positive groundwater withdrawals. 20 percent threshold is chosen because it provides a reasonable balance between including watersheds that are significantly influenced by groundwater withdrawals and excluding those with minimal or negligible groundwater use. Also, this threshold gives a reasonable coverage of watersheds that are likely to be dependent on groundwater resources for human use. In total, I identify 11,528 watersheds globally that meet this criterion. [Figure 1](#fig-map-watersheds) shows the watersheds selected for the analysis.

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| Figure 1: Watersheds selected for the analysis |

[Table 1](#tbl-data-source) summarizes the sources of major input data used for watershed-scale estimation of groundwater recharge rate using the InVEST SWY model. Other than the inputs listed in the table, the SWY model also requires some important parameters including biophysical table data, threshold flow accumulation value, Beta\_i parameter, and Gamma parameter. Although it is common to use the default values for these parameters, I use watershed-specific values for these parameters to better represent the local conditions of each watershed. The following sections describe how I prepare these watershed-specific parameters for the SWY model.

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| Table 1: Data sources for major inputs for the InVEST SWY model   | **InVEST input name** | **Source** | **Note** | | --- | --- | --- | | Area of Interest | HydroBASINS Level 6 from HydroSHEDS v1 (Lehner and Grill, 2013) | Groundwater withdrawal data (Nazari et al., 2025) will be also used to select watersheds of interest. | | Digital Elevation Model (DEM) | Void-filled DEM from HydroSHEDS v1 (Lehner et al., 2008) |  | | Land Use / Land Cover (LULC) | ESA CCI Land Cover (https://planetarycomputer.microsoft.com/dataset/esa-cci-lcc) |  | | Soil Hydrologic Group | HYSOGs250m v1 (Ross et al., 2018) |  | | Monthly precipitation | AgERA5 daily precipitation (Copernicus Climate Change Service, 2019) | Aggregated to monthly by watershed; used for monthly alpha table and precipitation events by climate zone. | | Monthly reference ET0 | AgERA5 daily Penman–Monteith ET0 (Copernicus Climate Change Service, 2019) | Aggregated to monthly by watershed. | | Climate zone map | Köppen–Geiger 1991–2020 (Beck et al., 2022) | Used to estimate precipitation event frequency by climate zone. | |

## 3.1 Threshold Flow Accumulation Value

To determine the Threshold Flow Accumulation (TFA) parameter required by the InVEST Seasonal Water Yield model, I combined a flow accumulation raster data from HydroSHEDS Core layers (v1) and observed stream network from HydroRIVERS (v10) (Lehner and Grill 2013)

I rasterized the stream polylines to the flow-accumulation grid and identified channel head cells—stream pixels with exactly one neighboring stream cell. I then extracted the flow-accumulation value at each channel head, representing the upstream contributing area where mapped channels begin to form. The median of these headwater flow-accumulation values (expressed in number of pixels) was used as the watershed’s TFA. This threshold defines the number of upslope cells required for a pixel to initiate a stream in the InVEST model and ensures consistency between the modeled and observed drainage networks.

## 3.2 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 watersheds, I prepare watershed-specific biophysical table data for each watershed used in the analysis.

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, and the LULC data for the watershed, I calculated the mean values of curve numbers for each soil group and LULC class within each watershed boundary. These mean curve number values are used as the watershed-specific curve numbers for each LULC class and soil hydrologic group in the SWY model.

As for global Kc values, although there is no consensus on the Kc values for each of the various land use/land cover classes, 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 (e.g., rainfed or irrigated cropland and deciduous forests), the Kc values can vary by month. For those 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, Kilic, and Hubbard (2013); Reyes-Gonzalez et al. (2015)). 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, monthly Kc values are calculated using the following linear equation (Bausch 1995):

## 3.3 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 (default value in the SWY model). 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 (group 2), C (group 3), and D (group 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.

## 3.4 Results and Discussion

# 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

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1. Technically, 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, I will focus only on the energy cost of pumping water. [↑](#footnote-ref-21)
2. , where is the density of water () and is the acceleration due to gravity (). So , [↑](#footnote-ref-22)