# Groundwater Recharge and Evapotranspiration: Fluxes at the Interface of Water, Energy, Biogeochemical and Human Systems

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1. **What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming Decade?**

Humans have altered the landscape by changing the vegetation cover over centuries but with increasing intensity over the latest decades. As a result two of the most critical fluxes in the water cycle have already changed by orders of magnitude. **Recharge to aquifers** and **evapotranspiration** from the landscape are two fluxes that are most dramatically changed in the historical era as a result of human alteration of the landscape.

Understanding how recharge and evapotranspiration have already changed and what consequences their changes have on: **1) sustainability of aquifers, 2) crop productivity, 3) ecosystems health and 4) climate** are priority questions in Earth System Science. Despite the importance of these fluxes and their historical change, there are no direct measurements – in situ or by remote sensing - that can allow any mapping or any global or regional estimation.

> **NRC (1999):** ***Hydrologic Science Priorities for the U.S. Global Change Research Program***
>
> … Evaporative flux linking the surface and atmospheric systems and the recharge flux linking the surface and subsurface systems are two key components of the hydrologic cycle that are poorly understood and are very poorly monitored. It is imperative that the characterization of these two fluxes be recognized as grand challenges for hydrologic science…

Because evapotranspiration and recharge are also key conduits for biogeochemical substances, they are also critical to Earth's biogeochemical cycles.

> **Bondeau et al.,** ***Global Change Biology*** **(2007)**
>
> Agriculture profoundly affects global carbon, water and nutrient cycles, as well as the planetary surface energy balance… Accounting for croplands, pastures and rangelands, nearly 50% of the potentially vegetated land surface has been affected by agriculture."

Evapotranspiration and recharge can *amplify* changes in precipitation and radiative forcing. Small changes in the magnitude, seasonality and intermittency of precipitation and radiation can be magnified in the recharge and evapotranspiration signals. As a result, the future of these two critical fluxes under a changing atmospheric composition may be even more uncertain.

Given:

- the central role of recharge and evapotranspiration in the global water, energy and biogeochemical cycles,
- the need to quantify and map the rate of sustainable aquifer use,
- the importance of the these fluxes to the health of natural and agricultural ecosystems,
- the already-realized several-fold changes in these fluxes through human alterations of the landscape,
- the potential for amplified change in these fluxes under climate change,
- the paucity – or total lack – of any direct estimates of these fluxes regionally and globally,

understanding recharge to aquifers, evapotranspiration and their linkages is a grand challenge for Earth System Science in the coming decade.

2. **Why are these challenge/questions timely to address now especially with respect to readiness?**

Recharge and evapotranspiration fields have already changed, often by large magnitudes. The rates and spatial patterns continue to change as humans further modify the physical landscape and alter the vegetation cover. Basic questions include:

*What are the rates of change of evapotranspiration and recharge?*

These rates remain unaddressed and essentially unknown. Even the climatology of these two critical fluxes is unknown other than as residual of differences between other fluxes.

To understand their historical change, current state and future outlook, a more complete understanding of the processes that drive variations in these fluxes is essential.

*How do the rates of evapotranspiration and recharge respond to human alterations to the physical landscape and vegetation cover and to shifts in climate and its seasonality?*

These changes remain as gaps in our knowledge of how the Earth System works. Understanding them is essential if we are to become better stewards of the terrestrial biosphere that we have appropriated so pervasively.

Recharge and evapotranspiration fluxes can experience changes that amplify shifts in the precipitation and radiation forcing. Knowledge of changes in their magnitude and regional patterns in the future are critical to understanding the impacts of climate change.

**Miralles et al., *Hydrology and Earth System Science* (2011)**

Evaporation remains one of the biggest unknowns within the global water balance. Improved representation of its global dynamics is essential to lead to a better understanding of the expected acceleration of the hydrological cycle.

*How do the rates of evapotranspiration and recharge respond to changes in precipitation and radiation forcing?*

These rates are not understood and they are a source of uncertainty in assessment of climate change impacts.

### 3. Why are space-based observations fundamental to addressing these challenges/questions?

Recharge and evapotranspiration are fluxes at the land-atmosphere interface. Their spatial variations are strongly related to soil type, topography, vegetation and climate. Their dynamics are affected by the variations in plant growth, weather and seasonal climate. To adequately characterize them mapping at tens to hundreds of meters and temporal sampling at days to a week are needed at minimum. Also as fluxes they cannot be directly sensed as they do not uniquely correspond to the thermal or dielectric state of the soil and the vegetation at one level. Rather they are controlled by vertical and temporal gradients of state variables.

Soil moisture is the fundamental state variable that directly controls both recharge and evapotranspiration. Vertical gradients in soil moisture drive recharge and regulate evapotranspiration. Vertical profiles of soil moisture need to be measured in order to allow estimation of these fluxes. *In situ* monitoring is not a viable approach for collecting the required data. Observations are needed that span large areas, but installing and maintaining instrumentation at even a single site is costly and challenging.

Space-based observations can provide the necessary data, as long as the sensing system includes three key attributes. The first attribute

#### Facts Box

**Recharge** and **evapotranspiration are:**

1. **Fluxes that are first-order determinants of biogeochemical cycles**. Water is the ultimate solvent and recharge and evapotranspiration are the circulatory system of biogeochemicals in the Earth System
2. **Fluxes that link the slow and fast components of the water cycle**. The atmosphere water vapor residence-time is about 9 days, the average residence-time of water in the land subsurface is about 8 years and the residence-time of water in the oceans is about 2500 years. Nevertheless they together constitute the global water cycle with evapotranspiration and recharge among the fluxes that link the storage components.
3. **Fluxes that to first-order determine and to first-order are determined by vegetation distribution**. Where vegetation grows is influenced by the availability of water and the trade-off between evaporative and recharge losses. At the same time, the rate of recharge and the rate of evapotranspiration are determined by vegetation species and its health status. The fluxes and the vegetation distribution are intimately linked and each is a first-order determinant of another.
4. **Fluxes that limit rate of sustainable use of surface waters and groundwater aquifers**. The rate at which we can pump water out of freshwater aquifers in a sustainable way is the recharge rate. Remarkably this flux has a shared definition in both Earth System Science and in water resources management practice.
5. **Fluxes that have most dramatically changed already in response to human activity**. Over the recent historical period, human alteration of the physical landscape and transformation of terrestrial ecosystems have resulted in changes in recharge and evapotranspiration that are several-fold and possibly orders-of-magnitude. We need to understand the past history of changes in these critical fluxes, assess their current state and project their prospects under a changing climate. This knowledge is fundamental to understanding the metabolism of the Earth System and its linked cycles and to the rational management of our agricultural and water resources systems.

of the appropriate sensing system is observations at multiple wave frequencies to probe multiple depths. Multi-frequency with varying penetration depth into the soil will provide vertical profiles of soil moisture. A second attribute of the appropriate sensing system is defined by the need to sense the interface across which these fluxes are occurring. The atmosphere and the vegetation canopy that stands in between a space-borne sensor and the flux interface needs to be as transparent, or at least quantifiable, as possible. This consideration leads to the selection of low-frequency microwave bands (L-band and below) for the multi-frequency-channel system. A final set of attributes of the appropriate sensing system is that it should have both sensitivity and resolution. Sensitivity is required if gradients in states and not the states themselves are the basis for estimation. Spatial resolution is required since the variations in soil type, topography, solar aspect and vegetation that drive recharge and evapotranspiration occur on a wide spectrum of spatial scales. The sensitivity and resolution requirements lead to the selection of combined active and passive low-frequency microwave sensors.

Therefore a desirable space-based sensors should be: 1) multi-channel, 2) low-frequency microwave, 3) active (radar) and passive (radiometer). A sensor package that combines all of these attributes is L- and P-band active passive. There is considerable air-borne and some space-borne heritage for such instruments, and their capabilities for sensing the relevant surface and root zone states have been demonstrated.

**a) Whether existing and planned U.S. and international programs will provide the capabilities necessary to make substantial progress on the identified challenge and associated questions. If not, what additional investments are needed?**

Several space programs, including JAXA's PALSAR-2 (L-band active), NASA's SMAP (L-band active passive), NASA/ISRO's NISAR (L-/S-band Active), ESA's Biomass (P-band active) and CONAE's SAOCOM (L-band active), are operational or in the development phase. They address individual observation capabilities, but not the combined multifrequency (L-/P-band) active passive observation requirements. The ESA Biomass mission P-band radar revisit rates are only seasonal. They are appropriate for biomass mapping but not for capturing surface water balance dynamics. The L-band SAR missions also have revisit rates of tens of days. The future combined L-/P-band system will require an operations concept that covers a wide swath for frequent revisit. A space system study is required to determine the architecture of a space-based sensing system for the multi-frequency active-passive observation requirement and to identify required technology development.

An active-passive L-/P-band system would also support continuity of surface soil moisture estimation using the NASA SMAP and ESA SMOS missions. Soil moisture is the state variable of the land branch of the water cycle. It has temporal variations ranging from weather to interannual. Long climate records are needed to characterize the variability of the water, energy and carbon cycles as affected by the soil moisture state. L-band radiometry of the Earth System has been continuous since 2009. The active-passive L-/P-band system will not only support the needed climate record but also enhance the capability for deeper sensing of the soil column that is more representative of the land branch of the water cycle. The system will also support higher spatial resolution to capture the heterogeneities induced by variations in topography, vegetation type, soil texture and precipitation intermittency.

**b) How to link space-based observations with other observations to increase the value of data for addressing key scientific questions and societal needs?**

The fluxes are related to gradients in the thermal and moisture (dielectric) states but nevertheless physics and factors related to the soil and vegetation properties need to be used as constraints in the retrieval from space-based observations. This means that a model value-added or data assimilation approach needs to be used in order to realize the science of the proposed set of space-borne measurements. To realize the societal benefits of the new knowledge, the retrievals have to be linked to observations of human-managed systems. The recharge fields need to be interpreted in the context of aquifer water-level observations. Crop productivity and yield information should be interpreted side-by-side with the evapotranspiration field estimates.

**c) The anticipated scientific and societal benefits; and**

The recharge rate is exactly the rate of the sustainable use of subsurface aquifers. This hydrologic flux is unique in that it has the same definition in an Earth System Science context and in operational water resources management. Evapotranspiration is the link between the water, energy and biogeochemical cycles at the land-atmosphere interface. Variations in the land branch of these three fundamental cycles of the Earth System would be essentially independent if it were not for the evapotranspiration flux that links the three. Understanding how the Earth System works and projections of how its metabolism will evolve in a changing climate necessitates that we capture the covariations of its three fundamental cycles. Ecosystem productivity – biomass accumulation and net Carbon exchange – is dependent on the evapotranspiration flux and its determinants. Similarly the productivity of agroecosystems that feed humans and their livestock depends on this flux. Knowledge of this flux, understanding its determinants, and assessing its vulnerability to climate change are the rational bases for managing human systems that depend on the environment and for charting a more sustainable future.

**Crosbie et al. ,*Water Resour. Res* (2013)**

Considering that past climate changes have significantly impacted groundwater resources, quantitative predictions of climate change effects on groundwater recharge maybe valuable for effective management of future water resources.

**Jasechko et al.,** ***Water Resources Research (2012)***

…The reversal of current nonsustainable groundwater extraction rates will require setting long-term pumping rate goals that will achieve a balance with groundwater recharge and ecosystem groundwater requirements. To determine sustainable groundwater pumping rates requires accurate estimates of groundwater recharge rates and thorough understanding of

**d) The science communities that would be involved.**

> **NRC (2004) *Groundwater Fluxes Across Interfaces***
>
> … Finding 1. Our ability to quantify spatial and temporal variability in recharge and discharge is inadequate and must be improved given the importance of groundwater in the hydrologic cycle….
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> Finding 2. The roles of groundwater storage, and recharge and discharge fluxes in the system are under-appreciated and poorly understood.

Evapotranspiration and recharge are fluxes across *the critical zone* and *at the interfaces* of the Earth System cycles including human systems. In order to tackle the grand challenge of understanding the past history, current state and future prospects of these fluxes, the science community from all the linked cycles and systems need to provide input. The organization and structure of the study needs to balance: 1) the formation of smaller groups and panels that can make progress, and 2) avoid the artificial division of the Earth System along historical science community boundaries that is backward-looking. The formation of panels along cycles ensures that communities from all components of that cycle assemble together and discuss priorities.

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