

1 The groundwater age-sustainability myth

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3 as a Commentary.

4 **Grant Ferguson^{1,2,3*}, Mark O. Cuthbert^{4,5} Kevin Befus⁶, Tom Gleeson⁷ and Jennifer C. McIntosh^{1,3}**

- 5
- 6 1. Civil, Geological and Environmental Engineering, University of Saskatchewan
- 7 2. School of Environment and Sustainability, University of Saskatchewan
- 8 3. Hydrology and Atmospheric Sciences, University of Arizona
- 9 4. School of Earth and Ocean Sciences and Water Research Institute, Cardiff University
- 10 5. Connected Waters Initiative Research Centre, University of New South Wales
- 11 6. Civil and Architectural Engineering, University of Wyoming
- 12 7. Department of Civil Engineering and School of Earth and Ocean Sciences, University of Victoria

13 Corresponding author email: grant.ferguson@usask.ca

14 Preface

15 **The ideas that old or “fossil” groundwater cannot be pumped sustainably, or that recently recharged**
16 **groundwater is inherently sustainable are both mistaken. Both old and young groundwaters can be**
17 **used in physically sustainable or unsustainable ways.**

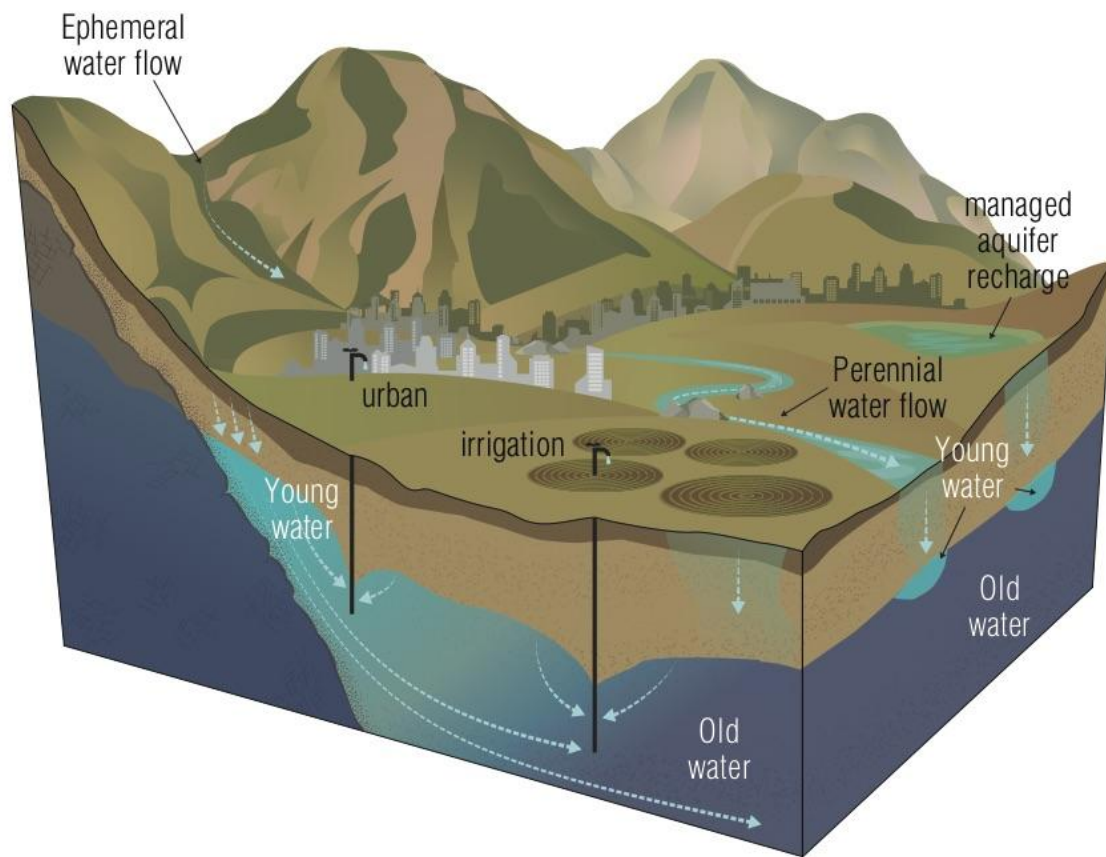
18 The myth that old groundwater with long residence times is a non-renewable resource has infiltrated
19 the scientific literature¹⁻³ and has been bolstered by media coverage of regional to global groundwater
20 issues. The propagation of this myth is problematic because it creates confusion around what
21 constitutes sustainable development of groundwater resources and their renewability (see box for
22 definitions). **We show how groundwater residence times and ages are not metrics that can directly**
23 **define groundwater sustainability. However, quantifying the distribution of groundwater ages in an**
24 **aquifer can improve our understanding of aquifer systems, which can indirectly enable sustainable**
25 **groundwater use.** Dispelling the groundwater age-sustainability myth is critical to enable clear thinking
26 about groundwater depletion which continues to emerge as a global problem⁴. Our commentary focuses
27 on what groundwater age and residence time can and cannot tell us about the functioning of past and
28 present groundwater systems and their connections to other Earth system processes.

29

Box: defining groundwater age, residence time, sustainability and renewability

Groundwater age is the interval of time that has elapsed since the water entered the groundwater system whereas mean **residence time** (herein just called 'residence time') is the volume of water in a groundwater system divided by the volumetric recharge (or discharge) rate, which gives an average turnover time for the system⁵. **Fossil groundwater** is groundwater that was recharged by precipitation more than ~12,000 years ago, prior to the beginning of the Holocene Epoch, whereas **modern groundwater** is often defined as being less than ~50 years old⁶. Ages are typically derived from interpretation of various isotope tracers, which may differ from the actual age of the water due to various mixing and transport processes that occur within groundwater systems as well as capture of different flowpaths over the screened interval of wells used for sampling^{5,7}.

Groundwater sustainability is maintaining long-term, dynamically stable flows and accessible storage of high-quality groundwater using inclusive, equitable, and long-term governance and management⁴. Physical groundwater sustainability is groundwater use that can be dynamically captured during pumping that leads to a new dynamically stable equilibrium in groundwater levels while maintaining environmental flows. Groundwater is **renewable** if this new equilibrium occurs within human timescales (i.e. decades to a century)⁴. This differs from previous definitions of renewable groundwater, which have invoked recharge rates⁸ or threshold residence times^{2,3}.



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34

35 Figure 1: Human activities interface with natural hydrologic processes to set the distribution of
 36 groundwater ages, which are not a metric of groundwater sustainability or renewability. Similar
 37 drawdown cones will develop from wells with identical pumping rates located in positions with different
 38 mixes of groundwater age.

39

40 **Infiltration of a myth**

41

42 Groundwater age and residence time are a function of groundwater recharge rate, contributing to the
 43 notion that they are important considerations in the sustainable development of groundwater. This is
 44 based on the idea that pre-development groundwater recharge represents the amount of renewable
 45 groundwater⁸. Defining groundwater renewability by balancing pumping with pre-development
 46 recharge has been called the “Water Budget Myth”⁹, as pumped groundwater actually has three

47 sources: 1) groundwater storage, and 'capture' which is a combination of changes in 2) recharge and/or
48 3) discharge.

49

50 Our focus is another myth: the notion that sustainable development of groundwater resources can be
51 defined on the basis of thresholds of groundwater residence times or age¹⁻³. The residence time of
52 groundwater in an aquifer is a function of its recharge rate and pore volume and larger aquifers will
53 have longer residence times for a given recharge rate. Using residence times as a renewability
54 benchmark therefore leads to the nonsensical conclusion that groundwater use from smaller aquifers
55 may be more sustainable, despite having the same rates of replenishment. Instead, we argue that
56 physical sustainability should only be defined relative to human use: whether water levels and flows
57 stabilize to acceptable levels on reasonable timescales (Box).

58

59 Further, groundwater age is a function of distance from the recharge area (Figure 1). If pumping older
60 groundwater is less sustainable than pumping young groundwater, in general terms this implies that
61 pumping will be more sustainable if wells are either shallower, or situated nearer to a recharge area.
62 However, situating pumping wells closer to a recharge area has no obvious connection to the
63 renewability of groundwater resources. In contrast, pumping a mixture of older groundwaters near
64 discharge areas may in some cases result in less groundwater depletion if induced recharge from surface
65 water occurs, which may be more sustainable if the impacts on environmental flows are insignificant. In
66 either situation, tradeoffs between reduced drawdown and increased capture of streamflow would
67 need to be evaluated to determine which locations allow for the sustainable development of the
68 system.

69

70 A variety of studies have documented the presence of very old groundwater, some of which were
71 recharged under climates that were more humid than those present today¹⁰. It has often been
72 suggested that use of such groundwater is unsustainable because these systems are being currently
73 recharged at much lower rates than they were in the past³. While pre-development recharge is not an
74 upper limit to the amount of water that can be sustainably withdrawn from an aquifer, reductions in
75 groundwater recharge over time may affect the amount of water available for capture and could lead to
76 increased groundwater depletion. However, in most cases where the presence of old groundwater has
77 been invoked to determine the sustainability of groundwater use, there has been no attempt to quantify
78 variation in groundwater recharge rates over time. Most studies that have compiled groundwater age

79 data covering regional groundwater systems, such as the Nubian aquifer¹⁰, Great Artesian Basin¹¹ and
80 Black Mesa Basin,¹² have found a continuum of ages, indicating continuous groundwater recharge over
81 long time periods. Further complicating this issue is the difference between the transport times that
82 lead to the observed groundwater age distributions and the time required for hydraulic heads to re-
83 equilibrate to shifts in climate¹³, which may be shorter. There is an opportunity to improve our
84 understanding of the past and future functioning of groundwater systems and the wider Earth system by
85 more rigorously integrating age data with hydraulic analyses than has been typically done.

86

87 **Rethinking groundwater age, residence times and sustainability**

88

89 Groundwater age does not provide a direct measure of whether groundwater resources can be
90 sustainably developed, and reducing groundwater sustainability decision making to such a simplistic
91 dichotomy undermines fundamental concepts in groundwater sustainability science. Pumping young
92 groundwater does not guarantee sustainability and pumping old groundwater does not guarantee non-
93 sustainability. Prohibiting use of old groundwater could needlessly decrease water security in some
94 instances. Similarly, the concept of renewable groundwater as defined by mean groundwater residence
95 times should be abandoned. In dispelling the myth that groundwater age is linked to sustainable
96 groundwater use, we are not advocating indiscriminate or wanton use of old or young groundwaters.
97 Rather, we argue for adopting a new definition of groundwater sustainability that uses field
98 observations of water levels and flows and water quality to directly be the metric of groundwater
99 sustainability⁴ (Box).

100

101 Despite the lack of a direct connection between groundwater age and sustainability, we are not
102 suggesting to cease collecting isotopic and other geochemical data used to estimate groundwater ages.
103 Detailed groundwater age data can be valuable in reducing uncertainty in models used to test
104 groundwater resource development scenarios because of the sensitivity of age data to spatial variations
105 in permeability⁷. However, mean residence times are unlikely to provide useful information because of
106 the broad spectrum of residence times of various flowpaths present in groundwater systems.
107 Characterizing the distribution of groundwater ages, using multiple age tracers that span the full age
108 spectrum, can be more valuable in the protection of water quality, evaluating capture, and
109 understanding the origin and distribution of natural or anthropogenic contaminants in the subsurface^{6,7}.
110 However, a substantial challenge exists in addressing dispersive processes in groundwater systems,

111 which lead to the presence of mixed ages within individual water samples. Recent development of new
112 intermediate age tracers (e.g., ³⁹Ar, ⁸⁵Kr) helps fill in the 'data gap' between modern and fossil recharge,
113 providing new opportunities to disentangle mixed ages, understand the myriad of groundwater
114 flowpaths, and constrain models used for water resource management.

115
116 An emerging use of groundwater age data is the documentation of the rearrangement and acceleration
117 of groundwaters in the Anthropocene. In addition to changes in age distributions due to altered
118 directions of groundwater flow and increased velocities associated with pumping⁷, other impacts may
119 occur due to variations in groundwater recharge patterns associated with land-use change and return
120 flows from irrigation¹⁴ (Fig 1). For example, managed aquifer recharge projects using either surface
121 water or effluent are becoming increasingly common in India, the United States, Israel and Australia¹⁵,
122 increasing the amount of young groundwater in these regions. Measurement of ages using multiple
123 isotopes can provide insights into mixing that has arisen in groundwater systems due to these and other
124 human interventions. These changes in flow patterns and associated mixing are likely not important to
125 physical groundwater sustainability, however, they may be important to groundwater quality⁶,
126 geochemical and carbon cycles¹⁶, and geomicrobiology¹⁷.

127
128 Groundwater age measurements are capable of providing valuable insights into the functioning of
129 groundwater systems both under natural and perturbed conditions. However, the use of groundwater
130 ages and mean residence times as metrics of sustainable development of groundwater is incorrect. This
131 myth must be dispelled in favour of more constructive metrics of groundwater sustainability based on
132 maintaining water levels, water quality, and environmental flows.

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