Defining renewable groundwater use and its relevance to sustainable groundwater management

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Abstract

Groundwater systems are commonly, but variously, defined as renewable or non-renewable based on natural fluxes of recharge or on estimates of aquifer storage and groundwater residence time. However, we show here that the principle of capture challenges simple definitions so that a groundwater system cannot be renewable or non-renewable in and of itself, but only with reference to how the groundwater is being used. We develop and propose more hydraulically-informed definitions for flux-renewable and storage-renewable groundwater use, and a combined definition that encompasses both the flux-based and storage-based perspectives such that: *renewable groundwater use allows for dynamically stable re-equilibrium of groundwater levels and quality on human timescales*. Further, we show how a matrix of combinations of (1) the ratio of pumping to possible capture along with (2) the response or recovery timescales implicit in this definition, leads to a useful four-quadrant framework for characterising groundwater use, illustrated using case studies from aquifers around the world. Renewable groundwater use may inform pathways to groundwater sustainability, which encompasses a broader set of dimensions (e.g. socio-political, economic, ecological and cultural) beyond the scope of groundwater science. We propose that separating physically robust definitions of renewable groundwater use from the inherently value-based, normative language of sustainability, can help bring much needed clarity to wider discussions about sustainable groundwater management strategies, and the role of groundwater science and scientists in such endeavours.

1. Motivation

As the largest store of accessible freshwater on Earth, groundwater is under increasing pressure as a resource since it a large proportion of irrigated agriculture worldwide and is the source of drinking water for around 2 billion people (Famiglietti, 2014). Over-abstraction of groundwater can harm groundwater-dependent ecosystems and cause groundwater salinization, increased frequency and severity of hydrological drought, land subsidence, and sea-level rise (Bierkens & Wada, 2019). Clear conceptual thinking and robust quantification of groundwater management options are necessary precursors, among other considerations, to inform sustainable groundwater use. However, it is increasingly clear that existing definitions and metrics of large-scale groundwater use are inconsistent and confusing which can undermine this goal (Ferguson *et al.*, 2020; Gleeson *et al.*, 2020).

There has been much deliberation in the literature on the issue of groundwater sustainability (for a comprehensive review see Mace (2022)). However, there have been noticeably fewer attempts to articulate what renewability means in the context of groundwater resources. Since Wood (2001) proposed *"that we recast the value-laden sustainability concept as "renewability" and address this better-constrained concept in scientific terms"*, we are unaware of any attempt to rigorously do so. Here we therefore aim to define more clearly the notion of renewable groundwater use from a groundwater science perspective, and how this concept relates to the distinct albeit related notion of groundwater sustainability. This is not just a semantic exercise: identifying paths toward robust groundwater management depends on defining clear goals, and recent research has shown how a clarification of terms is important to resolve existing inconsistency and confusion between other scientists, managers, policy makers and stakeholders (Rudestan & Langridge, 2014; Mace, 2022).

To begin, we address the question of whether groundwater is in fact a renewable resource and use a simple thought experiment to propose new definitions of renewable groundwater use. We then show how this leads naturally to a four-quadrant framework for characterising groundwater resource use that is illustrated with reference to case studies from aquifers around the world. Finally, we discuss how renewable groundwater use fits within a broader understanding of groundwater sustainability and how the quadrant framework presents challenges and opportunities for further developments to map groundwater management pathways.

2. Is groundwater a renewable resource?

We first question whether the common assumption that groundwater is a renewable resource is a sound one. It is instructive to begin by considering how a 'renewable resource' can be defined in more general terms as:

> *"A natural resource (such as fresh water, a forest, or renewable energy) that is replaced at a rate which is at least as fast as it is used, which has the ability to renew itself and be harvested indefinitely under the right conditions, but which can be converted into a non-renewable resource if subject to overexploitation."*

(Park & Allaby, 2017)

Hidden in a general definition of renewable natural resources such as this, is an implicit amalgamation of two distinct modes of resource use. First, there is the direct capture or abstraction of a *flux* of energy or matter. For example, this is the case for solar or wind energy which, while they may be used in conjunction with energy storage devices, essentially exploit the flux of photons or wind and convert them to other forms of useable energy at the point of capture. Renewability of some surface water resources can also be conceived in this ‘flux-based’ way, for instance where the capture of streamflow flux is used directly (e.g. for irrigation) or stored artificially for later use (e.g. in a reservoir). In contrast, other natural resources have a much greater propensity for natural *storage*, and it is predominantly the ‘stock’ of the resource which is allowed to accumulate and then be harvested or abstracted for human use. For example, such ‘storage-based’ definitions of renewability may be applicable in this way to forestry or fisheries, or large-volume surface water bodies such as lakes.

Groundwater flows, albeit slowly, but the recharge fluxes involved cannot be captured directly as for other ‘flux-based’ natural resources, aside from at locations of natural springs. Rather, groundwater must be pumped out of the ground at discrete points in a landscape via wells which are often very expensive to drill and maintain. The infrastructure required for the abstraction of groundwater is immobile (for example, in comparison to forestry or fishery harvesting), but groundwater is ‘captured’ from areas well away from the locations of the abstractions themselves. Furthermore, as we elaborate further below, the timescales of groundwater storage depletion are not solely determined by the rate of use and can span several orders of magnitude. Hence, groundwater does not easily fit into either a flux-based or storage-based categorisation as used for other types of resources. As a consequence, renewable groundwater has therefore previously been defined in several contradictory ways that are discussed below and are summarised in Figure 1.

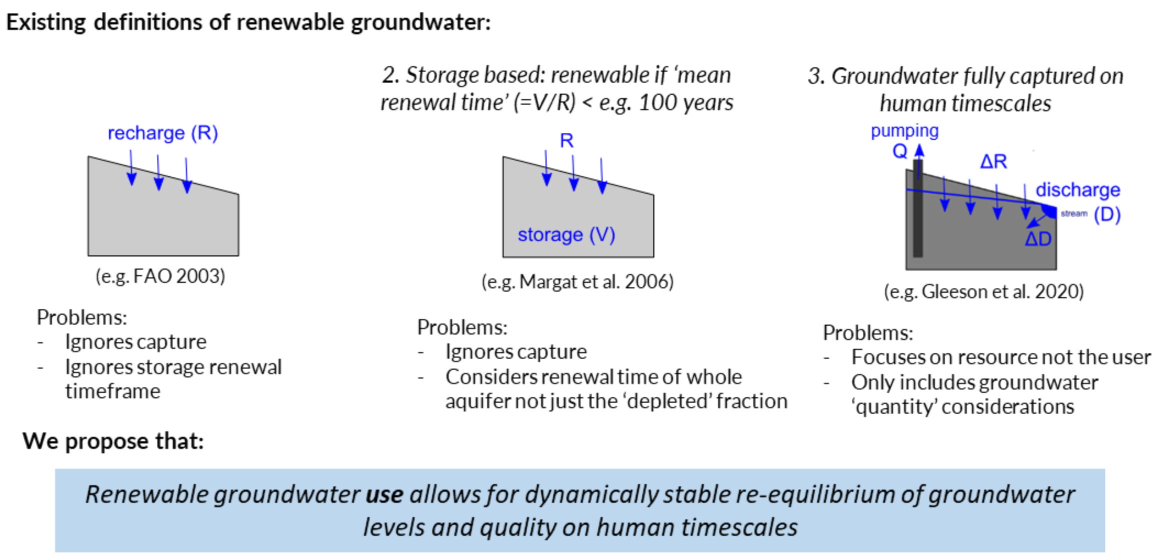

Figure 1. *Evolving definitions of groundwater renewability. We develop our proposed definition in Section 4 below. Parameters are all defined briefly in the figure and in more detail in Section 3. See FAO (2003), Margat et al. (2006), and Gleeson et al. (2020) for more detail of each definition, and the text for more description of the problems we perceive with each definition.*

As outlined in detail by Gleeson *et al.*, 2020, flux-based definitions equate renewable groundwater with the rate of (pre-pumping) natural recharge (Döll & Fiedler, 2008; Wada *et al.*, 2010). This is a potentially useful, conservative and clear definition but will be inevitably incorrect, equating to the minimum likely capture, unless it includes the principle of increased recharge occurring during capture (Theis, 1940; Lohman, 1972). These principles are outlined in detail in the next section since capture is a fundamental process to include in considerations of groundwater renewability. Flux-based definitions of renewable groundwater are convenient for integrated water resources management since they are readily combined with renewable surface water resources which are almost always defined using streamflows (Vörösmarty *et al.*, 2000; Alcamo *et al.*, 2003). However, when combined, they must not be double counted, and the overlaps between internally generated recharge and streamflow must be carefully accounted (Food and Agriculture Organization of the United Nations, 2003).

Storage-based approaches, on the other hand, define renewable or non-renewable groundwater using a threshold value of mean renewal time, normally defined as the ratio of groundwater storage (V in Figure 1) to the (pre-pumping) recharge rate (R in Figure 1) (Margat *et al*. 2006). Again, in this definition, the principle of capture is often ignored but, more problematically, the logic of defining renewability in this way may be questionable from a hydraulic perspective. For example, it implies that groundwater in a larger aquifer receiving the same recharge flux as a smaller aquifer is inherently less renewable. This appeals to the commonly held perception that older groundwater may be less renewable, but as has been outlined elsewhere, this is not a coherent position (Ferguson *et al.*, 2020).

The United Nations Food and Agricultural Organisation (FAO) take the view that "*While renewable water resources are expressed in flows, non-renewable water resources have to be expressed in quantity (stock)*" (FAO, 2003). Irrespective of the relative merit or coherence of the flux and storage-based definitions, the two definitions are inconsistent with each other since each implicitly excludes the other: i.e., for a given value of recharge which defines a given aquifer's renewable use in flux terms, an aquifer could be designated as non-renewable under a storage based definition if its volume of stored groundwater is sufficiently large (Figure 1). Gleeson *et al.* (2020) attempted to harmonise the flux-based and storage-based definitions defining renewable groundwater as: "any groundwater that can be dynamically captured during pumping that leads to a new dynamically stable equilibrium in groundwater levels within human timescales (∼100 years)". However, in this definition renewable groundwater is still seen as a property of the resource itself, rather than explicitly its relationship with its use (e.g. Taylor, 2009), a point we return to later when we propose a new definition, and also it does not include any considerations beyond the water balance.

In summary, determining a useful definition of renewable groundwater is more complex than it is for many other natural resources. Our view is that existing definitions currently make it a potentially cumbersome at best, or misleading at worst, concept in the context of sustainability science. We propose here that renewable groundwater use may be more clearly and practically defined and that doing so can also lead to new insights into its relationship to groundwater sustainability and strategies for quantitative groundwater management.

3. What happens when we pump?

Groundwater Quantity Considerations

To move towards a more robust definition of renewable groundwater use, we now use a thought experiment of a simple aquifer and consider changes to its overall water balance with and without groundwater pumping. The groundwater balance of the aquifer can be stated as:

$$\frac{dS}{dt} = R - D - Q \qquad (1)$$

where S is total groundwater storage [L], t is time [T], R is the recharge rate [LT^{-1}], D is the rate of groundwater discharge other than pumping [LT^{-1}] and Q is the rate of pumping [LT^{-1}]. Note, throughout the paper, by recharge we mean "the downward flow of water reaching the water table, adding to groundwater storage" (Healy, 2010, p. 3). For the following discussion, it is useful to break–down these terms further as follows:

$$R = R_0 + \Delta R_Q + \Delta R_N \qquad (2)$$

$$D = D_0 + \Delta D_Q + \Delta D_N \qquad (3)$$

Where R_0 is the pre-development recharge rate, the change in the recharge rate from the pre-development rate due to pumping or natural transients is given by ΔR_Q and ΔR_N respectively, D_0 is the pre-development natural groundwater discharge rate, and the change in the discharge rate from the pre-development rate due to pumping or natural transients is given by ΔD_Q and ΔD_N respectively. This is an extension, to account for natural transients, of the relationships given by Bredehoeft (2002).

We assume the abstractions are widely spatially distributed, and hence all our considerations here are on the large-scale water balance, not the detailed hydraulics of an individual abstraction well, in a similar conceptual framework as (Bierkens *et al.*2021). Further we assume that the aquifer has impermeable boundaries laterally and at its base, that it may receive recharge via precipitation and/or via stream leakage, and groundwater may also discharge naturally e.g. to streams as baseflow or as evapotranspiration. The recharge received by the aquifer reflects superposed climatic variations operating on multiple time periods, but is assumed to be in quasi-steady state and stationary over the time period of the groundwater development. i.e. in this thought experiment, $R_0 \sim D_0$ and $\Delta R_N \sim 0 \sim \Delta D_N$. Later we will also consider the implications of relaxing these assumptions.

In an unpumped situation, the hydraulic heads (hereafter "heads") in the aquifer fluctuate in a dynamic steady state around some value above the elevation of the lowest hydraulically-connected streambed overlying the aquifer (the 'drainage base-level'). If constant rate pumping begins, groundwater is taken out of storage as the well drawdown cones superpose themselves across the aquifer. The evolving change in hydraulic gradients due to pumping causes a combination of (1) changing rates of recharge (ΔR_Q) through the capture of evapotranspiration (ET) from the vadose zone or surface/shallow-subsurface runoff, (2) changing rates of discharge (ΔD_Q) through the capture of stream baseflow, evapotranspiration and/or altered rates of exchange with other neighbouring geological units. The combination of (1) and (2) are termed capture (C). i.e.:

$$C = \Delta R_Q - \Delta D_Q \qquad (4)$$

where ΔR_Q and/or ΔD_Q are negative when a decline in the value of R or D occurs, respectively, due to pumping. If the rate of pumping is less than the maximum possible rate of capture ($C_{\max}$), the heads will gradually come to a new dynamic equilibrium (e.g. green and orange lines on Figure 2) at which time all of the pumping is being sourced from capture, and no longer from changes in storage. This maximum rate of capture is sometimes also referred to as the physically sustainable pumping rate (Bierkens & Wada, 2019; Gleeson *et al.*, 2020); we discuss below why we choose not to continue this nomenclature here. Note that if the maximum rate of capture is achieved, the environmental impact would be devastating – for example all evapotranspiration of groundwater would cease, leading to the destruction of groundwater dependent ecosystems and all baseflow to streams would cease. Furthermore, any net groundwater discharge from the region of interest would cease, as might the extent of saturation-excess surface runoff. These effects all have knock-on ecological, societal and economic implications. Below the maximum rate of capture, groundwater-surface water interactions remain bi-directional and at least part of the stream network will be perennial. If pumping then ceases, the reverse of the capture process occurs, with 'release' of baseflow, runoff and evapotranspiration, assuming groundwater dependent vegetation becomes re-established, ensuing until the system returns to a new dynamic steady state once more.

There may be some differences in the timescales of capture and release, for example due to hysteretic relationships between heads via bi-directional stream-aquifer interactions. However, for the widely distributed pumping assumed here, both processes can be approximated using a characteristic timescale referred to variably as the reservoir co-efficient (Kraijenhoff van de Leur, 1958), aquifer response rate (Erskine & Papaioannou, 1997), time constant (Rousseau-Gueutin *et al.*, 2013), mean action time (Simpson*et al*., 2013), hydraulic response time (Alley *et al.*, 2002) or groundwater response time (GRT) (Cuthbert, Gleeson, *et al.*, 2019) which is the term we will use here. Such response times are principally related to the physical properties of the system in question (e.g. stream geometries, hydraulic properties of the aquifer, distance between geological and hydraulic boundaries) and not to the initial, pre-pumping, rate of recharge (Bredehoeft 2009, 2002). Note, these hydraulic response times should not be equated or confused with groundwater residence times or ages (Ferguson *et al.*, 2020).

Since the connection to surface water courses may vary with time for a given aquifer depending on the relative water level at a particular climatic state, the response time may also change through time. For an individual well, or group of wells, the time to full capture (Bredehoeft & Durbin, 2009) or release (t_C) may significantly deviate from the GRT of the aquifer as a whole depending on the relative position of the wells and boundary conditions. For example, shorter times to equilibrium and a smaller proportion of depletion compared to capture are expected for wells positioned closer to streams (Konikow & Leake, 2014). Whether the full capture timescale is considered in relative or absolute terms is also important. Where the timescale is calculated as the time to reach a threshold relative drawdown (or streamflow depletion) as a proportion of the maximum drawdown (or streamflow depletion), the timescale is solely related to the hydraulic properties of the system and not the pumping rate. However, if the timescale is defined in absolute terms, for example with respect to a threshold change in groundwater level or streamflow, then the pumping rate will also be a contributing factor in the magnitude of the timescale for a threshold to be reached.

If the rate of pumping is greater than the maximum possible capture, the heads in the aquifer will eventually fall below the drainage base level (red line on Figure 2) and stream-aquifer interactions will become uni-directional. In this situation, recharge may still be received by the aquifer from losing streams but the aquifer is no longer able to hydraulically feedback on this process (Bierkens & Wada, 2019; Quichimbo *et al*., 2020). In such cases the continued rate of lowering of heads, and the recovery of heads should pumping cease, will increasingly be governed by the relative rates of recharge and pumping in conjunction with the specific yield of the aquifer and the duration of the pumping. This rate of depletion or recovery thus has distinct controls from the lower pumping cases described above for situations where the groundwater is still able to feedback hydraulically to the stream network in a bi-directional sense. While heads are below the drainage base level, the rate of recovery will always be faster than the rate of depletion. This stems from the fact that during depletion the rate is determined by the difference between the recharge rate and pumping rate, whereas during recovery just the recharge rate becomes relevant (Figure 2). Longer recoveries are to be expected to result after longer pumping periods or higher pumping rates relative to rates of maximum capture. However, since there is a potentially complex trade-off between these two factors and the hydraulic properties of a particular aquifer, we do not propose quantitative metrics in a general sense here.

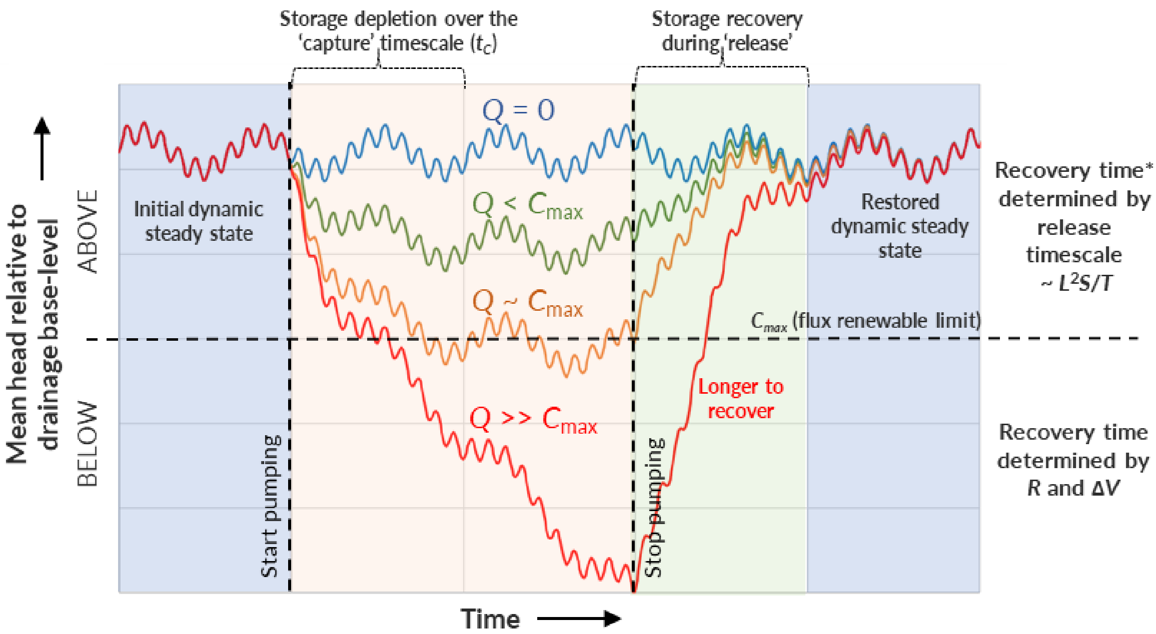

Figure 2. *Controls on the dynamics of pumping and recovery of a generic groundwater system. R = recharge, ΔV = storage depletion during pumping, Q = pumping,* C_{max} *= rate of maximum capture, L = characteristic aquifer length scale, S = storage coefficient, T = transmissivity. Plotted using a lumped explicit finite-difference solution to Equation 1, with R =* R_0 *defined by a superposition of sinusoidal signals of various periods, and D set as proportional to the head difference above the drainage base level while above the base level, and zero when below. Assumes fully elastic behaviour, no irreversible compaction, and re-establishment of groundwater dependent vegetation on recovery. *Relative recovery time; in absolute terms this will also depend on Q.*

Similar thought experiments can be carried out for more complex aquifer systems. For example, there may be head-dependent inflows or outflows with other neighboring geological units, large water bodies, or the sea. In such cases there will be a more complex balance of capture with the landscape (via changes in streamflow and evapotranspiration) and laterally with the adjacent sources or sinks of groundwater. However, despite the more complex quantification of capture and release in practice, the overall concepts outlined above will still hold.

Groundwater Quality & Hydromechanical Considerations

We have focussed so far only on groundwater quantity, in line with the previous literature on renewable groundwater. However, capture resulting from pumping can also have significant consequences for other aspects which may impact groundwater renewability such as groundwater quality and hydromechanical changes in the aquifer.

Of particular importance is the situation when the quality of captured water is inconsistent with the background groundwater chemistry of the aquifer which the development is targeting. For example, contaminated or naturally more saline water may be induced to recharge an aquifer. This may happen where pumping moves the position of the saline interface either in coastal areas or island aquifers (Werner *et al.*, 2013), or where lower quality water is brought in from adjacent formations (Ferguson *et al.*, 2018). In some contexts, pumping may also cause internal shifts in chemistry leading to deteriorations in groundwater quality, for example via the mechanism of anthropogenic basin closure (Pauloo *et al.*, 2021).

It is possible that if abstraction rates are high enough, the time taken for water quality to recover to its pre-pumping state may be much greater than the hydraulic response time. For example, with regard to saline groundwater, interfaces between saline and fresh water do not remain sharp since conductivity heterogeneity and anisotropy and larger dispersivities may induce mixing, which results in brackish zones that may take very long times to disperse (see Bierkens and Wada 2019 and references on salinization therein).

There are also contexts in which the lowering of heads in an aquifer can cause irreversible changes in the properties or state of the system. Firstly, dewatering can cause consolidation of more compressible formations leading to land subsidence and irreversible (i.e. non-elastic) loss of groundwater storage (Galloway & Burbey, 2011). For example, the California Central Valley aquifer system permanently lost an estimated 0.4–3.25% of its storage capacity due to pumping during a period of drought between 2012 and 2015 (Ojha *et al*., 2019). Secondly, although it is not yet well understood, it is possible that, as a result of non-linear dynamics in a coupled climate-vegetation-hydrological system, pumping may cause a groundwater system to switch states to a regime from which it will not recover simply by stopping pumping (Peterson *et al*., 2021; Zipper *et al*., 2022).

These considerations indicate that in certain contexts the maximum capture ($C_{\max}$) may be an overestimate of the maximum rate of pumping. Hence in the rest of the paper we instead use the notation Q_R for the maximum rate of pumping which also allows the aquifer to recover flows and storage of consistent quality groundwater.

4. Redefining renewable groundwater use

The above thought experiment indicates that, while some degree of storage depletion is always required for any groundwater development (Theis, 1940), there are two major controls on the extent and timescales for aquifer depletion and recovery:

- the rate of pumping (Q) relative to the maximum capture (Q_R) which amounts to a more restrictive definition of whether the pumped system is ‘capture-constrained’ or not (Konikow & Leake, 2014).

- the time to full capture or recovery (t_C) of pumping at the rate Q_R, relative to a given human timescale of interest (t_H).

We propose that these factors relate directly to improving 'flux-based' and 'storage-based' definitions of groundwater renewability respectively as follows.

1. **Flux-renewable groundwater use, defined as the rate of pumping being less than the maximum rate of capture**. This definition extends the renewable pumping rate to the maximum capture rather than restricting itself, unrealistically, to the pre-pumping recharge rate as per existing definitions.
2. **Storage-renewable groundwater use, defined as the potential full recovery of groundwater levels, flows and quality within human timescales**. This explicitly accounts for the timescale of renewal of groundwater storage, rather than the less meaningful ratio of storage to recharge given by previous definitions.

By using these two definitions as axes, we can then describe four quadrants of renewable groundwater use for each combination of flux-based and storage-based criteria as follows:

a) **Renewable Use** (lower left quadrant): *systems where pumping is less than the maximum capture, and also have short response times ($Q < Q_R$, $t_C < t_H$).* From a flux-based perspective this quadrant therefore represents renewable groundwater use. From a storage-based perspective, the situation also always represents renewable use irrespective of how long the pumping continues. This is the case in this quadrant since $Q < Q_R$and thus the recovery time is solely controlled by the hydraulic response which will be approximately equal to t_C and thus will also be less than t_H.

b) **Non-flux-renewable Use** (lower right quadrant): *systems where pumping is greater than the maximum capture, but have short response times ($Q > Q_R$, $t_C < t_H$).* From a flux-based perspective, this is a situation of non-renewable groundwater use. However, from a storage-based perspective, it is possible for the situation to represent renewable use depending on the specific combination of pumping duration and magnitude, t_C and water quality considerations.

c) **Flux-renewable Use** (upper left quadrant): *systems where pumping is less than the maximum capture, but have long response times ($Q < Q_R$, $t_C > t_H$).* From a flux-based perspective, this is a situation of renewable groundwater use. In this quadrant, the recovery time will be controlled only by the hydraulic response time since $Q < Q_R$and groundwater levels will never fall below the drainage base level. Hence, from a storage-based perspective, the quadrant will represent non-renewable use since $t_C > t_H$, with the exception of where pumping durations are less than t_H.

d) **Non-renewable Use** (upper right quadrant): *systems where pumping is greater than the maximum capture, and also have long response times ($Q > Q_R$, $t_C > t_H$).* From a flux-based perspective, this is a situation of non-renewable groundwater use. From a storage-based perspective, this quadrant may nevertheless represent renewable use for the same reasons as the lower right quadrant. However, the conditions under which this is possible are much more constrained owing to the larger t_C.

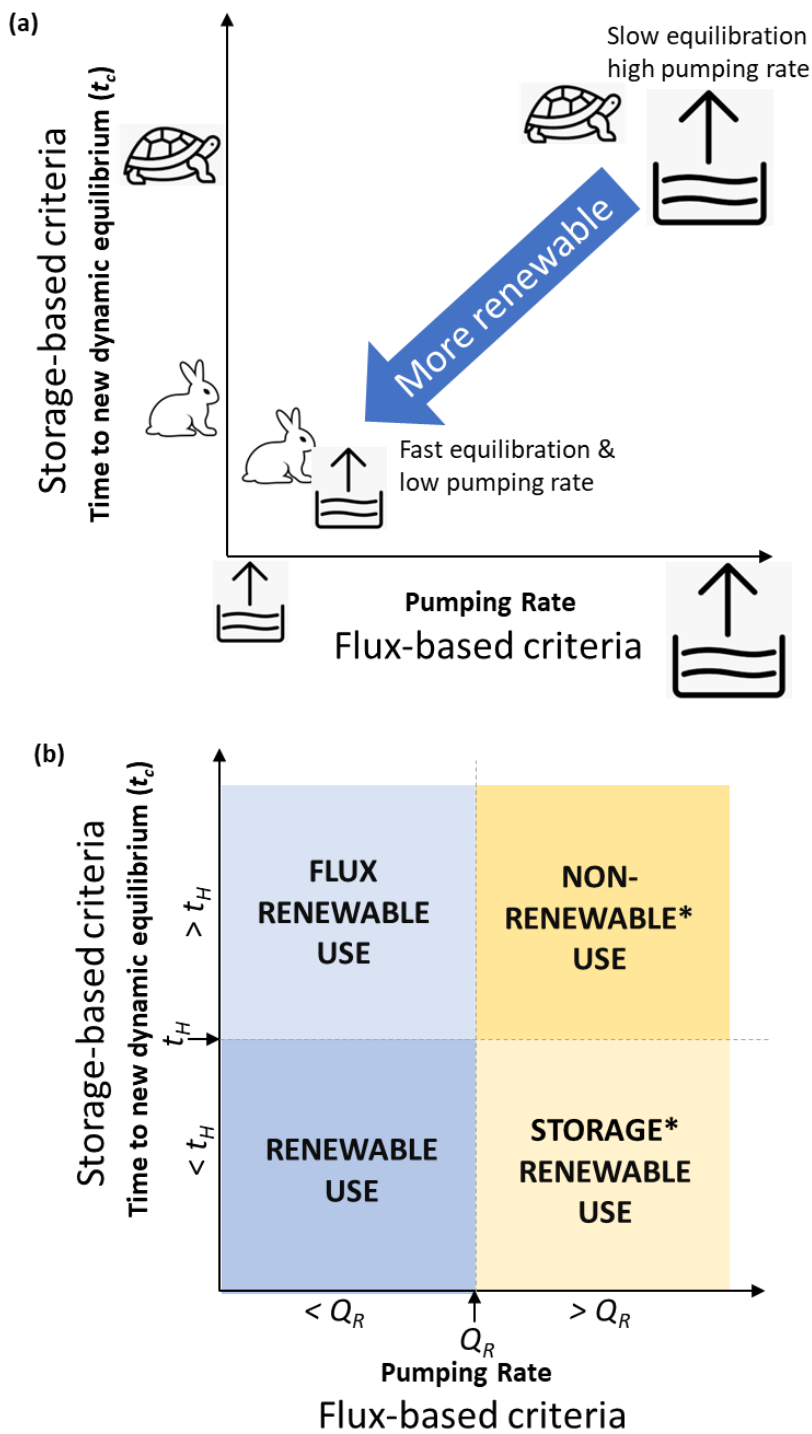

Figure 3. ***(a)*** *Illustrating the possible range of combinations of flux-based and storage-based criteria for renewable groundwater use* ***(b)*** *Four quadrants of renewable groundwater use* Q_R= *maximum rate of pumping which also allows the aquifer to recover flows and storage of consistent quality groundwater,* t_H = *human timescale. *See text for details of the sub-conditions for the right-hand quadrants which are never flux-renewable but may represent storage renewable use for lower pumping duration magnitudes*

Only in the bottom left quadrant is groundwater use always renewable under both flux and storage-based definitions. In this quadrant, unless the system is highly hysteretic, the recovery time will also approximately equal the time for an aquifer to reach a new dynamic equilibrium after the onset of pumping. Hence, we propose here that:

> ***Renewable groundwater use allows for dynamically stable re-equilibrium of groundwater levels and quality on human timescales.***

A key implication implicit in this definition is that *defining renewable or non-renewable groundwater without considering how it is being used is impossible*. For use to be renewable it must lead to full and reversible capture of consistent quality groundwater within human timescales. 'Groundwater renewability' *per se* cannot therefore be defined without consideration of the spatio-temporal distribution of the pumping itself. Note, in this paper we are being deliberately imprecise about how a 'human timescale' is defined, since we would like the definition to be as generally applicable as possible, and hence not beholden to culturally-defined generational or inter-generational quantification of what this timescale might be in a given context.

Long-term transients in groundwater levels and flows may occur well beyond human timescales due, for example, to non-stationary climate or land use change (i.e. $R_0 \neq D_0$ and $\Delta R_N \neq 0 \neq \Delta D_N$). In such a situation, from a flux perspective, the rate of pumping that can be considered renewable must also change through time. For example, if recharge is decreasing over time, a pumping rate that initially allows for renewable use may eventually lead to non-renewable use over time from a flux perspective. Furthermore, from a storage perspective, the concept of renewable groundwater use will only have meaning relative to the storage change that might have occurred naturally over a particular period of concern.

The bottom left quadrant is the only one that will always represent renewable groundwater use for both flux and storage/levels. If pumping is restricted in time, both the right-hand quadrants may also be considered renewable but only from a storage-based perspective. In other words, recovery of levels is possible over a human timescale after cessation of pumping but only under specific criteria particular to their quadrant i.e. depending on the particular $C_{\max}/Q$ ratio, duration of pumping and time to full capture. In these right-hand quadrants, such groundwater use may still have deleterious impacts on stream flows or other groundwater discharges.

The estimation of Q_R may be even more challenging than the pre-pumping rate of recharge. While this reality does not change the fact that our definition is more robust hydraulically than previous definitions, we discuss the practical implications of this in Section 6 below.

5. Illustrating the four quadrant framework with representative cases for characterising renewable groundwater use and management pathways

To illustrate how some of the features of each quadrant play out in the real-world, we now present a series of short case studies drawn from the literature, and show how this four-quadrant mapping may be a useful tool for delineating groundwater management pathways towards more renewable groundwater use. We have drawn these case studies from our understanding of the literature to help illustrate and contextualise our concepts, but acknowledge the limitations of our understandings and that local conditions in any of these case studies may differ from the generalities found in the literature.

Lower Quadrants ($t_C < t_H$)

Inherently, within these lower quadrants with fast response times (low t_C), the pre-development rates of recharge and discharge are likely to be in balance (i.e. $R_0 \sim D_0$). Furthermore, problems due to over-abstraction may become quickly apparent. While this may be a disadvantage when climatic shocks such as droughts occur, it also means problems related to over-pumping can quickly be addressed and mitigated within human timescales. In such systems, 'monitor and react' approaches to management (Thomann *et al*., 2020) may therefore be effective, whereby ongoing monitoring of field conditions supports managers to make adjustments in allowable groundwater extraction. However, it is important to note that the use of groundwater level triggers (so called 'trigger-level management,Werner *et al.*, 2011) maybe misleading in, at least, certain coastal contexts (Morgan *et al*., 2012) or for protecting groundwater dependent ecosystems (Currell, 2016). We give two contrasting groundwater-use case studies here for two different types of aquifers: crystalline basement and Chalk (limestone).

Crystalline Basement

Weathered crystalline rock aquifer systems in humid equatorial Africa are discontinuous but occur across much of the wet tropics (Taylor & Howard, 2000). They typically comprise a shallow unconfined (or semi-confined) aquifer within an unconsolidated regolith that is often hydraulically connected to an underlying aquifer within fissured bedrock (Lachassagne *et al*., 2021). Seasonal (monsoonal) recharge occurs annually (Owor *et al.*, 2009; Kotchoni *et al.*, 2019), groundwater levels consistently lie above the base level of surface drainage, and groundwater drains to perennial surface waters including lakes, rivers and wetlands (Cuthbert *et al.*, 2019). These systems are not often thought to form large-scale regional aquifers, with smaller local flow systems more common, governed by fracture networks, lithological discontinuities and faults. Furthermore, in the humid tropics where recharge is generally high, the distance between perennial streams is often less than a few km (Cuthbert *et al.*, 2019). Transmissivity is typically low (<10 m^2/day), and specific yield is moderate to low (5% +/- 4%), leading to characteristic groundwater response times commonly less than 50 years. In combination with typically low pumping rates, often but not always constrained by low transmissivities, groundwater use is likely to be renewable in many parts of such aquifers, thus they are situated in the lower left quadrant.

In other parts of the world, similar crystalline basement aquifer systems with quick response times are sometimes being over-pumped with respect to the maximum capture, moving them into the lower right quadrant. Some of the hard rock aquifers in Peninsular India fall into this category, commonly being storage-limited with dense drainage networks (Fishman *et al.*, 2011; Hora*et al*., 2019; Bhanja *et al*. 2020). For example, shallow, fractured hard rock aquifers with low yields in Telangana region, Andhra Pradesh are important sources of irrigation for a major rice producing area (Fishman *et al.*, 2011). Since most of these rocks have negligible primary porosity, while pumping rates may regularly exceed rates of maximum capture, the limited groundwater storage places a physical restriction on irrigation from year to year. Consequently, irrigated areas have to be reduced when the pre-season depth to groundwater is low, and water table fluctuations explain a significant part of the large annual variability in irrigated or rice cultivated areas. More broadly across Southern India, groundwater recovery has been reported based on GRACE satellites, water level measurements in groundwater monitoring wells and global hydrological models (Asoka *et al.*, 2017; Bhanja *et al*., 2020) which are at odds with reports of well failure and decreases in the land area irrigated from shallow wells (Hora *et al*., 2019). Hora *et al*. (2019) argue that recently reported results are skewed by the problem of 'survivor bias', with dry or defunct wells being systematically excluded from trend analyses due to missing data and that including these wells reveals increasing groundwater stress in South India.

Chalk (limestone), northwestern Europe

The Chalk (limestone) is an important regional aquifer in north-western Europe. Its hydraulic properties derive primarily from the presence of fractures and their development through dissolution that is enhanced under phreatic (unconfined) conditions and in valley bottoms (MacDonald & Allen, 2001; Allen & Crane, 2019). Groundwater response times are generally <<50 years owing to the high transmissivity (>1000 m^2/d is common) in combination with low specific yield (< a few percent) and relatively short distances between perennial streams. Seasonal (predominantly winter) recharge (Goderniaux *et al.*, 2021) occurs annually and groundwater discharge provides baseflow to rivers and chalk streams, some of which are seasonal. Groundwater abstraction in Europe is often well-regulated to protect streamflows under the EU Water Management Directive, hence in many parts of the aquifer the licenced as well as actual use is significantly less than the maximum rate of capture. This is the case in the Paris Basin (Rouillard, 2020) for example where an agreement with farmers to restrict abstraction volumes for irrigation has been achieved (Lejars *et al.*, 2012).

However, incidences of localized intensive pumping exceeding capture have recently been noted in the drying of Chalk streams following successive dry winters in southeastern England (Jackson *et al*., 2015; Allen & Crane, 2019). Overall, the groundwater use of this aquifer is often renewable, and when the impacts of prolonged drought do manifest, the levels and flows are quick to recover once winter recharge resumes.

Upper Quadrants ($t_C > t_H$)

Inherently, within these upper quadrants with slow response times (high t_C), problems due to over-abstraction may take more than a lifetime to become apparent. While this may be an advantage when climatic shocks such as droughts occur, it also means problems related to over-pumping cannot quickly be addressed and mitigated within human timescales. Hence, in such systems, adaptive management (Thomann *et al.*, 2020) may therefore be more problematic, and a strategy of flux-based management, alongside ongoing monitoring, may need to predominate (Werner *et al.* 2011). We give two contrasting groundwater-use case studies here for contrasting sedimentary aquifers.

Nubian Sandstone Aquifer, northeastern Africa

An important example of a regional aquifer with a long groundwater response time, the Nubian Sandstone Aquifer, is a partly phreatic aquifer of fine to coarse grained sandstones of Late Triassic to Early Cretaceous age (Heinl & Brinkmann, 1989; Salem, 2016). Current recharge rates are thought to be low for the Nubian Sandstone Aquifer, although exactly how low is a matter of some debate (Darling *et al.*, 1987; Sultan *et al.*, 2011; Ahmed & Abdelmohsen, 2018), with little opportunity for increasing recharge due to pumping. The large response times cause long lag times between recharge and discharge such that the aquifer heads (i.e. storage) are still receding from the last major recharge period 10,000 years ago (Lloyd & Farag, 1978). Hence, while capture of discharge to oases and the seaward boundary will eventually occur, any significant groundwater development will also lead to long-term aquifer depletion. In light of this, very low rates of abstraction would be required to keep this aquifer in the upper left quadrant to maintain a state of flux-renewable use. In the present state of development, the rates of abstraction are much larger, meaning that ‘managed aquifer depletion’ is the current groundwater management situation (Ahmed & Abdelmohsen, 2018). Owing to the combination of very high response time and major historic change in recharge rate, the concept of renewable use with respect to storage is perhaps not very meaningful in this, or similar, cases.

Permo-Triassic sandstone aquifers, UK

Alongside the Chalk aquifers discussed above, Permo-Triassic sandstone aquifers represent the most important groundwater resources in the UK. They comprise aeolian and fluvial, weakly cemented, red sandstones with high intergranular hydraulic conductivity enhanced by fracturing (Allen *et al.*, 1997). Owing to the moderate transmissivity (median ~200 m^2/d) in combination with high specific yield (~10% is typical) groundwater response times are expected to be >50 years where distances between discharge boundaries are large enough (Rushton, 2004; Shepley & Streetly 2007). Recharge occurs predominantly in winter and groundwater abstraction is now well-regulated to protect streamflows under the pre-existing EU Water Management Directive and follow-on post-Brexit legislation. In many parts of the aquifer both licenced and actual uses are significantly less than the maximum rate of capture (Morris, 2021), although over-licensing has been highlighted in some areas and was particularly acute historically in the East Midlands sandstone (Hudson, 2002; Shepley, 2005). Hence these aquifers most often likely straddle the upper-left and lower-left quadrants, being operated under flux-renewable use, but not always being used renewably from a storage perspective where response times are greater than human timescales.

Implications for Groundwater Management Pathways

In many instances, response times of groundwater systems may not change significantly on management timescales. As such, groundwater in aquifers situated in the upper quadrants may never be used in a renewable way from a storage perspective even if pumping was reduced. In such cases the quadrant diagram is nevertheless a potentially useful a tool for characterising groundwater status within a management context. Management pathways towards more renewable use in such contexts will, therefore, generally represent movement on the quadrant plot from right to left rather than from upper to lower quadrants. Increasing pumping shifts aquifers from left to right on Figure 3a, but we focus here on the implications and strategies for shifting from right to left. This may occur via reducing pumping towards flux-renewable use from situations where pumping is currently greater than Q_R (Figure 3a, A arrows). The ensuing increases in groundwater levels may be an important economic imperative with respect to equitable access to groundwater in regions where domestic wells are at risk from drying owing to agricultural or industrial abstraction (Jasechko and Perrone, 2021).There are also many examples of urban aquifers around the world where post-industrial decline of abstraction or switching from groundwater to surface water sources has led to aquifer recoveries along both such pathways (Render, 1970; Buxton & Shernoff, 1995).

In other instances, there may be significant transience in a groundwater system's hydraulic response time. This can occur for a number of reasons such as aridification of a recharge area as occurred historically for the Nubian Sandstone aquifer over the last 10 ka (Abouelmagd *et al.*, 2014; Voss & Soliman, 2014), or land use change such as the clearing of native vegetation for agriculture in Niger in the more recent past which has led to increased groundwater levels and a greater degree of groundwater-surface water connectedness (Favreau *et al.*, 2009). In other contexts, further pumping reductions within situations of already flux-renewable use would enable the re-establishment of previously perennial streams and groundwater dependent ecosystems, as discussed in the Chalk example above, and this may have knock-on impacts on reducing response times. Hence, the context for groundwater management within the quadrant diagram may not be fixed in time due to transience in such groundwater systems. This behaviour may allow for movement from upper to lower quadrants (in the case of pumping reductions, Figure 3b, B arrow).

Aquifers currently in the right-hand quadrants, despite being in a situation of non-renewable use from a flux perspective, are sometimes managed for 'strategic aquifer depletion' (Figure 3a, C arrows, and time series in Figure 3b). This is where the aquifer is used temporarily, for example during a long drought period, at a pumping rate that is well above than Q_R, but in the knowledge that once pumping ceases, groundwater levels and flows will return to their previous equilibrium values within human timescales.

The High Plains Aquifer (HPA or Ogallala Aquifer), USA, usefully illustrates some of these issues. It is one of the largest aquifers in the world, comprising Neogene-age, generally poorly consolidated, gravels, sand, silt and clay (Divine *et al*., 2018; Bruun *et al. 2016*) and is mostly unconfined. The central portion of the Northern HPA in Nebraska is thought to receive recharge of 100-200 mm/y (Scanlon *et al.*, 2012) and has the greatest saturated thicknesses, and hence transmissivities, of the whole aquifer unit, which is still well connected to the surface drainage (Scanlon *et al.*, 2012). Hence, response times may be within human timescales indicating a fully renewable case (lower left quadrant) where pumping is often less than the maximum capture rates. However, as one moves further southwards within the aquifer, recharge decreases substantially by as much as two orders of magnitude but the aquifer is still highly utilised for irrigated agriculture. Hence in the Southern Ogallala Aquifer (SOA), currently groundwater levels are, to a great extent, well below drainage base levels, and pumping rates are larger than maximum capture. While strategic depletion as part of groundwater management may be theoretically possible, in principle, in parts of the aquifer, withdrawal rates have been persistently exceeding capture for the SOA for decades. Recent efforts to reduce further depletion in the HPA have shown that if recharge and pumping are balanced after maximum capture has been exceeded, a new equilibrium can be achieved (Butler *et al.*, 2018; Butler *et al*., 2023). While this does not reverse ecological damage that has been done by lowering groundwater levels below streams, it does provide a path forward that allows for continued groundwater extraction in heavily stressed aquifers.

6. Challenges and approaches to implementing the quadrant framework

For the proposed framework to be useful, the key metrics of capture magnitudes and timescales need to be reliably estimated. Recommending specific management approaches for specific quadrants or aquifers is beyond the scope of this manuscript but herein we outline the sorts of approaches that could be taken and tailored to more local needs.

A spectrum of approaches is available, of increasing detail depending on the data availability, budgetary constraints and risk-reward context of the decision making process. Space precludes a thorough review of various available methods (e.g. Li *et al.*, 2022), but developing a hydrogeological conceptual model should always be the starting point (Rushton, 2004; Rushton and Skinner, 2012). Where sufficient data are available the well-tested combination of iterative field observation and analytical or numerical modelling is recommended (Ferré, 2017).

Appropriately evaluated groundwater models with properly constrained uncertainty bounds can provide the necessary tools for testing the likely capture magnitudes and timescales of a groundwater body, and subsequent management. However, in many parts of the world, long-term groundwater monitoring data and detailed field investigations of aquifer parameters or forcing data are often unavailable. Furthermore, sufficient economic or human resources may be too sparse to make this 'gold standard' approach viable. In such contexts implementing the quadrant framework may be challenging. Hence, we offer the following suggestions for ways to combine expert judgement with a minimum amount of data, and to guide the appropriateness of any simplifications to the water budget equations (Equations 1-4) which might make the calculations more tractable until more data and/or resources are available.

Where detailed modelling is not possible due to resource constraints, or warranted due insufficient data for forcing or evaluation, the capture timescale may be approximated via a groundwater response time (GRT) calculation (Kraijenhoff van de Leur, 1958; Alley *et al.*, 2002; Rushton, 2004; Rousseau-Gueutin *et al.*, 2013; Simpson *et al.*, 2013; Cuthbert *et al.*, 2019). However, this should be used with care, and with due attention to the likely direction and magnitude of any uncertainties involved. The distance between groundwater fed perennial streams or other hydraulic boundaries (L) is normally straightforward to approximate (Erskine and Papaioannou, 1997; Cuthbert, Gleeson, *et al.*, 2019), but since this term is squared in the GRT equation, its uncertainty should be duly incorporated. Hydraulic properties of the aquifer (S, T) under consideration may be more uncertain, depending on the available mapping and prior field investigation.

The groundwater response time is then proportional to L^2S/T with the constant of proportionality to be chosen depending on the geometry of the system and the proportion of the total re-equilibrium (e.g. 63%, 90%, 99%) as appropriate.

If the system has a short groundwater response time, it is likely to be in dynamic equilibrium and it may be safe to assume $R_0 = D_0$. If no significant trends in recharge are expected due, for example, to climate or land-use changes, then it can also be assumed that $\Delta R_N \sim 0 \sim \Delta D_N$. Once full capture has been achieved, $\frac{dS}{dt} = 0$, and using Equation 1-3, the maximum capture becomes $C_{\max} = \Delta R_Q - \Delta D_Q$. In this case, since the maximum value of ΔD_Q will equal $-D_0$ ($= -R_0$), the maximum capture becomes $C_{\max} = R_0 + \Delta R_Q$. In some situations where the assumption $\Delta R_Q \sim 0$ is warranted, an estimate of the maximum capture may be made by assuming $C_{\max} = R_0 = D_0$. In similar situations and where ΔR_Q is likely significant but unknown, R_0 will be a minimum estimate for the rate of $C_{\max}$. It is crucial to note, however, that pumping at this rate would lead to zero groundwater discharge which would be disastrous to terrestrial and aquatic groundwater-dependent ecosystems.

This discussion raises the issue of the so-called 'water budget myth' (Bredehoeft et al. 1982) which asserts that the rate of R_0 is not of relevance to the "size of a sustainable groundwater development" (Bredehoeft 2002) . The logic of the previous paragraph negates the relevance of the water budget myth argument, at least in some circumstances. Furthermore, it is of note that every paper (that we are aware of) that has engaged with the water budget myth debate over the past 40 years has been either explicitly or implicitly predicated on the assumption of a short response time aquifer situated in a stationary recharge regime i.e. $R_0 = D_0$ and $\Delta R_N = 0 = \Delta D_N$ (Bredehoeft, et al. 1982; Bredehoeft, 2002; Devlin and Sophocleous, 2005, 2006; Kalf and Woolley, 2005; Loáiciga, 2006, 2017; Zhou, 2009). Presumably this is for didactic reasons for conceptually dealing with the principle of capture in a similar vein to our thought experiment above.

However, since it is likely that many, if not most, of the world's major aquifers actually have response times rather longer than human timescales (Bredehoeft and Durbin, 2009; Rousseau-

Gueutin *et al.*, 2013; Cuthbert, Gleeson, *et al.*, 2019), this is a fundamental oversight. Theoretically at least, for periodic recharge forcings, R_0 and D_0 are likely to be out of phase as long as GRT is greater than the period of the forcing (Townley, 1995). The lag time between a recent step change in R and the subsequent impact on D, will also approximate the GRT (Rousseau-Gueutin *et al.*, 2013). Furthermore, it shouldn't be assumed that recharge is stationary on human timescales owing to climate variability (both natural and anthropogenically altered) or land-use change (Favreau *et al.*, 2009).

Hence for large response time systems, there may be transients in the long-term water balance, R_0 and D_0 may be in disequilibrium, and it should not be assumed that $R_0 = D_0$. Neither should it be assumed that it is only pumping which could cause a long term change in R and D since these fluxes may effectively always be in disequilibrium i.e. that $\Delta R_N \neq 0 \neq \Delta D_N$. However, very large GRT systems tend to be more prevalent in more arid parts of the world where it may be safe to assume less feedback between recharge and heads in the aquifer. In these contexts it may be reasonable to assume that $\Delta R_Q \sim 0$, but we note that recent research indicates this may not be as safe an approximation than is often presumed (Quichimbo *et al.*, 2020).

These considerations indicate that, for many aquifers around the world, transients in various water balance elements may be important to consider and therefore the long term influence of widespread pumping may be hard to ascertain clearly amidst these natural transients from monitoring alone. Hence we maintain here that the key to robustly understanding capture is through a combination of long term monitoring and bespoke numerical modelling, in the context of environmental change. This is, after all, one of the main reasons 'why hydrogeologists model' (Bredehoeft, 2002). In this context, the advice of Bredehoeft & Durbin (2009) is apposite:

> *"...it takes some ground water systems an inordinately long period to reach a new equilibrium. The time may be so long that the fact that a new equilibrium eventually is reached becomes meaningless. The bottom line is—it is important to predict the time trajectory of ground water systems, especially if one hopes to manage the system."*

With respect to collecting the critically important long-term groundwater monitoring for good groundwater management, data not just of levels, flows and groundwater quality are needed (Rau *et al*., 2020) , but also improved ways of recording or estimating variations in groundwater abstractions at large scales (Butler *et al.*, 2021).

Even if the hydraulic response times and maximum capture rates can be estimated with sufficient certainty using a relatively simple approach, the inclusion of water quality aspects in these calculations may be more challenging. In most contexts as stated above, we anticipate that the time taken for water quality to recover to its pre-pumping state may be much higher than the hydraulic response time, and the rate of maximum quality capture (Q_R) may be significantly lower than the flux-renewable pumping rate ($C_{\max}$). This is a key challenge for the application of the framework and the importance of a sound conceptual hydrogeological model is again paramount.

7. The relationship between renewable and sustainable groundwater use

The process of outlining a new definition of renewable groundwater use led us to delineate the four quadrants shown in Figure 3. This raises the question as to how this framework relates to the broader question of groundwater sustainability. For example, can sustainable groundwater use only be present in the lower left, renewable use, quadrant?

A comprehensive review by Mace (2022) makes it clear that there is a great diversity of opinion as to what groundwater sustainability means within wider society, and also within the groundwater science community. Indeed, despite having written on this topic previously themselves, the various authors of this commentary, while being in full agreement about the nature of how to define renewable groundwater use more robustly, hold subtly different opinions about what should constitute sustainable groundwater use. This highlights the normative nature of the term 'sustainable', not just within the context of groundwater but more broadly, since it is inherently about value judgements.

As such, Mace (2022) suggested his preferred definition of groundwater sustainability to be that of Alley et al. (1999) as follows:

> *"the development and use of ground water in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences"*

His reasons for this are in preferring to *"see sustainable production as being defined solely from the perspective of the aquifer"*. Using such a definition, sustainable groundwater use can only intersect with our definitions of renewable use within the two left-hand quadrants of Figure 3, where pumping is less than the maximum capture, since only in these quadrants can pumping be maintained indefinitely. In many societies, what is deemed unacceptable with regard to environmental, economic, or social consequences will lead to sustainable pumping being much less than the rate of maximum capture, as indicated by the 'fuzzy' zone of 'potentially sustainable use' indicated in Figure 4.

In contrast, a more recent definition of groundwater sustainability extends the scope of groundwater sustainability to explicitly include the notion of dynamic stability of the system, something that can be physically monitored, as well as being more explicit about the socio-economic outcomes involved in sustainability:

> *"Groundwater sustainability is maintaining long-term, dynamically stable storage and flows of high-quality groundwater using inclusive, equitable, and long-term governance and management."* Gleeson *et al*. (2020)

Importantly, and in contrast to previous definitions including Alley *et al*. (1999), this definition argues for approaching groundwater sustainability from a 'stronger' sustainability perspective. Gleeson *et al*. (2020) described the distinction is between 'weak' sustainability, where all forms of capital (natural, economic, etc.) can be substituted, and 'strong' sustainability, where some natural capital stocks are non-substitutable and thus must be maintained independent of the growth of other forms of capital. This definition has broad support internationally as evidenced by the >1300 signatures from >100 countries of the Global Groundwater Statement (https://www.groundwaterstatement.org/) which includes this definition of groundwater sustainability (Gleeson *et al*. 2020). Under this definition, the first criteria of '*dynamically stable storage and flows'* restricts us to the left-hand quadrants where pumping is less than Q_R. The second criterion of '*high-quality groundwater'* is more open-ended and context specific, but as a minimum we can imagine further restrictions on the pumping rate to ensure local environmental flow and quality requirements can be met.

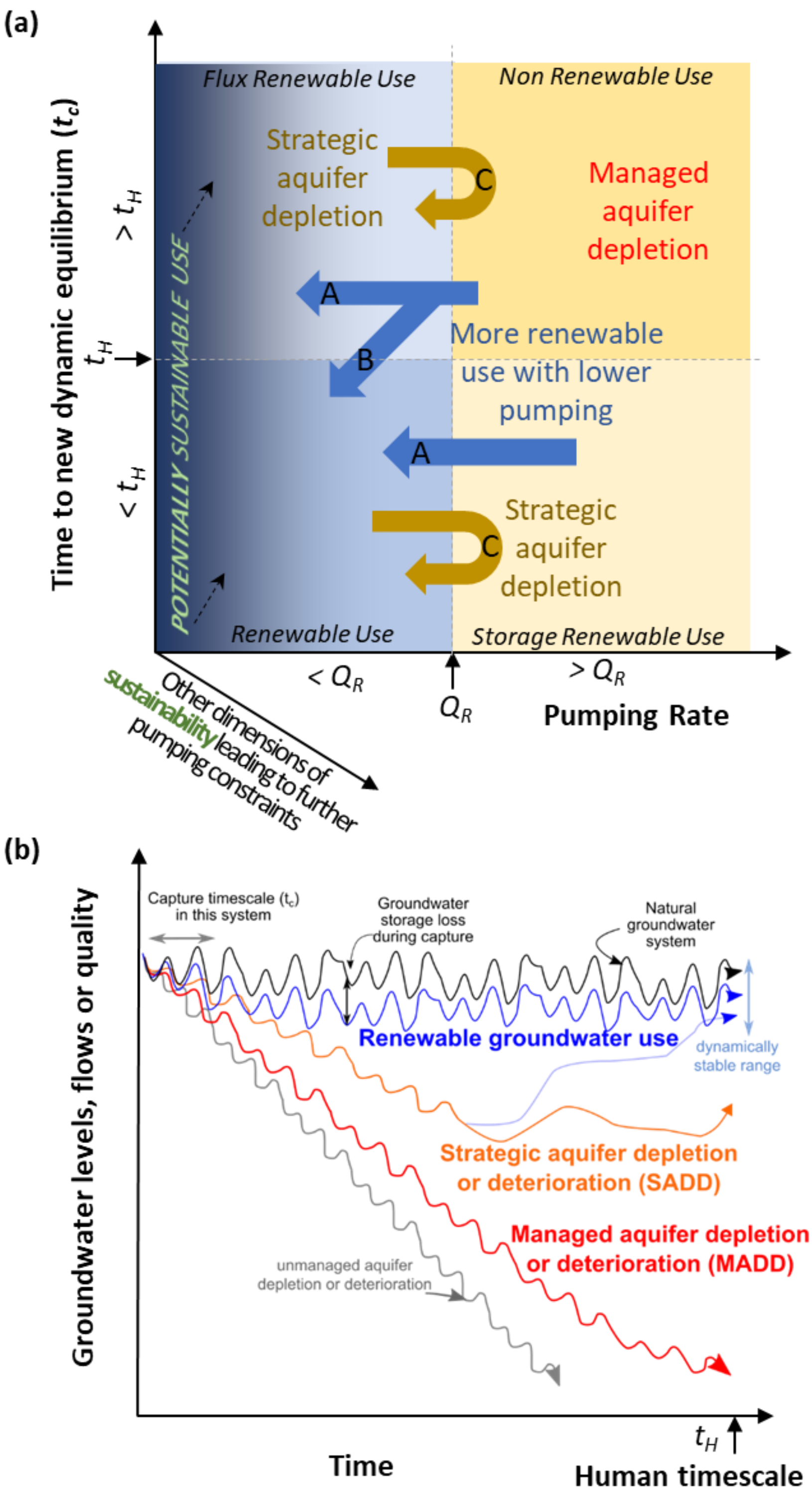

***Figure 4**. **(a)** Renewable groundwater use quadrants related to different aquifer management strategies and groundwater sustainability. Groundwater management pathways denoted by arrows A-C are described at the end of Section 5. The third axis of 'other dimensions of sustainability' is shown to illustrate the deliberately 'fuzzy' mapping of potential relationships between renewable and sustainable groundwater use as discussed more fully in Section 7 **(b)** Illustrative trajectories in time for renewable use status and various common groundwater management strategies shown in (a).*

The third criteria '*using inclusive, equitable, and long-term governance and management'* implies it is important to consider how groundwater is embedded in complex socio-political, economic and ecological systems which are not well represented in conventional approaches to study and promote groundwater sustainability . Furthermore, it could be imagined in different contexts that this determination may or may not allow for groundwater use in the upper left quadrant to be considered sustainable (Figure 3a), despite being non-renewable use from a storage perspective; this will depend on whether the extent of the storage depletion and associated environmental impacts are considered socially and economically acceptable.

In contrast to, but in the spirit of, Mace's suggestion above, we consider that definitions of renewable use such as proposed here are viewed "solely from the perspective of the aquifer", i.e. by just considering the relevant groundwater hydraulics and changes to the water balance that ensue from pumping, but without normative considerations. However, once value judgements are placed into the discussion and decision-making process, then the language of sustainability, rather than renewability, becomes appropriate. We propose, consistent with Wood (2001), that this distinction be made in future discussions of groundwater management in order to delineate the physical processes (of which humans are one part) of renewable use from wider, normative, and value-driven processes of sustainable use. In other words, renewable groundwater use can be defined using the principles of groundwater science alone and based solely on the physical properties and behaviour of the groundwater system. Determinations of sustainable groundwater use, in contrast, necessarily draw upon renewable groundwater use as just one criteria among many. Hence, renewable use will often be deemed a necessary, but insufficient, criteria for determining sustainability.

A recent and nuanced example of how the meaning of renewable and sustainable groundwater use may diverge, is the case noted above in the Chalk aquifer of SE England, where streamflows have been adversely impacted by a combination of dry winters and groundwater abstraction. There is currently an active and important debate about the relative cost/benefit of decreasing or relocation of groundwater abstractions to improve the health of such Chalk streams. For example, in comparison with stream augmentation and nature-based solutions Soley (2023) argues, on solid hydrogeological grounds, that "*The well-meaning environmental drive to switch off groundwater abstractions often results in disappointing river low-flow recovery and ineffective biodiversity outcomes*". The extent of low-flow recovery is highly dependent on the local aquifer dynamics and how stream-aquifer interactions operate in the context of particular spatio-temporal arrangements of groundwater abstractions. Thus, despite the overall situation in the SE England Chalk being one of renewable use, as defined here, it is not a given that pumping relocations, or even reductions, are the most societally desirable actions towards more sustainable groundwater management.

8. Having "renewed" the discussion, how can we sustain it?

This commentary was motivated by our collective perception of inconsistency in the meaning and use of the terms 'renewable groundwater' and 'groundwater renewability' and their relationship to sustainability. Clarification of these terms is surely vital in the quest to improve sustainable management of groundwater, by enabling identification of clear goals and pathways to that end, and aiding clear and consistent communication among scientists, managers, policy makers and stakeholders.

We began by questioning in what way groundwater can be considered a renewable resource and concluded that it can't be defined as such without reference to the manner in which it is being used. We proposed a new definition: *Renewable groundwater use allows for dynamically stable re-equilibrium of groundwater levels and quality on human timescales*. We then showed how this leads to a useful four quadrant framework for quantitative groundwater resource characterisation and management and illustrate this with reference to case studies from aquifers around the world.

We show that renewable groundwater use may be deemed a necessary, but not sufficient, criteria for determining groundwater sustainability, which typically encompasses several dimensions (e.g. socio-political, economic, ecological and cultural) beyond the scope of groundwater science. We propose that separating physically robust definitions of renewable groundwater use from the inherently value-based language of sustainability, can help bring much needed clarity to the wider discussions about sustainable groundwater management.

A logical next step is to extend our framework more fully with respect to groundwater quality and other hydro-mechanical or other linked groundwater abstraction related impacts. We would also like to see how our framework could be applied spatially towards realising the water management typology called for by (Foster and MacDonald, 2014):

"By understanding the aquifer characteristics relevant to water security, it should be possible to establish aquifer typologies which will respond in a similar manner to external stresses—either from humankind or climate. These typologies could then be mapped along with current groundwater status, permitting clearer communication on the groundwater dimensions of water security at the political level."

As with any overarching framework, important local details cannot be resolved at the same time as taking a panoramic view. However, we realise that for robust groundwater management such details will need to be brought into clear focus to give the necessary contextualisation in any given environment.

Aspirationally, we hope that increasing experience of recovering, previously highly-stressed, aquifer systems will aid the conversation (Butler *et al.*, 2021). Within the urban context, useful lessons can also no doubt be learned from recovering groundwater systems in many post-industrial cities around the world (Lerner & Barrett, 1996).

Groundwater science has a clear strength and role in defining and analysing renewable groundwater use, as is the focus of this paper. However, we consider that it is also critical as groundwater scientists, that we also contribute to broader discussions of defining and analysing groundwater sustainability. For example, we need to rigorously assess the likely impacts of proposed 'solutions' to real or perceived problems caused by groundwater abstraction, through dialogue and training while respecting, collaborating and working with other disciplines using an agreed, robust and transparent shared vocabulary. Our definitions and clarifications in this paper are our attempt to contribute to this endeavour.

We hope this paper will stimulate practical reflections and therefore we end with the following questions, as a way to promote further and wider dialogue on this issue, and to encourage the reader to reflect on the practical possibilities of groundwater resources in their own experience:

- *Where do aquifers of concern currently plot on the quadrant diagram (Figure 3b)?*
- *Where would stakeholders, managers and decision makers like them to plot?*
- *What actions can be taken to get them there?*

We leave it to the community to explore the utility of the conceptual framework and implications we have proposed here and continue the discussion. We hope that by renewing such conversations we can help yield safer, more sustainable and less stressful or depleting definitions of groundwater use.

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Open Research – Data and Software Availability

There are no data or code associated with this Commentary.

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