1 Reviews and Syntheses: Variable Inundation
2 Across Earth's Terrestrial Ecosystems

3   James Stegen[1,2], Amy J Burgin[3], Michelle H. Busch[3], Joshua B. Fisher[4], Joshua Ladau[5], Jenna
4   Abrahamson[6], Lauren Kinsman-Costello[7], Li Li[8], Xingyuan Chen[1], Thibault Datry[9], Nate
5   McDowell[1], Corianne Tatariw[10], Anna Braswell[11], Jillian M. Deines[1], Julia A. Guimond[12], Peter
6   Regier[1], Kenton Rod[1], Edward K. P. Bam[13], Etienne Fluet-Chouinard[1], Inke Forbrich[14], Kristin L.
7   Jaeger[15], Teri O'Meara[16], Tim Scheibe[1], Erin Seybold[3], Jon N. Sweetman[8], Jianqiu Zheng[1],
8   Daniel C Allen[8], Elizabeth Herndon[16], Beth A. Middleton[17], Scott Painter[16], Kevin Roche[18],
9   Julianne Scamardo[19], Ross Vander Vorste[20], Kristin Boye[21], Ellen Wohl[22], Margaret Zimmer[23],
10 Kelly Hondula[24], Maggi Laan[1], Anna Marshall[22], and Kaizad F. Patel[1]
11
12 [1]Pacific Northwest National Laboratory, Richland, WA, USA
13 [2]School of the Environment, Washington State University, Pullman, WA, USA
14 [3]University of Kansas, Lawrence, KS, USA
15 [4]Chapman University, Orange, CA, USA
16 [5]University of California San Francisco, San Francisco, CA, USA
17 [6]North Carolina State University, Raleigh, NC, USA
18 [7]Kent State University, Kent, OH, USA
19 [8]Penn State University, State College, PA, USA
20 [9]National Institute for Agriculture, Food, and Environment (INRAE), Villeubanne, France
21 [10]Rowan University, Glassboro, NJ, USA
22 [11]University of Florida, Gainesville, FL, USA
23 [12]Woods Hole Oceanographic Institution, Woods Hole, MA, USA
24 [13]International Water Research Institute (IWRI), Mohamed VI Polytechnic University, Benguerir, Morocco
25 [14]University of Toledo, Woods Hole, MA, USA
26 [15]U.S. Geological Survey, Washington Water Science Center, Tacoma, WA, USA
27 [16]Oak Ridge National Laboratory, Oak Ridge, TN, USA
28 [17] U.S. Geological Survey, Wetland and Aquatic Research Center, Lafayette, LA, USA
29 [18]Boise State University, Boise, ID, USA
30 [19]University of Vermont, Burlington, VT, USA
31 [20]University of Wisconsin, La Crosse, WI, USA
32 [21]SLAC National Acceleratory Laboratory, Menlo Park, CA, USA
33 [22]Colorado State University, Fort Collins, CO, USA
34 [23]U.S. Geological Survey Upper Midwest Water Science Center, Madison, WI, USA
35 [24]Arizona State University, Tempe, AZ, USA
36
37
38
39
40 Correspondence: James C. Stegen, E-mail: james.stegen@pnnl.gov; Phone: (509) 371-6763
41

42 **Abstract**

43 The structure, function, and dynamics of Earth's terrestrial ecosystems are profoundly
44 influenced by the frequency and duration that they are inundated with water. A diverse array of
45 natural and human engineered systems experience temporally variable inundation whereby they
46 fluctuate between inundated and non-inundated states. Variable inundation spans from extreme
47 flooding and droughts to predictable sub-daily cycles. Variably inundated ecosystems (VIEs)
48 include hillslopes, non-perennial streams, wetlands, floodplains, temporary ponds, tidal
49 systems, storm-impacted coastal zones, and human engineered systems. VIEs are diverse in
50 terms of inundation regimes, water chemistry and flow velocity, soil and sediment properties,
51 vegetation, and many other properties. The spatial and temporal scales of variable inundation
52 are vast, ranging from sub-meter to whole landscapes and from sub-hourly to multi-decadal.
53 The broad range of system types and scales makes it challenging to predict the hydrology,
54 biogeochemistry, ecology, and physical evolution of VIEs. Despite all experiencing the loss and
55 gain of an overlying water column, VIEs are rarely considered together in conceptual,
56 theoretical, modeling, or measurement frameworks/approaches. Studying VIEs together has the
57 potential to generate mechanistic understanding that is transferable across a much broader
58 range of environmental conditions, relative to knowledge generated by studying any one VIE
59 type. We postulate that enhanced transferability will be important for predicting VIE function
60 under future, potentially non-analog, environmental conditions. Here we aim to catalyze cross-
61 VIE science that studies drivers and impacts of variable inundation across Earth's VIEs. To this
62 end, we complement expert mini-reviews of eight major VIE systems with overviews of VIE-
63 relevant methods and challenges associated with scale. We conclude with perspectives on how
64 cross-VIE science can derive transferable understanding via a 'continuum approach' in which
65 the impacts of variable inundation are studied across multi-dimensional environmental space.

66 **Introduction**

67 The chemical and biological processes within terrestrial ecosystems hinge on the presence,
68 residence time, volume, and chemistry of water. A variety of factors influence water retention,
69 infiltration and flow, such as land surface relief, topographic slope, subsurface permeability,
70 evapotranspiration, and human-based modifications of the landscape. Water supply is most
71 commonly 'top down' in the form of precipitation and overland flow or 'bottom up' due to rising
72 water tables and transient saturation in the subsurface (Smith et al. 2017). Inundation, however,
73 may also occur from lateral inputs, as is common in tidal systems, or from upslope inputs, as in
74 floodplains. Regardless of where water comes from, inundation occurs when the rate of water
75 supply is greater than the rate of export via infiltration, evapotranspiration, and runoff.
76   Here we define inundation as occurring when there is a near continuous aqueous barrier
77 that limits gas phase transport between the atmosphere and the subsurface. This
78 conceptualization is inclusive of diverse conditions, spanning from extreme events such as
79 hurricane-driven flooding to shallow short-lived overland flow across hillslopes. We define
80 variably inundated ecosystems (VIEs) as those that experience dynamic shifts between the
81 presence and absence of inundated conditions, at any spatial and temporal scale. Variably
82 inundated ecosystems cover at least 5-9 million km^2, or 4-7% of the Earth's land surface
83 excluding Greenland and Antarctica. These estimates are according to monthly data over

84   multiple decades (Zhang et al. 2017, 2021, Davidson et al. 2018), and are likely significant
85   underestimates as many VIEs are not resolvable by commonly used remote sensing
86   techniques.
87   Variable inundation occurs across a wide range of terrestrial ecosystems, but the factors
88   governing its influences are typically studied independently without cross-ecosystem
89   comparisons. Some examples of VIEs are hillslopes with overland flow, non-perennial streams,
90   floodplains and parafluvial zones, variably inundated wetlands, vernal ponds/pools/playas, tidal
91   systems, coastal systems impacted by storm-driven flooding, and human-engineered systems
92   intended to shift inundation dynamics (e.g., flood-irrigated agriculture, stormwater infrastructure,
93   and constructed wetlands) (**Fig. 1**). While VIEs may be classified as wetlands under the
94   broadest definition from the Ramsar Convention (Secretariat 2016), there is significant variation
95   in how wetlands are defined (Finlayson and Van Der Valk 1995) and we do not attempt to rectify
96   or clarify variation in those definitions. Here, when using the term 'wetland' we simply align with
97   the perspective that wetlands are similar to marshes, swamps, and bogs.
98   Inundation dynamics are changing due to increased variability and magnitudes of
99   precipitation and evapotranspiration, accelerated sea level rise, and human modifications to the
100   Earth's land surface, including an increase in extreme events (Konapala et al. 2020, Li et al.
101   2022a). Extreme events such as coastal flooding are increasingly frequent, and while seasonal
102   drying of streams is now more common (Sweet et al. 2014, Zipper et al. 2021), some streams
103   are shifting from non-perennial to perennial (Döll and Schmied 2012, Datry et al. 2018a) while
104   others have fewer no-flow days than they did historically (Zipper et al. 2021). Wetland
105   inundation extent, duration, and seasonal timing are also projected to be altered by climate
106   change (Londe et al. 2022a). Thus, the dynamics of inundation are changing in different ways
107   across different VIEs (Zipper et al. 2021) such that we cannot rely exclusively on historical
108   dynamics to predict future impacts (e.g., on species diversity) of changing inundation dynamics
109   (Culley et al. 2016, Quinn et al. 2018, Rameshwaran et al. 2021, Li et al. 2022b).

Figure 1. *Variably inundated ecosystems (VIEs) span numerous ecosystem types and are globally distributed across the Earth's land surface.* *There are few places across Earth's land surfaces that do not experience variable inundation, which is defined here as the loss/gain of an aqueous barrier between the atmosphere and porous media (e.g., soil) that inhibits gas phase transport. Due to global changes in the dynamics of variable inundation, there is a need to integrate knowledge into models that are predictive across VIEs. This will require intentionally studying VIEs together to understand how the details of any given VIE modulate the impacts of variable inundation. Credit: Nathan Johnson. There are several photos from different sources and permissions granted as follows: (a) Sullivan et al 2019; (b) Jon Sweetman, co-author; (c) Shutterstock; (d) @WeirdBristol [Twitter] 2018; (e, f, g, h) Shutterstock; (i) Mikac et al 2018.*

123   Mechanistic knowledge that is transferable across inundation regimes (i.e., from extreme
124   events to predictable cycling) and across VIEs is required to develop models that are predictive
125   across contemporary and future conditions. We envision the impacts of variable inundation as
126   dependent on the location of any given VIE in multi-dimensional environmental space. This
127   space can be defined with a variety of environmental variables such as inundation return
128   interval and duration, topographic slope, vegetation composition, precipitation, and temperature.
129   Many other variables could be used, but regardless, environmental change will cause VIEs to
130   move to different areas within multi-dimensional environmental space. Predicting future impacts
131   of variable inundation requires mechanistic understanding of how the location of a VIE in this
132   space influences those impacts. We propose that our best chance to achieve such
133   understanding is to generate knowledge of variable inundation impacts that is transferable
134   across VIEs.
135   Here we aim to catalyze cross-VIE science for the pursuit of transferable knowledge and
136   ultimately models that are predictive across and aid in conserving contemporary and future
137   VIEs. We briefly summarize high-level divergences in drivers of variable inundation,
138   commonalities in the impacts of variable inundation, and then present expert mini-reviews of
139   eight major VIE systems. Variable inundation occurs across vast ranges in spatial and temporal
140   scales, which presents challenges to cross-VIE science. As such, we overview these challenges
141   and offer suggested solutions along with a summary of methods that are most relevant to VIE
142   science. We conclude with perspectives on how cross-VIE science can derive transferable
143   understanding to better protect these systems and their biodiversity.
144
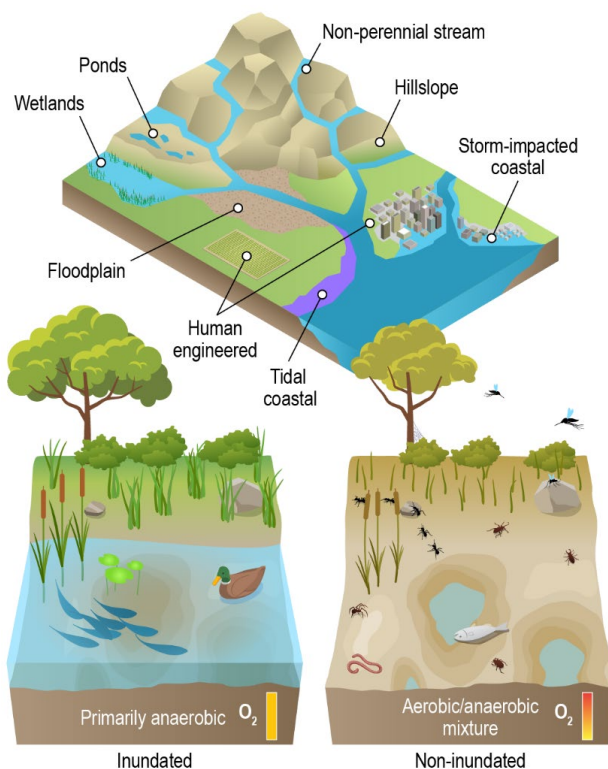
Figure 2. *Conceptual overview of where different types of VIEs are commonly found within watersheds and some common shifts in system states across inundated and non-inundated conditions. VIEs are found from headwaters to coastal environments (Top) and the impacts of variable inundation have some consistencies across these diverse landscapes (Bottom). Organismal ecology, physiology, and demographics are altered by variable inundation, leading to shifts in community composition. Biogeochemical processes also shift, such as greater gas-phase transport of oxygen into soil/sediment when surface water is lost, with associated shifts in redox processes. The details of these responses to variable inundation are, however, likely to vary across VIEs due to variation in system properties such as dominant vegetation types, rhizosphere development, soil/sediment texture, water salinity, flow velocity, etc. A key goal for cross-VIE science is to mechanistically link variation in these system properties to impacts of variable inundation across the multi-dimensional environmental space occupied by VIEs. Credit: Nathan Johnson.*

Divergent Drivers, Common Responses, and VIE Mini-Reviews

The drivers of variable inundation differ markedly across VIEs and are linked to factors such as long-term drought, heavy precipitation, evapotranspiration, changing groundwater storage, soil/sediment properties, extreme climatic events, and dam operations. This leads to significant variation across VIEs in inundation regimes, which includes inundation timing, return interval,

165   duration, spatial extent, depth, and flow rate. For example, sediments within the active channel
166   of tidal rivers can experience sub-daily losses and gains of surface water, while other coastal
167   zones may experience extreme inundation events on a 100 year return interval. Other systems,
168   such as non-perennial streams and vernal ponds, also experience a broad range of inundation
169   regimes, ranging from sporadic and extreme inundation following rain events to more regular
170   seasonal cycles. Variation in the spatial scale of inundation is also large, with floodplains and
171   storm-impacted coastal zones experiencing inundation over tens of kilometers, whereas non-
172   perennial streams and ponds can experience changes across a few meters. As discussed
173   below within the series of VIE mini-reviews, the temporal and spatial scales of inundation also
174   vary substantially within each type of VIE. Variation within a given type of VIE is large enough
175   that we suggest it cannot be used to clearly differentiate VIEs into named categories. As
176   discussed in the "Toward cross-VIE transferable understanding" section, this is one motivation
177   for pursuing a continuum approach to cross-VIE science.

178   Variable inundation impacts physical [e.g., sediment transport (Peruccacci et al. 2017, Siev
179   et al. 2019)], chemical [e.g, water quality (Whitworth et al. 2013)], and biological/ecological [e.g.,
180   invertebrate communities (Plum 2005)] attributes of both natural and anthropogenically modified
181   ecosystems, in addition to human society (Dube et al. 2021) (**Fig. 2**). Due to intense periods of
182   inundation and drought, these systems are often referred to as hotspots or ecosystem control
183   points (Bernhardt et al. 2017), with disproportionately high reaction rates or areas of high
184   diversity (Davidson et al. 2012, Palta et al. 2014). In a qualitative sense, some of these impacts
185   are common across VIEs even if the quantitative details vary.

186   During inundated periods, biogeochemical processes in VIEs often shift from a dominance
187   of aerobic respiration during drier periods to a diverse suite of anaerobic processes, such as
188   methanogenesis (Datry et al. 2018b, Hondula et al. 2021b). Changes in the frequency of
189   inundation events change the dynamics of dry-wet, hot-cold, and aerobic-anaerobic transitions
190   (Valett et al. 2005). Such dynamics can challenge existing theories. For example, while rates of
191   soil respiration are expected to peak under aerobic conditions, periodic anaerobic conditions
192   can lead to unexpectedly high rates of soil carbon loss (Huang et al. 2021) and the anaerobic
193   process of methanogenesis can be fastest in well-oxygenated dry soils (Angle et al. 2017). More
194   broadly, variable inundation can alter fluxes of greenhouse gasses to the atmosphere such as
195   the common observation of soil rewetting leading to significant carbon loss arising from sudden
196   intensification of soil respiration (Schimel 2018, Shumilova et al. 2019). Variation in inundation
197   also has large impacts on the global CH_4 budget (Zhang et al. 2017, Peng et al. 2022) and
198   rewetting of dry sediment in intermittent streams can contribute considerably to the total CO_2
199   emissions from streams (von Schiller et al. 2019). More generally, top down and bottom up
200   hydrologic inundation events broadly influence biogeochemical cycles (Smith et al. 2017) and
201   can result in hysteretic responses to wetting and drying (Patel et al. 2022).

202   Across VIEs, inundation impacts the structure, composition, and function of vegetation
203   communities. Growth and survival can either increase or decrease with inundation depending
204   on local aridity and the impacts on soil hypoxia. Hypoxia kills roots, leading to reduced water
205   uptake, reduced photosynthesis, mortality (Pedersen et al. 2021, McDowell et al. 2022, Cubley
206   et al. 2023), and shifts in vegetation composition. More broadly, inundation dynamics impact
207   organismal ecology (Datry et al. 2023) across all VIEs, such as herbivores responding to
208   inundation-induced shifts in vegetation (De Sassi et al. 2012). Inundation can also alter

209   arthropod communities leading to reductions in diversity, abundance, and biomass with flooding
210   (Plum 2005). Changes at the base of food webs can have further, cascading effects (Chen and
211   Wise 1999).
212   To pursue cross-VIE science requires knowledge of the diverse array of ecosystems that
213   can be considered VIEs. Researchers that design and carry out cross-VIE studies may be
214   considered generalists in terms of the breadth of systems they study, even if their science
215   questions are highly specialized. To facilitate such researchers in the pursuit of cross-VIE
216   science, we go beyond the high-level summaries of divergences and commonalities (above)
217   and provide expert mini-reviews of eight primary VIE types. The following subsections present
218   these mini-reviews which summarize system characteristics, drivers, and impacts of variable
219   inundation with an emphasis on biogeochemistry and organismal ecology, and opportunities to
220   better understand spatiotemporal patterns and impacts of variable inundation. Each mini-review
221   is accompanied by a graphic that either provides a conceptual overview or imagery-based
222   examples, with the goal of collectively touching on key drivers, dynamics, impacts, and tangible
223   system examples. The collection is not meant to be a comprehensive classification of all
224   possible VIE types, but does cover a broad range of VIEs. The sequence of mini-reviews
225   roughly follows the flow of water moving from hillslopes to coastal environments (**Fig. 2**) and
226   includes variably inundated components of: (*i*) hillslopes, (*ii*) non-perennial streams, (*iii*) riverine
227   floodplains and parafluvial zones, (*iv*) wetlands, (*v*) temporary ponds, (*vi*) storm-impacted
228   coastal zones, and (*vii*) tidal systems. The final mini-review (*viii*) is focused on ecosystems that
229   have been engineered to modify inundation regimes, which occur throughout the continuum
230   from hillslopes to coasts.
231   We separate VIEs into categories as a heuristic simplification that allows for an appreciation
232   of variation and commonalities in drivers, impacts, and opportunities. We anticipate that the
233   disciplinary foci of individual researchers will align most closely with a subset of the summarized
234   VIE types. One goal of this manuscript is to facilitate researchers thinking about how their
235   science applies across VIEs. We emphasize that in many (and maybe all) cases there is not a
236   clear distinction among the types of VIEs we discuss below (e.g., non-perennial streams can be
237   flooded due to storm surge, resulting in floodplains or parafluvial zones). Ultimately, we
238   encourage a continuum perspective that does not rely on discrete system names or hard
239   boundaries, and instead views VIEs across multi-dimensional environmental space based on
240   inundation regimes and physical settings.

**Hillslopes with Surface Runoff**

242   Hillslopes provide water to lower-lying areas, often concentrating the water in gullies and
243   depressions (**Fig. 3**). Hillslopes produce relatively transient VIE features and may often be seen
244   as extensions of other VIEs, such as hillslope seeps co-located with a wetland or the
245   unchannelized swales that contribute to a non-perennial network. In cold regions, snow, ice and
246   permafrost can create an impermeable layer resulting in near-surface soil being inundated for
247   days to weeks during spring thaw (Coles et al. 2017, Patel et al. 2020). In dry regions, intense
248   precipitation that exceeds the local infiltration capacity can result in water ponding on the
249   surface of hillslopes or overland flow generation down hillslopes, which can be exacerbated by
250   initial hydrophobicity of dry soil (Kirkby et al. 2002). Exceeding the infiltration capacity is more
251   likely on hillslopes with low-permeability, such as clay-rich soil or when near-surface soils are

252 frozen. This can be exacerbated by restrictive soil horizons located at shallow depths across
253 hillslopes that generate seasonal perched water tables and lead to inundation (McDaniel et al.
254 2008). Overland flow can be spatially heterogeneous due to variations in soil characteristics as
255 well as flow accumulation, leading to infiltration or exfiltration along the hillslope (Betson and
256 Marius 1969).
257   In forested hillslopes, soil infiltration often exceeds rainfall intensity (McDonnell 2009, Burt
258 and Swank 2010) and lateral flow towards topographic depressions can lead to saturation and
259 ponding (Anderson and Burt 1978) (**Fig. 3a**). Microtopography within hillslopes (**Fig. 3b**) can
260 also lead to temporary ponding, e.g., from rain in tropical environments and from spring
261 snowmelt in colder environments (Clark et al. 2014). Toe slopes can generate wedges of
262 saturation that grow upslope (Weyman 1973, Choularton and Perry 1986), although subsurface
263 saturation and ponding can also occur on upper slopes where the soil is thinner [e.g., (Tromp-
264 van Meerveld and McDonnell 2006)]. Finally, spatial variation in topographic characteristics
265 (e.g., aspect, slope, curvature) can result in differences in soil moisture, incoming energy, and
266 vegetation, affecting evapotranspiration and inundation patterns (McVicar et al. 2007).
267
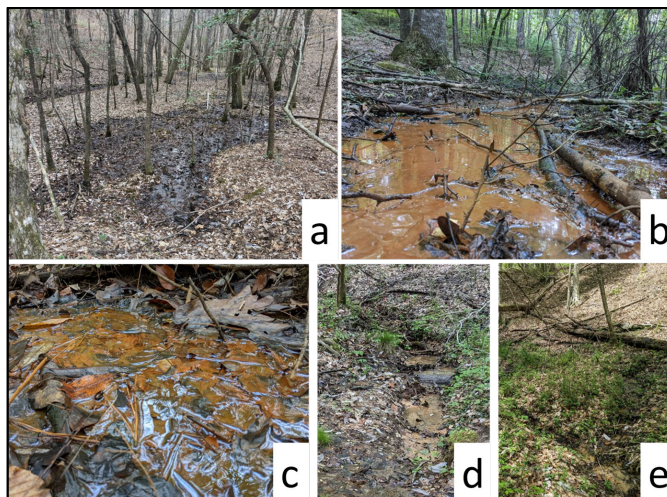
269 **Figure 3**. *Examples of variable inundation along hillslopes. a) looking downslope at an*
270 *inundated slope; b) ponding due to microtopography; c) sheet wash across the surface of a*
271 *hillslope; d) rill formation with turbid water from erosion; e) vegetation community change on*
272 *slope due to differences in soil moisture. All photos taken by Corianne Tatariw at Tanglewood*
273 *Forest, Alabama.*
274

275   Surface runoff and inundation on hillslopes can result in the export of soil nutrients,
276 salinization of soil from groundwater seeps, erosion, and landslides. There is a balance between
277 the effects of variable inundation on hillslope vegetation and erosion. In water-limited systems,
278 inundation can increase plant productivity and diversity, as well as increased rooting strength of
279 soils (Zhao et al. 2022) (**Fig. 3e**). However, increased inundation can also lead to increased
280 chemical weathering and lower shear strength in hillslope soils during storms, leading to higher
281 erosion and landslide potential. Along with erosion, landslides and soil compaction are inherent

282 to many hillslopes, which also can create areas ripe for inundation (Bogaard and Greco 2016).
283 At shoulder and midslope positions, increased overland flow due to saturation- or infiltration-
284 excess increases sediment detachment, which is then deposited in foot and toe slopes (Huang
285 et al. 2002). The transport of particles also leads to the transport of nutrients that are sorbed to
286 the particles, such as phosphorus. Erosion can be concentrated in rills and gullies or can spread
287 out across a slope as 'sheet wash' that impacts large areas of hillslopes (**Fig. 3c,d**). Impacts of
288 erosion are dependent on interactions between the persistence of inundation and soil properties
289 (Thomas et al. 2020).
290   The aqueous chemistry of water that is transported over hillslope surfaces reflects the
291 chemistries of contributing water sources such as precipitation, shallow soil water, and
292 exfiltrating groundwater. Shallow soils in hillslopes have abundant organic materials and
293 nutrients (Herndon et al. 2015), whereas organic matter decreases with depth, solutes derived
294 from the parent rock material increase with depth (Brantley et al. 2017). These stratifications
295 collectively regulate source water chemistry in hillslopes. Dry to wet transitions shift flow paths
296 from groundwater to soil water dominance in streams, therefore shaping stream chemistry (Zhi
297 and Li 2020, Stewart et al. 2022). Dry to wet transitions also shift water content and pore space
298 oxygen concentrations (Jarecke et al. 2016, Smyth et al. 2019), often triggering the release of a
299 cascade of solutes produced under anaerobic conditions (Schlesinger and Bernhardt 2020).
300 These entangled, complex interactions among hydrological and biogeochemical processes
301 often challenge the differentiation of individual processes and mechanistic understanding on
302 how variable inundation regulates flow paths, reactions, stream chemistry, and solute and gas
303 export fluxes (Li et al. 2021).
304   Investigations of variably inundated hillslopes present significant and challenging research
305 opportunities due to their inherently dynamic nature. One key challenge is quantifying the
306 occurrence and spatial extent of hillslope VIEs across the globe. Remote sensing could be used
307 to identify and quantify these areas, spatially and temporally, based on sky-visible vegetation
308 (e.g., plant morphologies, leaf nutrient contents) and topographic signatures (e.g., erosional
309 patterns) caused by variable inundation. To fully understand the ecological and biogeochemical
310 impacts of variable inundation on hillslopes, research needs to focus on shallow subsurface
311 physical properties, hydrology, and their linkage to biogeochemical processes. This can be
312 pursued via environmental geophysics to map and characterize the influence of subsurface
313 restrictive layers (Fan et al. 2019 p. 201). Understanding the subsurface soil architecture is key
314 to predicting variable inundation from bottom-up and top-down water sources, along with the
315 follow-on impacts to ecology and biogeochemistry.

316 **Non-Perennial Streams**

317 Non-perennial streams, defined as rivers and streams that cease to flow at some point in either
318 space or time (Busch et al. 2020), are ubiquitous and comprise 50-60% of the global river length
319 (Messager et al. 2021). These systems occur across all continents and biomes (Messager et al.
320 2021). Streamflow in non-perennial streams ranges from nearly perennial (year-round) flow, to
321 seasonal flow, responding to drivers like snowmelt, to daily or sub-daily flow events responding
322 to rainfall/flood events or evapotranspiration (Price et al. 2021). At the reach scale, non-
323 perennial streams shift between three main states - flowing, ponded/pooled, or no-surface water
324 present (**Fig. 4**). As reaches become hydrologically connected (or disconnected), the spatial

325   footprint/extent of the connected stream network can grow or shrink over sub-daily to seasonal
326   to interannual timescales (Xiao et al. 2019). Spatial and temporal shifts among the three
327   hydrologic states strongly influence the network's capacity to process, transport, and export
328   material to downstream systems (Allen et al. 2020).
329   The high variability in the spatial and temporal scales of streamflow intermittency is
330   indicative of the complex set of interacting drivers that induce stream drying. At the global and
331   regional scales, the degree of aridity is a primary control on the abundance of non-perennial
332   streams (Hammond et al. 2021, Zipper et al. 2021). At smaller scales, catchment properties
333   exert strong control over both the capacity of water delivery to the channel and the subsequent
334   balance between the channel and near subsurface capacity to transport water (Hammond et al.
335   2021, Zipper et al. 2021, Price et al. 2021). Non-perennial flow can occur anywhere in the steam
336   network, from headwaters to higher order rivers. While some networks display longitudinal
337   transitions from non-perennial to perennial flow (or vice versa), other networks exhibit more
338   complex patterns in surface water flow and connectivity, which may be driven by topography,
339   geology, vegetation, or groundwater abstraction/use (Costigan et al. 2015, 2016).
340   The variable inundation dynamics in non-perennial streams have cascading implications for
341   biogeochemical cycling, water quality, ecosystem function, and community ecology. Under non-
342   flowing conditions, riverbeds are characterized by dry conditions or discontinuous and stagnant
343   water pools, often with high temperatures, low dissolved oxygen levels, and long residence
344   times, functioning more like soils (Arce et al. 2019), as described also in the hillslope section.
345   Pooled, non-flowing conditions can lead to steep redox gradients in the shallow subsurface that
346   drive nutrient processing (Datry and Larned 2008, Gómez-Gener et al. 2021, DelVecchia et al.
347   2022). During dry/non-flowing states, terrestrial organic matter accumulates in the channel and
348   is subjected to varying degrees of breakdown (Datry et al. 2018c, Del Campo et al. 2021).
349   Rewetting of accumulated substrates can stimulate microbial activity, nutrient attenuation
350   (Saltarelli et al. 2022), and generate pulses of greenhouse gasses such as CO_2 and N_2O (Datry
351   et al. 2018a, Song et al. 2018). During re-wetting and resumption of flow, non-perennial streams
352   can contain large amounts of terrestrial and aquatic organisms that can be flushed downstream
353   (Corti and Datry 2012, Rosado et al. 2015), with high sediment, dissolved organic carbon, and
354   solutes (Laronne and Reid 1993, Hladyz et al. 2011, Herndon et al. 2018, Wen et al. 2020,
355   Fortesa et al. 2021, Blaurock et al. 2021).
356   Biological responses to rewetting depend on the distribution of habitats and biota at the
357   watershed scale and the duration of the preceding dry phase. In highly dynamic river systems,
358   such as braided rivers, drying and wetting cycles can be spatially patchy and short-lived but
359   frequent, and thus ecological recovery following wetting can be very rapid due to the very active
360   hyporheic zones characterizing these systems (Arscott et al. 2002, Vorste et al. 2016). In other
361   systems recovery can be slow, depending on the proximity of refuges, such as springs, isolated
362   pools, and perennial reaches (Sarremejane et al. 2021, Fournier et al. 2023). Systems with
363   frequent and severe drying events are more likely to be colonized by aerial or other overland
364   dispersers than by aquatic dispersers (Bonada et al. 2007, Bogan et al. 2017a, Sarremejane et
365   al. 2021). Life-history events of some species coincide with predictable rewetting events, such
366   as post-snowmelt fish spawning (Hooley-Underwood et al. 2019) and amphibian and insect life
367   histories (Bogan et al. 2017a). Rewetting also partly determines the germination success and
368   establishment of riparian vegetation (Merritt and Wohl 2002).

369   Compared to their perennial counterparts, non-perennial streams have received less
370   research and monitoring attention and tend to be undervalued relative to ecological/functional
371   performance of perennial streams (Palmer and Hondula 2014). As such, many of the pressing
372   research needs in non-perennial streams are limited by data availability (Van Meerveld et al.
373   2020, Zimmer et al. 2022). Non-perennial streams are systematically under-represented in
374   global gaging networks (Messager et al. 2021, Krabbenhoft et al. 2022), leading to major gaps
375   in our understanding of the timing, magnitude, and duration of flow in diverse non-perennial
376   streams. In addition, our ability to predict the onset or cessation of flowing periods is limited by a
377   lack of gaging. Infrequent grab sampling for water chemistry tends to undersample non-
378   perennial streams specifically, leading to an even greater paucity of biogeochemical data from
379   these systems, particularly during rapid re-wetting events. Spatially explicit data on streamflow
380   intermittency and subsurface conditions at fine spatial scales (10s of meters) remain limited to a
381   few intensively studied catchments [e.g., (Zimmer and McGlynn 2017)]. While some global scale
382   datasets on streamflow intermittency have been developed (Messager et al. 2021), the
383   resolution of these products necessarily omit smaller, headwater reaches, hindering our ability
384   to quantify hydrologic and biogeochemical processes in non-perennial streams broadly
385   (Benstead and Leigh 2012).
386   Major challenges and opportunities include accurate mapping of non-perennial streams and
387   accurate predictions of flow timing at annual, seasonal, and shorter time scales across scales.
388   With limited time series data, predictions of flow in terms of duration, frequency, and spatial
389   extent can be challenging. How the timing and frequency of flow will change under climate
390   change remains an open question. It is expected that an increased frequency and duration of
391   droughts will shift streams toward more non-perennial flow states (Döll and Schmied 2012). In
392   contrast, flow permanence may increase in select areas where streams are fed by melting
393   glaciers or snowpack, or where anthropogenic intervention occurs (Datry et al. 2023). The
394   changing frequency of extreme flow events and rapid no-flow/high-flow oscillations also have
395   the potential to further alter streamflow, biogeochemical processes, and organismal ecology in
396   non-perennial streams, necessitating further integrated hydro-biogeochemical studies in these
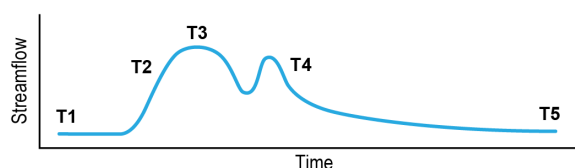397   dynamic systems.
398

a) Inundation mechanisms in non-perennial streams
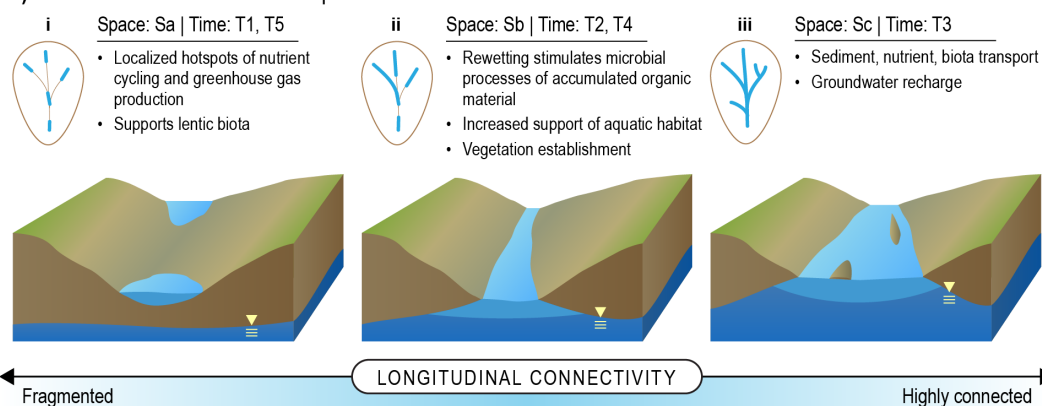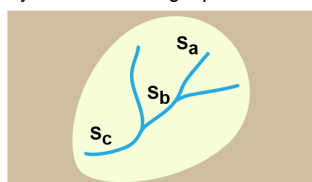
399
400 **Figure 4**. *Conceptual model of variable inundation in non-perennial streams. a) Water*
401 *connections between groundwater, near surface, and surface regions at locations within a given*
402 *network result in varying degrees of longitudinal connectivity with associated biogeochemical*
403 *processes. b) At a single snapshot in time, water connections result in spatial variation in*
404 *surface water inundation. c) Under time varying flow states, extent of surface inundation will*
405 *also vary at a given location. Inundation mechanisms depicted in a) represent a losing system*
406 *that is transitioning to a flowing state. We acknowledge that in some systems, a low flow*
407 *fragmented state also occurs in gaining streams with locally connected groundwater. Spatial*
408 *variation is signified by Sa - Sc and temporal variation is signified by T1 - T5. Credit: Nathan*
409 *Johnson.*

410 ## Floodplains and Parafluvial Zones

411 Rivers, both perennial and non-perennial, create two types of VIEs, floodplains and parafluvial
412 zones (**Fig. 5**). Floodplains are alluvial landforms generated by river erosion and deposition and
413 hydrologically connected to the contemporary active channel but outside the active river channel
414 (Nanson and Croke 1992). Parafluvial zones are areas in the active channel without surface
415 water at low flow, i.e., at higher-elevation areas within an active channel that contains perennial
416 flow (Goldman et al. 2017). Nearly all rivers have parafluvial zones and adjacent floodplains,
417 although these may be longitudinally discontinuous (e.g., absent where the river flows through a
418 narrow bedrock gorge or descends into the subsurface). Consequently, the global distribution of
419 these environments is extensive, as few terrestrial surfaces do not include a river network.

420   Spatial scales of inundation in floodplains and parafluvial zones are variable between rivers
421   and through time along a river. Fundamentally, spatial scales are governed by the interaction
422   between the magnitude of flow and available space as defined by topography. Floodplains of
423   the world's largest rivers such as the Amazon, Congo, or Mississippi can extend laterally for
424   kilometers on both sides of the active channel. In contrast, the floodplain of a headwater
425   channel may be only 1-2 m wide on each side of the channel.
426   Temporal scales of inundation (e.g., frequency, periodicity, intensity) vary substantially
427   across climates, topographic regions, and river network position. A snowmelt-dominated or
428   monsoon-fed river will have a regular annual flood that lasts for weeks, whereas a small stream
429   dominated by convective rainfall or tropical depressions may have irregular floods that only last
430   for hours. Although precipitation-driven over bank flow from the main and tributary channels is
431   the primary driver of inundation on floodplains and parafluvial zones, inundation also results
432   from direct precipitation, rising water tables, and overland flow from adjacent uplands (Mertes
433   2011). Thus, inundation of floodplains may be directly related to their proximity to variably
434   inundated hillslopes and streams.
435   The nature of floodplain/parafluvial inundation affects the dynamics of surface and
436   subsurface water, solutes, particulate organic matter, sediment, and biota (Junk et al. 1989).
437   Dynamics include volume and duration of storage; rate of movement; direction of movement
438   between surface, hyporheic, and groundwater; and biogeochemical alterations that in turn
439   impact river water quality, greenhouse gas emissions, plant function, and organismal ecology.
440   The duration, frequency, and areal extent of floodplain/parafluvial inundation control ecosystem
441   function, and the types and abundances of organismal communities, including both aquatic and
442   terrestrial species (Ward et al. 1999). Species distribution, movement, and biological
443   interactions, such as predator-prey, are intricately tied to these inundation patterns (Robinson et
444   al. 2002, Stanford et al. 2005). Fish species, for example, can migrate from dry season refugia
445   into floodplains during inundation, influencing food web structure and ecosystem productivity
446   (Crook et al. 2020).
447   Among the primary challenges to answering questions regarding the variation in
448   floodplain/parafluvial inundation are limited monitoring data and a lack of numerical models that
449   integrate knowledge across disciplines and processes. Measurements and models of hydrology
450   commonly treat floodplains as flat, impermeable surfaces, which ignores surface-subsurface
451   water exchanges that influence hydrology and ecosystem function (Wohl 2021). Models also
452   often ignore the micro-heterogeneities that influence spatially and temporally variable patterns
453   of inundation, biogeochemical cycling, and ecology in both floodplains and parafluvial zones.
454   The degree of physical detail represented in models often involves tradeoffs in spatiotemporal
455   extent; a one-dimensional model might ignore microtopography that influences important
456   inundation details, whereas a more representative two-dimensional or three-dimensional model
457   becomes computationally intensive for larger spatial extents. This problem gives rise to the
458   challenges and opportunities for (i) designing measurement campaigns across disciplines that
459   can create integrative data for diverse floodplains and parafluvial zones to adequately represent
460   the physical complexity of variable inundation processes at broad scales, and (ii) developing
461   floodplain/parafluvial functional groups [e.g., (Fryirs and Brierley 2022)] that can facilitate
462   understanding of scaling and transferability of data.
463
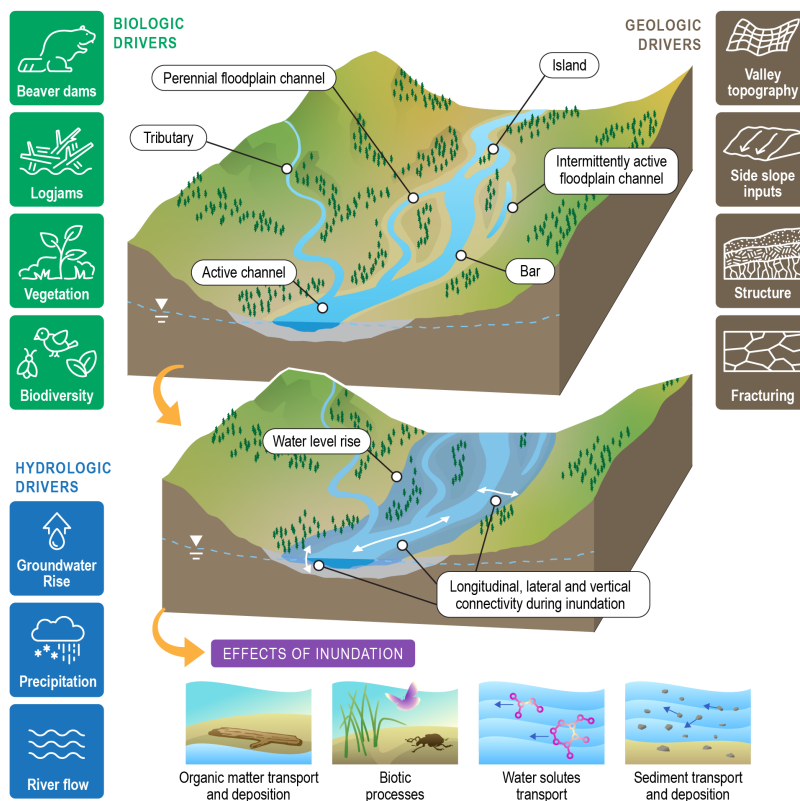
Figure 5. *Conceptual model of variable inundation in floodplain and parafluvial systems. Across floodplains and parafluvial zones a suite of biological, hydrologic, and geologic factors drive inundation regimes in terms of spatiotemporal duration, timing, depth, flow rate, etc. These systems include diverse subsystems as summarized in the top panel. Rising water levels, due to one or more drivers, can inundate these subsystems as shown in the middle panel, resulting in a variety of biogeochemical, ecological, and physical effects (bottom sub-panels). Credit: Nathan Johnson.*

Variably Inundated Wetlands

While not all wetlands are variably inundated, variable inundation is a common feature of many wetland ecosystems [e.g.("Convention on wetlands of international importance espeically as waterfowl habitat" 1994), US 33 CFR § 328.3]. Here we focus primarily on wetlands that are similar to swamps, marshes, and bogs (**Fig. 6**). Wetlands cover about 10% of the global land area, and nearly half of global wetland area (46%) is temporarily inundated (Davidson et al. 2018). Generally, wetland inundation regimes are shaped by the wetland's connectivity to surface and subsurface hydrologic sources and landscape position (Åhlén et al. 2022). The landscape position of wetlands is a first order indicator of the water source and chemistry, ranging from headwater depressional locally-fed wetlands, to flow-through and fringing wetlands

483   to groundwater-fed low-lying wetlands (Fan and Miguez-Macho 2011, Tiner 2013). Wetland

484   typologies applied in several national inventories generally rely on a combination of three

485   criteria: soil type, hydrophytic vegetation and hydrology (Cowardin and Golet 1995).

486   Alternatively, hydrogeomorphic classification systems propose to exclusively draw on physical

487   drivers, such as geomorphology, hydrology and substrate to allow for cross-site comparisons of

488   biota and serve functional assessments (Brinson 1993, Semeniuk and Semeniuk 1995, 2011,

489   Davis et al. 2013).

490   While changes to inundation extent and depth can occur at time scales ranging from days to

491   decades, the most conspicuous inundation patterns occur on event (e.g., flooding due to rain

492   events), seasonal (e.g. snow melt or wet/dry seasons), and interannual time scales. Primary

493   drivers of inundation in unmanaged wetlands come from subsurface groundwater discharge and

494   surface flows including rainfall or snowmelt runoff that occur when antecedent soil moisture

495   conditions are high, preventing quick infiltration of water (Rasmussen et al. 2016). Many

496   wetlands are actively managed, such as to provide bird habitat, so that inundation can vary

497   based on management decisions [see below and (Fredrickson and Taylor 1982)].

498   The spatial scales of variable inundation are shaped both by wetland size and

499   geomorphology. Wetlands can be shallow over large spatial scales, and thus the size of variably

500   inundated wetland area can range from microtopographic (i.e., hummock/hollow, ~m^2 scales) to

501   larger ecosystem scales. Large wetland areas, especially in the tropics, experience strong

502   seasonal inundation cycles which depend on changes in water balance and local topography

503   (Zhang et al. 2021). While the largest variably inundated wetlands are connected to floodplains,

504   like the 130,000 km^2 Pantanal (Ivory et al. 2019), non-floodplain wetlands surrounded by upland

505   (also known as geographically isolated wetlands) as large as ~6 ha may also experience whole-

506   system drying and rewetting (Lane and D'Amico 2016).

507   Embedded within wetland ecosystems, microtopographic structures can create within-

508   system mosaics of inundation regimes. Microtopography in peaty wetlands is particularly

509   pronounced, ranging from several tens of meters [e.g., ridges and sloughs (Larsen et al. 2011)]

510   to meters [e.g. hummock-hollows (Shi et al. 2015)], These spatial patterns result from dynamic

511   feedbacks between ecological processes (e.g. peat accumulation) and hydrology that reinforce

512   these patterns (Belyea and Baird 2006, Eppinga et al. 2008, Larsen et al. 2011).

513   Wetlands are widely acknowledged to be biogeochemical hot spots and ecosystem control

514   points (McClain et al. 2003, Bernhardt et al. 2017) because of the confluence in space and time

515   of allochthonous substrates into reactive environments (e.g., nitrate produced under oxic

516   conditions entering anaerobic environments where denitrification can occur). In addition,

517   variable inundation is associated with nutrient influx into wetlands that replenishes nutrient pools

518   and can drive productivity and organic matter decomposition (Venterink et al. 2002). The depth

519   and duration of flooding shapes the wetland vegetation community by controlling germination

520   success, modifying oxygen availability and changing concentrations of toxins and nutrients, by

521   desiccating aquatic plants or inundating terrestrial plants, and by changing the light availability

522   (Casanova and Brock 2000). Wetland vegetation is structurally adapted to low oxygen

523   environments, for example, some vegetation has developed air channels in leaves, stems, and

524   roots to transport oxygen belowground (Tiner 2017). Alternatively, wetland vegetation can also

525   respond to shifts in oxygen levels physiologically on shorter time scales (Colmer 2003).

526   Variable inundation provides an environmental filter for biota adapted to live either under dry

527   or inundated conditions, resulting in distinct communities including wetland obligate and

528 facultative species (Gleason and Rooney 2018). The temporal duration of inundation (i.e.,
529 hydroperiod) indirectly controls the bird community composition through absence and presence
530 of wetland vegetation and availability of aquatic macroinvertebrate prey (Daniel and Rooney
531 2021). Amphibian communities are particularly impacted by hydroperiod: It needs to be long
532 enough for eggs to hatch and tadpoles to reach metamorphosis, but should not allow the
533 establishment of many predator species (Resetarits 1996).
534 　　Predicting how complex inundation patterns in wetlands will change under changing climate
535 is a major research challenge. Predictions span the range from a decrease in inundation in
536 some regions (Londe et al. 2022b) to an increase in others (Watts et al. 2014), with uncertain
537 consequences for wetland persistence overall. To improve regional or global predictions,
538 accurate maps of wetland extent on different scales that can be incorporated into mechanistic
539 models will be necessary (Melton et al. 2013). This is particularly challenging for non-permanent
540 wetlands, which are hard to reliably map and are generally understudied (Gallant 2015, Calhoun
541 et al. 2017), but which are, by definition, VIEs. As climate change alters wetland inundation
542 regimes, the net impacts to carbon storage and greenhouse gas fluxes are of particular concern
543 (Moomaw et al. 2018), because together they will determine the net climatic impact of changes
544 in wetland area and dynamics (Neubauer and Megonigal 2015).

545
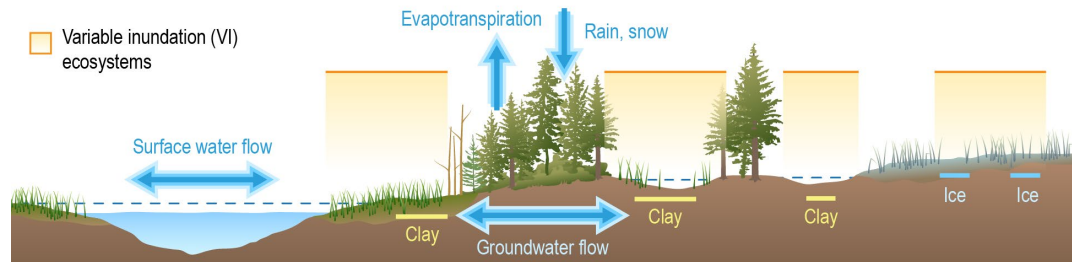
547 **Figure 6**. *Conceptual model of variable inundation in wetland systems. Different wetland*
548 *types are influenced and shaped by variable inundation. Absence and presence of surface*
549 *water is driven by (e.g., seasonally) changing water supply and the hydrologic function of the*
550 *wetland in the landscape. Sediment characteristics (e.g., clay or ice) and topographic positions*
551 *of wetlands in the landscape influence water loss to infiltration or gain from groundwater. Credit:*
552 *Nathan Johnson.*

553 **Freshwater Ponds**
554 Freshwater ponds are among the most abundant and common freshwater ecosystems
555 worldwide, with estimates between 500 million and 3.2 billion ponds globally (Davidson et al.
556 2018, Hill et al. 2021). Ponds are generally small (less than 5 ha) and shallow (less than 5 m),
557 and consequently, are highly sensitive to changes in water levels that can result in highly
558 variable inundation regimes (Gendreau et al. 2021, Richardson et al. 2022a). Pond ecosystems
559 are extremely diverse, and include arctic thermokarst ponds, prairie potholes, vernal pools,
560 playas, rock pools and agricultural dugouts. The numbers of ponds globally are likely
561 underestimated, as their size and ephemeral/temporary nature has meant they are often

562 excluded from physical inventories and they are below the resolution of many remote sensing
563 techniques (Hayashi et al. 2016, Calhoun et al. 2017, Hill et al. 2021).
564   As in many other VIEs, inundation of freshwater ponds can be highly variable, and the
565 timing, duration and frequency of inundation can vary considerably (Williams 2006). Many
566 temporary or ephemeral ponds can become intermittently or seasonally flooded (**Fig. 7**). For
567 some ponds, particularly vernal pools, seasonal inundation is relatively predictable, as these
568 systems become inundated following snowmelt or spring runoff, and are subsequently drawn
569 down with increasing summer evapotranspiration (Zedler 2003, Brooks 2004). Variation in the
570 hydroperiod can alter the composition of biotic communities (Brooks 2004, Gleason and Rooney
571 2018), as well as impact biogeochemical and hydrological processes (Bam et al. 2020, Hondula
572 et al. 2021b). In more temperate regions, the timing of inundation is often driven by heavy
573 rainfall, and periods of inundation can be highly variable, with inundation durations lasting from
574 days to months, and sometimes occurring intermittently as ephemeral systems dry and rewet
575 multiple times in a year (Ripley and Simovich 2009, Kneitel 2014, Florencio et al. 2020). For
576 nearly permanent ponds, the pattern of wet and dry periods are more predictable, but the
577 initiation and length of the hydroperiod can vary spatially as water levels fluctuate, inundating
578 and exposing shallower areas (Brendonck et al. 2017). Freshwater ponds often demonstrate
579 both high inter- and intra-annual variability, and diurnal, annual and multidecadal periods of
580 inundation can occur due to changes in evapotranspiration, drought, drainage, flooding, and / or
581 hydrologic function of the pond on the landscape (Brooks 2004, Gendreau et al. 2021).
582 Modifications to ponds by humans (e.g. irrigation ponds, urban stormwater ponds; see section
583 on human-engineered systems) or other organisms, such as beavers, can also impact
584 hydroperiod and inundation regimes (Renwick et al. 2006, Brazier et al. 2021).
585   Like many of the other ecosystems that experience variable inundation, freshwater ponds
586 are also considered biodiversity and biogeochemical hotspots, providing many critical
587 ecosystem services (Capps et al. 2014, Marton et al. 2015). Despite their relatively small size,
588 ponds can have considerable variability in both community composition and in biogeochemical
589 processes, in part due to differences in inundation regimes, where pond margins are more likely
590 to be more frequently desiccated for longer periods than central regions (Reverey et al. 2018).
591 Models that explicitly incorporate remotely sensed variable inundation predict that ephemeral
592 systems with shorter hydroperiods retain nitrogen at greater rates than larger systems with less
593 variable inundation and longer hydroperiods, particularly in semi-arid regions like the Prairie
594 Potholes of the North American northern Great Plains and playas in the south-central United
595 States (Cheng et al. 2023). In addition, research suggests reproduction is largely impacted by
596 inundation. Salamanders, for example, tend to lay more eggs during years with greater rainfall
597 while hatching success decreases with desiccation (Della Rocca et al. 2005). Variable
598 inundation across ponds can result in ecosystem heterogeneity at the landscape scale,
599 increasing local abiotic and biotic variation (Jeffries 2008), but the number and distribution of
600 inundated ponds can also impact regional biodiversity through processes like dispersal
601 (Brendonck et al. 2017).
602   Climate change will likely alter the inundation regimes in freshwater ponds in terms of timing,
603 frequency, duration, and extent. Decreases in precipitation and increases in extreme drought
604 can result in shortened hydroperiods, and increasing temperatures can alter water temperatures
605 and evaporation rates (Matthews 2010). The persistence of freshwater ponds may, therefore, be

606 reduced with climate change (Londe et al. 2022b). Understanding how future changes in
607 inundation regimes impact freshwater ponds will be critical. Similar to wetland ecosystems,
608 improved remote sensing methods, including incorporating multispectral imagery and radar
609 along with finer spatial resolution mapping approaches may improve the mapping, counting and
610 inclusion of small ponds in freshwater inventories (Bie et al. 2020, Rosentreter et al. 2021,
611 Hofmeister et al. 2022). As inundation regimes may become more variable, increasing
612 conservation and protection efforts for ephemeral and temporary ponds may become more
613 essential to maintain these critical VIEs.

614
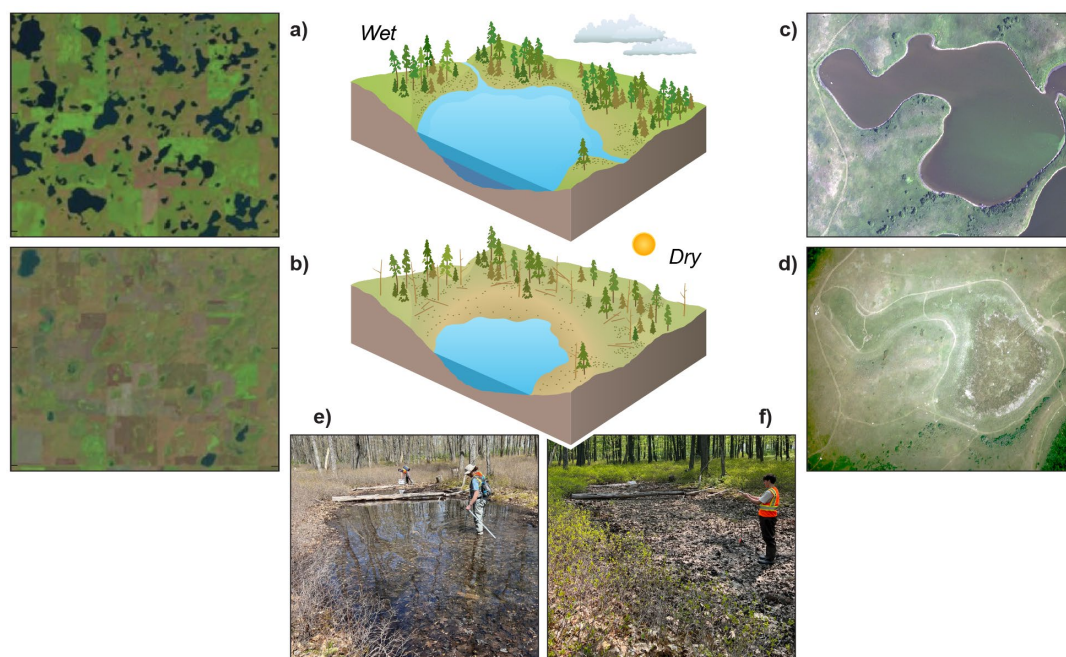
615
616
617 **Figure 7.** *Examples of variable inundation across scales in pond systems.* *Satellite*
618 *imagery of the Prairie Pothole Region, North Dakota, USA illustrating decadal variable*
619 *inundation at a landscape scale a) September 2, 1992; b) May 23, 2013 [modified from*
620 *(Scientific Investigations Report 2015)] and at the pond scale; Aerial Imagery of Pond P1,*
621 *Cottonwood Lake Study Area, North Dakota c) September, 2002 d) September, 1992 (Images*
622 *from (U.S. Geological Survey 2017). Seasonal changes in a vernal pond in Moshannon State*
623 *Forest, Pennsylvania, USA) inundated (May 11, 2023) non-inundated (May 23, 2023) (J.N.*
624 *Sweetman). Conceptual drawings by Nathan Johnson.*

Storm-Impacted Coastal Zones

626 The coastal zone includes ecosystems and communities (cities/towns) that are adjacent and
627 hydrologically connected to a large water body (e.g., ocean, Great Lakes). These systems
628 influence, are impacted by, and are dependent on coastal zone hydrologic processes, such as
629 flooding, that occur at the interface between terrestrial and aquatic domains. Unlike tidal

630 environments, inundation that affects the coastal zone is driven by temporary, often stochastic
631 events including storms, seiches, and king tides. Depending on the topography of the area,
632 infrastructure of the community, and size of the event, the size of coastal inundation varies from
633 event to event (both geographic impact and aerial extent of inundation; **Fig. 8**). The frequency of
634 these events ranges from multiple times a season to decadal (**Fig. 8**). Tropical storms and
635 cyclones develop in tropical regions during seasonal periods of warm water each year. Due to
636 their high energy and movement, they influence more temperate regions as well (Colbert and
637 Soden 2012). In temperate or cold regions, storms develop in the winter time due to large
638 temperature differences between land and ocean (Liberato et al. 2013). Natural systems will
639 display some form of resilience and recovery to storm impacts (Lugo 2008, Wang et al. 2016),
640 but human settlements and infrastructure are vulnerable to both intense winds and flooding
641 (Lane et al. 2013, Hinkel et al. 2014, Braswell et al. 2022). Land use development also alters
642 the natural resilience of coastal environments through the proliferation of gray infrastructure
643 such as jetties and seawalls (Gittman et al. 2015). Systems in low-lying regions are particularly
644 vulnerable to inundation as opposed to rocky shores with steep slopes. While regional or global
645 data sets based on elevation data exist, the extent at any given time of storm surges, king tides,
646 and other high water episodes depend locally/regionally on where the event hits, flooding
647 infrastructure, and topography of the area.
648
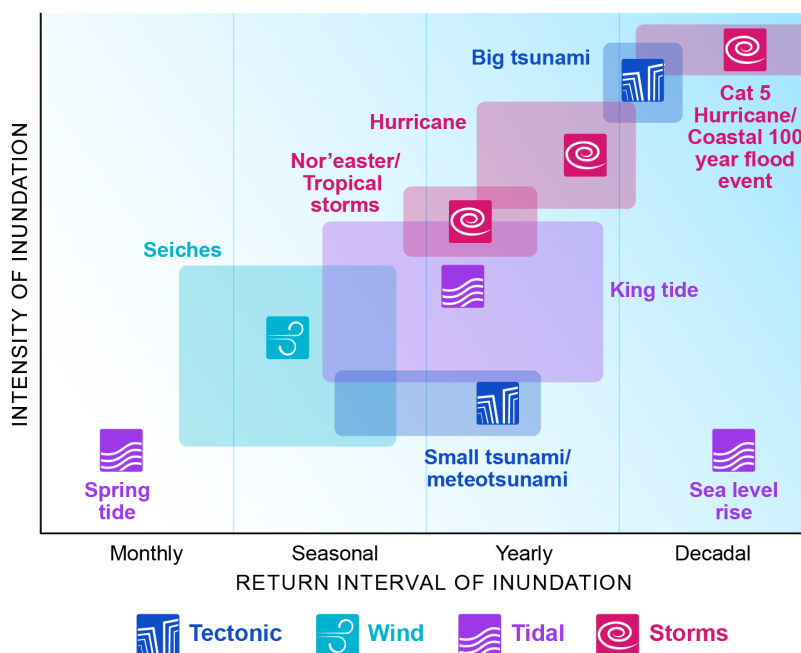
649
650 **Figure 8**. *Coastal VIEs experience inundation events with different frequencies and*
651 *intensities. Some events occur rarely, but are very high intensity events (category 5 hurricanes;*
652 *large tsunamis), increasing the area of inundation and affecting areas that seldom experience*
653 *flooding. The impacted systems are often less adapted to inundation, increasing the extent of*
654 *destruction or reorganization of the system. Other events occur more regularly and/or are lower*

655 *in intensity (spring tide, seiches), leading to less extensive inundation and impacting coastal*
656 *systems that are more adapted to inundation. Credit: Nathan Johnson.*
657
658   Inundation in the coastal zone impacts sediment transport, solute and nutrient mobilization,
659 vegetation distribution, biological diversity, and biogeochemical processes. Erosion and
660 sediment deposition alter ecosystem geomorphology (e.g., dune shape, marsh accretion)
661 (Houser and Hamilton 2009, Dissanayake et al. 2015) and ecosystem nutrient pools [e.g.,
662 (O'Mara et al. 2019, Castañeda-Moya et al. 2020)]. In coastal zones adjacent to marine and
663 estuarine waters, saltwater intrusion changes surface (Schaffer-Smith et al. 2020) and
664 groundwater (Cantelon et al. 2022) quality and mobilizes nutrients through porewater ionic
665 exchange processes (Herbert et al. 2018). Coastal zone inundation as a natural process alters
666 dune systems, which generates a mosaic of habitats that increase biodiversity (Smith et al.
667 2021) and alter distributions of vegetation and animals. For example, the frequency of overwash
668 events affects plant composition and diversity on sand dunes (Stallins and Parker 2003) and
669 regular inundation is thought to provide necessary habitats for some insects and birds (Smith et
670 al. 2021). Increased salinity and associated geochemical changes alter microbial community
671 diversity and population heterogeneity (Nelson et al. 2015), shifting to more specialized
672 communities as an adaptation to anaerobic conditions, redox fluctuation, and salt stress.
673 Previous studies found high variability in relationships between salinity and ecosystem carbon
674 dioxide fluxes (Morrissey and Franklin 2015, van Dijk et al. 2015, Dang et al. 2019, Hopple et al.
675 2022).
676   Human communities within the coastal zone are impacted by inundation events as well.
677 Inundation of coastal agricultural lands from storm surge and sea level rise reduces agricultural
678 productivity (Lei et al. 2016). In particular, risk is high to coastal zone communities in developing
679 nations, where inundation events can lead to food insecurity, loss of livelihood, and increased
680 transmission of waterborne diseases. As climate change alters the magnitude and frequency of
681 inundation in the coastal zone, it will be necessary to integrate both natural and human
682 adaptations, such as enabling salt marsh transgression (marsh migration upland) to mitigate
683 storm surge impacts on crop yield (Guimond and Michael 2021).
684   While we understand many of the linkages between the ecology, biogeochemistry,
685 hydrology, and geomorphology that regulate ecosystem structure and function in coastal
686 systems (Fagherazzi et al. 2012, Hinshaw et al. 2017, Braswell and Heffernan 2019, Cantelon
687 et al. 2022), we know little of how to predict the future effects of the interacting stressors
688 associated with climate change (O'Meara et al. 2017, Ward et al. 2020, Arrigo et al. 2020). Our
689 ability to predict is reliant on our understanding of shifting inundation regimes in the context of
690 elevated CO_2, nutrient pollution, and coastal development which can generate antagonistic,
691 synergistic, or additive effects. These knowledge gaps stem from the dynamic and
692 unpredictable nature of events that drive coastal inundation. Observational data to inform
693 mechanistic models is limited and governed by where and when events happen (not necessarily
694 within monitored sites), funding periods, and accessible coastlines. This difficulty is exacerbated
695 by the fact that 40% of the world's population lives within 100 km of the coast (Maul and Duedall
696 2019), which heightens social impacts of variable inundation while also adding logistical
697 difficulty to coastal monitoring. When events do overlap with instrumented sites, the extreme
698 nature of inundation events threaten instrumentation arrays, risking washout or flooding of

699 monitoring infrastructure. Lastly, high-latitude coastlines are also susceptible to coastal
700 inundation, yet few models incorporate physical, biogeochemical, and ecological implications of
701 inundation on permafrost bound coastlines and environments (Ekici et al. 2019, Bevacqua et al.
702 2020). Opportunities of critical knowledge advancement exist in 1) monitoring events through *in-*
703 *situ* or remotely sensed monitoring data, 2) model development that integrates more robust
704 process-based understanding, and 3) expansion into urban and permafrost-bound coastlines.

Tidally Driven Coastal Zones

706 Tidally-influenced coastal zones exist at the intersection of terrestrial and marine environments
707 and encompass diverse intertidal ecosystems including tidal wetlands, flats, and beaches (**Fig.
708 9**). Globally, tidal wetlands exist on 6 of 7 continents, and are spread across tropical, temperate,
709 and polar latitudes (Murray et al. 2022a). Tidal flats are predominantly found along low sloping
710 coastlines with approximately 70% of global tidal flat area existing in Asia, North America, and
711 South America (Murray et al. 2022b), while beaches encompass 31% of ice-free shorelines
712 (Luijendijk et al. 2018).
713 Tidally-driven coastal zones are inundated semi-diurnally (i.e., twice a day) or diurnally (i.e.,
714 once a day). Unlike VIE systems summarized above, where inundation events may be difficult
715 to predict, inundation in tidally-driven coastal zones varies primarily based on predictable
716 drivers. For example, high tide and low tide water levels dictate the spatial extent and duration
717 of inundation. In addition, intra-annual tidal dynamics are largely controlled by lunar cycles
718 which drive approximately monthly highest (spring) and lowest (neap) tides, as well as annual
719 high (king) and low tides. Inter-annual tidal dynamics are linked to sea level rise, which is
720 shifting the zone of variable inundation inland (Ensign and Noe 2018, Tagestad et al. 2021). We
721 note that while the timing of king tides is predictable (perigean spring tide), their impacts can be
722 difficult to predict, as mentioned in the storm-impacted coastal zones section. In addition,
723 topography (e.g., slope) and other natural physical factors, including wind speed and direction,
724 waves, and even localized high and low pressure events mediate the lateral extent of surface
725 water inundation in tidal ecosystems. Human modifications further alter both vertical and
726 longitudinal extent of tidal flooding via control structures which may exclude tides (gates, weirs,
727 etc.) and channels that transport tidal waters well inland of the natural intertidal zone.
728 The extent of tidal influence, which spans microtidal (< 2 meter tidal range) to macrotidal (>
729 10 meter tidal range in some locations), controls water quality, terrestrial-aquatic interactions
730 and resulting biogeochemical and ecological responses [e.g., (Tweedley 2016)]. Estuaries,
731 where tides mix saltwater and freshwater, are dynamic biogeochemical mixing zones
732 characterized by sharp chemical gradients that regulate biological activity [e.g., (Crump et al.
733 2017)]. Shifts in tidal zones associated with sea-level rise are predicted to alter the extent of key
734 intertidal habitats, with potential disruptions to coastal food webs (Rullens et al. 2022). Changes
735 in duration and extent of inundation associated with tides control soil saturation and salinity,
736 which influence redox dynamics, and hydrologically driven exchange of carbon, nutrients, and
737 pollutants (Pezeshki and DeLaune 2012, Bogard et al. 2020, Regier et al. 2021). Biological
738 activity, including crab burrows that alter hydrologic flow paths (Crotty et al. 2020), also
739 influence tidal exchanges across the coastal terrestrial-aquatic interface (Crotty et al. 2020).
740 Increased saltwater exposure due to shifting tidal ranges can alter the stability of coastal soils
741 [e.g, (Chambers et al. 2019)], which represent a globally important carbon sink (Mcleod et al.

742   2011). In addition, tidal regimes structure vegetation gradients, where salt-sensitive
743   communities including low-lying forests and freshwater marsh species are replaced by salt-
744   tolerant communities including mangroves and saltmarsh species (Kirwan and Gedan 2019,
745   Lovelock and Reef 2020). This shift in tidal range leads to the creation of ghost forests (Kirwan
746   and Gedan 2019), which can impact coastal biogeochemical cycles [e.g., (Cawley et al. 2014).
747   Similarly, sea level rise may lead to mangrove or marsh retreat as inundation patterns change
748   (Xie et al. 2020).
749   Due to the frequency of inundation, tidally inundated ecosystems are hydrologically,
750   biogeochemically, and geomorphologically dynamic, creating challenges for scientists and land
751   managers seeking accurate estimations of land surface area, elevation, and carbon storage.
752   These challenges are exacerbated by sea level rise, which exerts heterogeneous and non-linear
753   influences on tidal ranges (Du et al. 2018). Methodological approaches to assess tidal
754   ecosystem area and elevation that are based on satellite imagery will be critical for present and
755   future management and decision making. Similarly, complex feedbacks across three-
756   dimensional physical space exist among hydrology, biogeochemistry, ecology, and
757   geomorphology (Xin et al. 2022); these dynamics may need to be considered in future
758   ecosystem projections. Thus, a deeper understanding of feedbacks and their variability in space
759   and time in response to tidal activity is needed (Ward et al. 2020). Lastly, with sea-level rise,
760   tidal constituents may change, with nonlinear impacts on tidal range and inundation extent
761   (Pickering et al. 2017). Tidally inundated VIEs represent the interface between marine and
762   terrestrial ecosystems, and to predict their future will require understanding bi-directional
763   connections among physical, chemical, and biological system components.
764

765
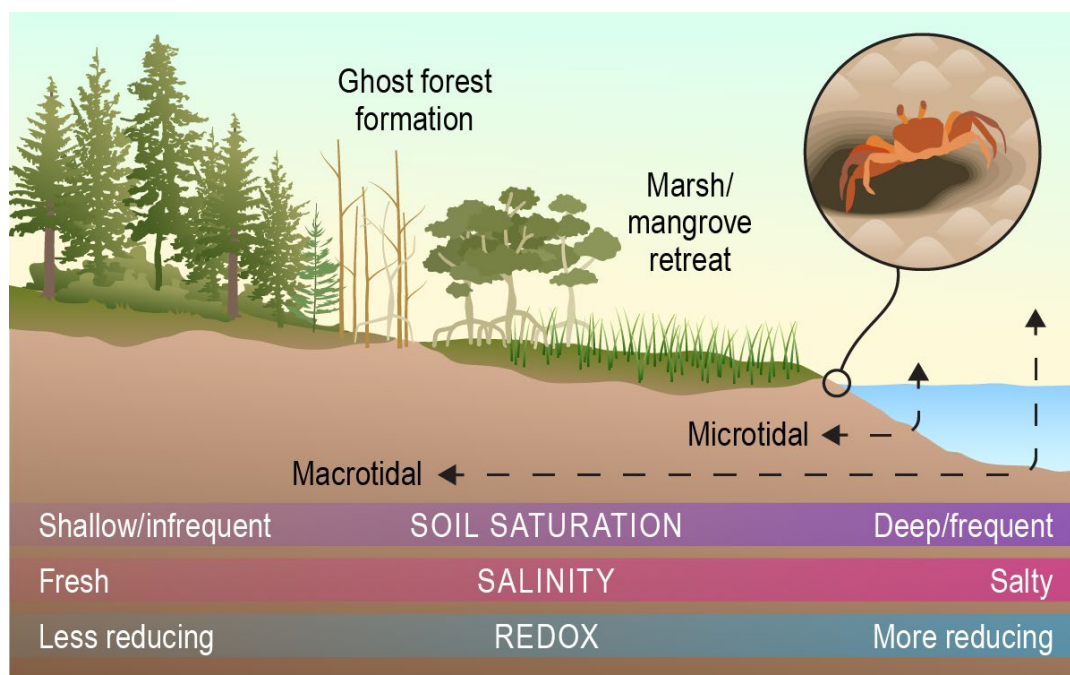
766 **Figure 9**. *Conceptual model of variable inundation in tidal systems. Tidally driven coastal*
767 *zones span sediments exposed at low tide to marshes and coastal forests inundated at high*
768 *tide. This lateral gradient of tidal exposure is characterized by gradients in vegetation and soil*
769 *characteristics, and modified by the physical, chemical, and biological factors discussed in the*
770 *tidal systems section. Credit: Nathan Johnson.*

Human-Engineered Systems

772 Human-engineered systems are environments where inundation magnitude, frequency, timing,
773 and duration are either actively managed or have been dramatically altered by structural
774 modifications to the landscape (**Fig. 10**). Human-engineered VIEs rival natural systems in area
775 and extent (Clifford and Heffernan 2018), yet the significance of engineered VIEs in influencing
776 landscape processes is relatively unexplored compared to natural systems (Koschorreck et al.
777 2020) and they are historically excluded from water and nutrient budgets (Abbott et al. 2019).
778 The primary drivers of human-engineered VIE formation explored here are land use change and
779 restoration, though hydrologic modifications impact inundation regimes of the natural VIEs
780 explored earlier in the manuscript. Examples of land-use driven human-engineered VIEs
781 include, but are not limited to, croplands irrigated by flooding (e.g., rice paddies, cranberry
782 bogs); irrigation and drainage canals, stormwater control structures (e.g., roadside ditches,
783 retention ponds), as well as unintentional VIE formation following landscape modification such
784 as "accidental" urban wetlands (Palta et al. 2017) or ponding in agricultural fields (Saadat et al.
785 2020). Whereas the purpose of land-use driven engineered VIEs is to redistribute water for
786 human purposes, the goal of VIEs engineered for restoration is to either replace or enhance
787 ecosystems lost or damaged as a result of human activity. VIE restoration efforts vary in scope
788 and form, spanning local (e.g., residential living shorelines, individual stream reaches,
789 agricultural ditch wetlands) to ecosystem [e.g., adding sediment to degrading marshes
790 (VanZomeren et al. 2018)], to regional (e.g., dam removal) scales.
791   While the full extent of human-engineered VIEs is difficult to quantify, key examples highlight
792 their significance in the landscape. Agriculture covers nearly 40% of the earth's land surface
793 (Siebert et al. 2010), and nearly a quarter of that is variably inundated by flood irrigation (Wu et
794 al. 2023). In urban systems, the extent of stormwater control networks rival those of natural
795 systems. For example, the total linear length of residential canals in North America nearly
796 equals that of the Mississippi River (Waltham and Connolly 2011). While restoration efforts are
797 not as widely distributed as land-use change, restoration still contributes to extensive VIE
798 creation. For example, restoration accounts for 14% of areal gain of tidal wetlands globally
799 (Murray et al. 2022b). Inundation regimes in human-engineered VIEs can be driven by natural
800 hydrologic processes, such as connectivity with the water table or tidal inputs. This is
801 particularly important in VIEs built for restoration, as establishing natural inundation regimes
802 enhances landscape connectivity and mediates ecosystem functions (Reis et al. 2017, Jones et
803 al. 2018). However, unlike the previously discussed natural systems, the drivers and duration of
804 inundation in human-engineered VIEs may be decoupled from natural hydrologic processes.
805 Controlling drainage, such as for stormwater management, land reclamation, or effluent
806 releases, is a key motivation for VIE construction and system design, resulting in inundation
807 periods largely driven by precipitation that persist at event to seasonal scales depending on
808 local hydrology and climate. Inundation duration may also occur on longer timescales, such as

809   seasonal flooding in paddy systems (De Vries et al. 2010). Finally, direct human interventions,
810   such as floodgates, weirs, and dams, may affect water residence time at timescales that are
811   asynchronous from natural drivers, such as seasonality or tides.
812   Human-engineered VIEs fundamentally alter the landscape, changing the spatial and
813   temporal patterns of ecosystem processes. Agricultural inundation, such as flood irrigation or
814   ponding, alters redox conditions, greenhouse gas emissions, groundwater recharge,
815   evapotranspiration fluxes, plant growth, and pollutant export to natural water bodies (Hale et al.
816   2015, Pan et al. 2017, Pool et al. 2021, Buszka and Reeves 2021). For example, a recent study
817   showed that variably inundated depressions in agricultural fields can account for ~30% of
818   nitrous oxide emissions across cultivated areas despite comprising ~1% of the land surface
819   (Elberling et al. 2023). The creation of drainage canals increases waterborne carbon fluxes from
820   VIEs by producing a newly decomposed stock of labile soil carbon to be leached as well as by
821   increasing the hydrological runoff rate through the soil and receiving canals and ditches (Stanley
822   et al. 2012). Human-engineered VIEs can also provide ecosystem services that supplement or
823   replace those of natural VIEs in the landscape (Clifford and Heffernan 2018). For example, they
824   can enhance habitat (Connolly 2003, Herzon and Helenius 2008), nitrogen removal (Bettez and
825   Groffman 2012, Reisinger et al. 2016), and recreation (Beckingham et al. 2019). Further, the
826   services these systems provide can be improved through targeted management [e.g.,
827   vegetation composition; (Castaldelli et al. 2015)] or restoration practices [i.e., two-stage ditches;
828   (Speir et al. 2020)].
829   Including human-engineered systems in our conceptualization of VIEs emphasizes the
830   growing significance of these systems as human landscape modifications continue to alter and
831   eliminate natural VIEs. Recent efforts have synthesized the role and impacts of human-
832   engineered VIEs at large scales (Peacock et al. 2021, Li et al. 2022b) but, as with many natural
833   systems, the majority of studies on human-engineered VIEs are based in North America and
834   Europe (González et al. 2015, Zhang et al. 2018, Bertolini and da Mosto 2021). Thus, our
835   knowledge may not reflect the social, political, and economic challenges of developing areas
836   where the highest rates of VIE modification are occurring (Wantzen et al. 2019). The knowledge
837   gaps surrounding human-engineered VIEs will become increasingly important to address as
838   global change continues to alter the spatial and temporal patterns of inundation. Given that
839   human-engineered VIEs can enhance or disrupt hydrologic connectivity, they potentially
840   magnify the effects of human driven changes such as sea level rise and impacts of
841   contamination from anthropogenic "chemical cocktails" (Kaushal et al. 2022). We lack a
842   baseline standard for how human-engineered VIEs function in the landscape, even as global
843   change continues to shift existing baselines [e.g., (Palmer et al. 2014)]. Addressing these
844   knowledge gaps will require the incorporation of human-engineered VIEs into large-scale
845   synthesis and modeling efforts, particularly those that address hydrologic and biogeochemical
846   fluxes. Conclusive definitions and inventories of human-engineered VIEs is essential for
847   estimating their ecological and biogeochemical roles at the global scale. Finally, human-
848   engineered VIEs need to be conceptualized within an ecological, rather than managerial,
849   context for integration and comparison with natural systems. Human-engineered VIEs rival the
850   range of natural VIEs in structure, inundation regime, and global distribution. Understanding
851   their role in the Earth system is, therefore, critical for understanding both the impacts of and
852   potential solutions to global change.

853
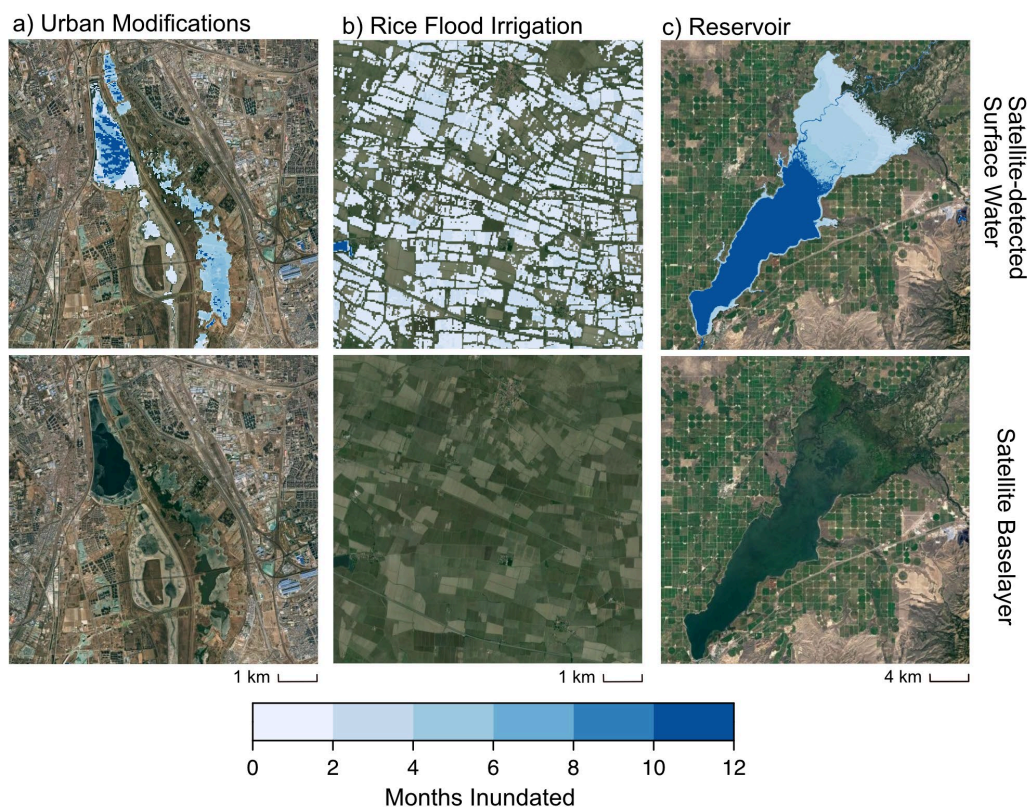
Figure 10. *Examples of human-engineered Variably Inundated Ecosystems. a) Yongding River in Beijing, China; b) Paddy rice fields in northern Italy; c) American Falls Reservoir on the Snake River in Idaho, United States. These three examples emphasize significant variation in the degree of variable inundation across human-engineered VIEs, with some regions being perennially inundated. Top row: Satellite-derived map data on months inundated is derived from the "seasonality" product in the Global Surface Water Mapping Layers v1.4* (Pekel et al. 2016)*. Credit: Jillian Deines.*

Inundation Processes are Relevant at the Scale of the Beholder

VIEs span broad spatiotemporal scales of variable inundation, from microenvironments like mosses and pore spaces that are periodically covered by droplets of water, to vast endorheic lakes and rivers. Inundation volumes and surface areas of VIEs vary by at least sixteen orders of magnitude, from under 10^{-3} L to over 10^{13} L (https://www.k26.com/lake-eyre-papers-lake-eyre-basics), and 10^{-6} m^2 to over 10^{10} m^2 (https://www.guinnessworldrecords.com/world-records/92443-largest-ephemeral-lake), respectively. The duration of inundation varies by up to eight orders of magnitude, spanning a few seconds, in the case of droplets, to decades, in the case of endorheic lakes, and centuries in the case of sea level rise. Non-inundated periods

872   likewise span seconds to centuries and longer. This variability in spatial and temporal extent has
873   profound consequences for the ecology and biogeochemistry of VIEs. This section highlights
874   the importance of considering scale and explores hypotheses regarding how scale drives
875   variability in drivers, processes, and impacts across VIEs and how we study them.
876   Spatial and temporal scales of VIEs can be categorized along two axes – extent and
877   granularity. Extent comprises the total size of the spatial domain or time duration of a defined
878   system, while granularity pertains to the spatial or temporal intervals of system transitions
879   (Ladau and Eloe-Fadrosh 2019). For example, the dynamics of water droplets across North
880   America would represent a large extent with fine granularity, relative to the inundation dynamics
881   of a several square meter desert playa (smaller extent but coarser grain). The impacts of
882   variable inundation are dependent 'on the scale of the beholder' relative to the extent and grain
883   of variable inundation, where a 'beholder' may be a molecule, organism, population, community,
884   land manager, or otherwise. The expressed metabolism of an individual microbe will be
885   influenced by inundation down to the spatial scale of water films and on hourly or shorter time
886   scales. An individual microbe may not, however, be influenced by whether variable inundation
887   occurs only within a square meter or across many square kilometers because it does not
888   perceive these larger scales. In contrast, macroinvertebrate behavior is influenced by variable
889   inundation down to scales of meters and days, and is likely further influenced by larger and
890   longer scales of stream network connectivity (Bogan et al. 2017b, Sarremejane et al. 2017).
891   VIEs can be viewed as habitat patches of different sizes that vary in how long they persist in
892   a given state and that have dynamic connectivity among patches. Terrestrial and aquatic biota
893   respond on ecological and evolutionary time scales to the expansion and contraction cycles of
894   inundation (Bornette et al. 1998, Ward et al. 2002). Biotic diversity is influenced by productivity,
895   connectivity, disturbance severity and disturbance frequency, all of which operate at hierarchical
896   scales (Ward et al. 1999). Biogeographical and ecological theories posit that patch size (e.g.,
897   species area scaling) and disturbance regimes (e.g., intermediate disturbance hypothesis) are
898   strong determinants of community composition (Adler et al. 2005, Svensson et al. 2012),
899   suggesting that VIE community composition may vary predictably with these factors. The
900   duration, predictability, and frequency of inundation likely have consistent community-level
901   consequences that vary predictably with VIE extent and grain. Different extents and grains of
902   inundation have the potential to change habitat connectivity in addition to directly selecting for
903   different groups of organisms. Isolated marshes may, for example, become merged during a
904   flood, thereby enhancing dispersal of aquatic organisms. The scale of variable inundation has
905   numerous influences over ecological processes and dynamics that need to be understood.
906   From a biogeochemical perspective, variable inundation generates spatial and temporal
907   variation in rates and patterns of biogeochemical processes. This variability is important for
908   scaling biogeochemical rates because of process nonlinearity and Jensen's inequality (Ruel and
909   Ayres 1999). That is, a rate based on average conditions differs systematically from the average
910   rate across variable conditions. This is important because the scales of processes (e.g.,
911   microbial activity occurring within pore channels) are typically not aligned with the scales of
912   measurements and models (e.g., core-scale or above). The lack of clear understanding for how
913   variable inundation influences variation in biogeochemical processes and how these
914   relationships change with extent and grain of inundation can, therefore, lead to unreliable
915   predictions for the scaling of biogeochemical processes.

916 Understanding the biogeochemical influences of variable inundation across a broad range of
917 scales is important for informing a diverse suite of needs across models, decision makers, and
918 other interested parties. Our ability to inform these needs depends on our ability to rigorously
919 understand and predict influences of variable inundation across scales. This is a challenge as
920 variable inundation likely has direct, but unknown, influences over the scaling of biogeochemical
921 function. For example, cumulative metabolism in streams is predicted to increase faster than
922 their upstream drainage area for perennial stream networks (Wollheim et al. 2022). The
923 influence of variable inundation on biogeochemical processes cannot yet be accounted for in
924 such scaling theory. More generally, perturbations like variable inundation can drive systems
925 away from steady-state assumptions from which scaling relationships are derived (McCarthy et
926 al. 2019), therefore, we expect significant changes in scaling behavior across inundation
927 regimes. A research frontier is to quantify the direction, magnitude, and duration of changes in
928 scaling patterns in response to variable inundation and to modified variable inundation regimes
929 wrought by climate, land-use, and other environmental changes.

Summary of Primary Methods used to Study VIEs

931 The multi-scale nature of VIE systems has led to experimental and observational studies that
932 span from point-scale lab-based characterization, to reach- or watershed-scale monitoring
933 networks, and to regional- and global-scale remote sensing. Point-scale measurements at the
934 smallest scales help reveal processes that underlie larger scale dynamics. For example, point
935 measures of water presence, water absence, and low flow detection within a watershed are
936 increasingly available with the development of small, inexpensive, and easily deployable
937 sensors, meters, and time-lapse cameras [e.g., (Soupir et al. 2009, Chapin et al. 2014, Costigan
938 et al. 2017, Zimmer et al. 2020)] (**Fig. 11**). While these measurements are easy to take and can
939 provide a long temporal dataset for little effort, they are not always detailed and require regular
940 calibrations.
941 A broad range of methods can be used to link the hydrologic dynamics to ecological and
942 biogeochemical responses. Standardized field surveys and biomolecular methods (e.g., isotopic
943 ratios, including compound specific analyses) are commonly used to study organismal,
944 population, and community ecology across multiple taxa [e.g., (Ode et al. 2016, Gates et al.
945 2020)] and can be standardized for both inundated and non-inundated states. There is
946 increasing use of crowdsourcing for biogeochemical characterization to consistently obtain
947 samples across diverse systems (von Schiller et al. 2019, Garayburu-Caruso et al. 2020).
948 Sample collection can be followed by a variety of laboratory measurements of properties (e.g.,
949 carbon content, redox potential and redox-active elements, microbial genetic potential, sediment
950 grain size) and processes, such as CO_2 production and methanogenesis related to variable
951 inundation. Point-scale measurements often operate at instantaneous to daily scales.
952 Conversely, larger scale measurements integrate across finer-scale processes to quantify
953 ecosystem dynamics and properties, but without necessarily revealing the governing the
954 processes. Spatially distributed monitoring networks using *in situ* sensors (e.g., the United
955 States Geological Survey, USGS, gage network) can connect event-scale responses across
956 hydrologically linked locations as well as reveal long-term trends [e.g., (Zipper et al. 2021)].
957 Long-term field manipulations are another complementary *in situ* technique that can reveal

958   mechanisms underlying system responses to changes in inundation state. There are numerous
959   configurations of such experiments that directly or indirectly impact inundation dynamics, such
960   as intentional inundation (Hopple et al. 2023), water exclusion (Kundel et al. 2018) and heating
961   (Hanson et al. 2017). Despite the plethora of data produced by such large scale projects, these
962   are expensive and require deep buy-in of researchers and landowners.
963   Remote sensing can complement *in situ* measurements to facilitate more spatially
964   continuous characterization of surface water dynamics and their impacts. There are different
965   types of remote sensing techniques that can capture different aspects of VIEs. For example, soil
966   surface saturation may be captured through passive microwave radiometer as well as C and L-
967   band radar backscatter, which can also penetrate through thin canopies, clouds, and through
968   the top few centimeters of the soil (Schumann and Moller 2015). Recent missions such as the
969   Surface Water and Ocean Topography (SWOT) mission provide increased capabilities for
970   monitoring changes in surface water over time with radar data (Biancamaria et al. 2016), while
971   NASA's forthcoming NISAR mission will allow for detection of inundation even under tree
972   canopy. Thermal infrared measurements can indirectly reveal saturation at very high
973   spatiotemporal resolutions, as well as evapotranspiration associated with water table depth, soil
974   moisture, and rooting depth (Fisher et al. 2020, Lalli et al. 2022). Long time series from
975   moderate resolution (~30 m) optical satellites can document multi-decadal open water trends
976   and seasonal regimes across the globe (Pekel et al. 2016), while some combinations of indices
977   have shown success in detecting mixed vegetation and inundation cover (Jones 2019).
978   Recently launched satellite constellations provide daily global imagery at < 4 m resolution,
979   enabling monitoring of more dynamic water bodies [e.g., Arctic lakes, (Cooley et al. 2017) and
980   forested wetlands (Hondula et al. 2021a)]. Finally, deep groundwater and changes in the total
981   water column storage are detectable through measurements of gravitational anomalies at very
982   high precision but low spatial resolution (Bloom et al. 2010, 2017, Richey et al. 2015, Pascolini-
983   Campbell et al. 2021).
984

986   **Figure 11**. *Monitoring inundation regimes is increasingly possible via in situ sensors.*
987   *Stream Temperature, Intermittency, and Conductivity Sensors (STICs) (Chapin et al. 2014), one*
988   *of the types of increasingly available sensors to measure water presence/absence in an*
989   *inexpensive and easily deployable manner. These sensors can be used across all types of VIEs.*
990   *Credit: Amy Burgin.*
991

992   To advance predictive understanding requires integration of data with models. Process-
993 based models can be used to simulate hydrological and biogeochemical processes under dry
994 and wet conditions (Fatichi et al. 2016, Li et al. 2017). These models are often built upon mass
995 conservation principles, with ordinary or partial differential equations that describe coupled
996 hydrological, ecological, and biogeochemical processes. They rely on existing knowledge on
997 processes, including, for example, theories or empirical relationships between discharge and
998 water storage (Wittenberg 1999), biogeochemical reaction rate dependence on temperature and
999 water content (Davidson et al. 1998, Mahecha et al. 2010) and redox reactions (Borch et al.
1000 2010). Among process-based models, there are spatially distributed models that couple surface
1001 and subsurface flow dynamics explicitly (Kollet and Maxwell 2006, Coon et al. 2020). This class
1002 of models has recently been extended to include reactive transport (Wu et al. 2021), which may
1003 be considered as a set of tools to understand the biogeochemical effects of variable inundation
1004 (Molins et al. 2022). However, spatial resolution and data requirements for the integrated
1005 surface and subsurface models are high, which places practical limits on the spatial scales that
1006 can be addressed. Semi- or fully-distributed models with coarse spatial resolution are able to
1007 work at larger scales, but require theories or empirical relationships to represent processes and
1008 impacts at subgrid-scales. Data-driven machine learning methods present new opportunities to
1009 blend models with various levels of mechanistic representations into hybrid models (Reichstein
1010 et al. 2019). Increases in the volume of observational data sets combined with advances in high
1011 performance computing have triggered a shift towards machine learning applications for
1012 capturing inundation dynamics. More recently, integration of physics-based models with
1013 machine learning have improved the interpretability of machine learning methods and increased
1014 their ability to model complex ecosystem processes (Sun et al. 2022). These hybrid approaches
1015 have the potential to optimize the characterization and prediction of inundation dynamics by
1016 incorporating the strengths of multiple models to achieve predictions with minimized uncertainty
1017 and greater accuracy than either model alone.
1018   Coordinated integration (Patel et al. 2023) between model development and data generation
1019 is key to deepening our understanding of VIEs and increasing our ability to predict their future
1020 ecosystem function and ecological integrity. More specifically, we promote iterating between
1021 model-guided data generation and observation-informed model development. This iterative
1022 cycle between models and 'experiments' (i.e., real-world data generation) has previously been
1023 termed 'ModEx' (Atchley et al. 2015) and is similar to approaches used in 'ecological
1024 forecasting' (Dietze et al. 2017, 2018). It also aligns generally with the scientific method based
1025 on continuous iteration between conjectures (hypotheses / models) and refutation (falsification
1026 of hypothesis using observations and data) to drive scientific discovery and knowledge growth
1027 (Popper 2014). The ModEx approach often starts by using experimental or field data to
1028 parameterize and calibrate models and/or generate new data based on known model input
1029 needs. This can be expanded whereby models generate hypotheses via *in silico* experiments,
1030 and field or lab studies can be designed to test those hypotheses. Models can also be used to
1031 optimize the design of real-world experiments by indicating when, where, and what to measure
1032 to provide the strongest hypothesis evaluation. In the context of VIEs, we expect ModEx to
1033 touch scales ranging from molecular microbiology to landscape ecology to regional ecosystem
1034 function to Earth system elemental cycles. Key to enabling this is the further development of
1035 models and measurement techniques that can capture system states in both inundated and

1036   non-inundated conditions. Techniques/models designed for specific kinds of ecosystems (e.g.,
1037   perennial rivers) may be difficult to adapt. This emphasizes a need to do ModEx using models
1038   and measurements intentionally designed to span inundated and non-inundated system states.
1039   Across the continuum of ModEx, it is important to consider the scales at which models and
1040   measurements operate, as discussed above. The issues around scale could, in part, be
1041   addressed by Integrated Coordinated Open Networked (ICON) science principles (Goldman et
1042   al. 2022). ICON is based on intentional design of research efforts to be Integrated across
1043   disciplines and scales, Coordinated across research efforts via consistent methods, Open
1044   throughout the research lifecycle, and Networked across stakeholders to understand collective
1045   needs. We propose using ICON principles for *in situ* data generation and remote sensing, jointly
1046   guided by model-generated predictions (i.e., ModEx). Embedding ICON throughout the research
1047   life cycle can help to ensure that new data are at the right scale and can be used to link
1048   disciplines (e.g., hydrology, biogeochemistry, and community ecology). This can also ensure
1049   that data are interoperable across VIEs, are available to everyone and connected to deep
1050   metadata, and are useful to a broad range of stakeholders with interests spanning different
1051   types and locations of VIEs. The use of ICON in cross-VIE science could bridge existing data
1052   across multiple spatial and temporal scales, and potentially bridge gaps among VIEs.

Towards Cross-VIE Transferable Understanding

1054   We propose that a key goal for VIE science is the development and open sharing of knowledge,
1055   models, algorithms, and data that transcend individual system types. This can enhance our
1056   capacity to predict and protect the future of VIE function and integrity. Knowledge that crosses
1057   VIE systems will inherently span scales and levels of certainty from predictable, sub-daily
1058   inundation regimes to rare extreme events; integrating perspectives of these dynamic systems
1059   can aid in understanding and anticipating tipping points of physical, chemical, and biological
1060   components across VIEs. Development of such knowledge should be done via ModEx
1061   approaches coupled with ICON principles, which can generate models that can be used across
1062   VIEs with different physical settings and hydrologic dynamics. We suggest this can be achieved
1063   by taking a continuum approach based on key physical characteristics of VIEs (**Fig. 12**). While
1064   the categorical approach in the above mini-review sections was used to emphasize the breadth
1065   of VIE systems, we encourage research efforts to move beyond those artificial bins by invoking
1066   this continuum approach. For example, a dynamic, unified classification model has been
1067   proposed in wetlands, including a suite of temporally variable ecological and geomorphological
1068   characteristics (Lisenby et al. 2019). This framework has improved the understanding of human
1069   impacts on wetlands and led to more effective management (Wierzbicki et al. 2020, Mandishona
1070   and Knight 2022).
1071   The impacts of variable inundation depend on multiple characteristics of the inundation
1072   regimes (e.g., return interval and duration) and factors that influence those regimes (e.g.,
1073   subsurface permeability, topography, climate, and vegetation). Furthermore, there are dynamic
1074   attributes that influence process rates (e.g., water residence time and hydrologic connectivity),
1075   which can create additional feedback to the impacts of inundation variation. We hypothesize
1076   that despite this complexity, cross-VIE science can make progress towards transferable
1077   understanding by studying impacts of variable inundation across relatively simple physical

variables that can be easily measured. Two such variables are inundation return interval and
topographic slope (**Fig. 12**).

Inundation return interval represents a key component of the continuum of inundation
regimes and may be considered as a forcing factor. Topographic slope represents a key
component of the continuum of VIE characteristics that influence how VIE systems respond to
inundation-based forcing. In turn, these two variables can jointly influence nearly every physical,
chemical, and biological aspect of VIEs. We do not, however, imply that these two variables
capture all relevant processes. Other variables such as sediment/soil mineralogy and climate
also have influences over biogeochemistry and community ecology. Nonetheless, we propose
that significant progress can be made towards cross-VIE understanding of the controls over
biogeochemistry and community ecology by pursuing the continuum approach via inundation
return internal and topographic slope.

The continuum approach can be applied to questions representing science challenges that
span all VIEs, such as how greenhouse gas fluxes and biological diversity respond to variable
inundation (**Fig. 12**). Similarly, metabolism research has suggested using a continuum of flow
predictability and light availability to better unify river metabolism research (Bernhardt et al.
2022). In this approach there is no need to bin VIEs into discrete categories, many of which
have varying definitions and levels of overlap. Rather, we can observe and study continuous
response surfaces across multiple physical axes and identify patterns within this quantitative
space. In addition to generating transferable understanding, bringing all VIEs together via the
continuum approach could help raise awareness of VIE diversity, importance, vulnerabilities,
and how they may change in the future. This may, in turn, help address the fact that VIEs are
often overlooked in terms of conservation and monitoring efforts (Calhoun et al. 2017, Hill et al.
2018, Krabbenhoft et al. 2022, Zimmer et al. 2022). The continuum approach can also be used
to learn where, along environmental continuums, functional thresholds exist that could help with
categorizations important for policy and management (Richardson et al. 2022b).

Cross-VIE understanding of the drivers, patterns, and processes linking inundation to
system responses can greatly improve with increased collaboration and communication across
scientific fields and systems. Communities working in VIEs are scattered across different
societies and funding programs. Studying VIEs together via the continuum approach can bring
these science communities together. To this end, we encourage training and collaborations
focused on consistent data generation methods that may be adopted across the VIE community
and in pursuit of the continuum approach. In addition, disciplinary conferences could also
recognize VIE commonalities with special sessions to bring people together from across the VIE
continuum to discuss research needs.

Cross-VIE knowledge and models are needed to address human impacts to environments
across the globe. Humans both directly (i.e., dams, weirs, surface water and groundwater
abstraction, channelization, draining, invasive species introduction and spread, etc.) and
indirectly (i.e., climate change) alter VIEs. As climate change and other anthropogenic impacts
increasingly alter these already dynamic systems, it is imperative that knowledge and models
transcend VIEs. Future environmental change can alter the position of a given VIE within
environmental space, including what is depicted in **Fig. 12** (e.g., by changing the inundation
return interval). The ability to predict impacts of such environmental change can be facilitated by
mechanistic knowledge that is transferable across the environmental space occupied by VIEs.

1122   We hypothesize that use of the continuum approach proposed here can be an effective
1123   approach to achieving this mechanistic, transferable knowledge.
1124
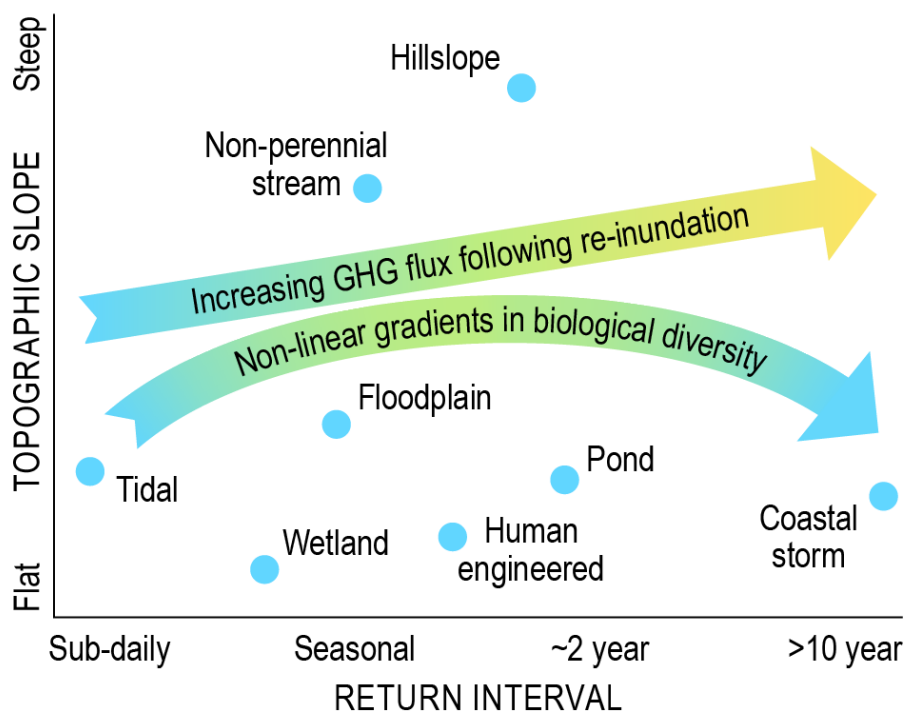
1125
Figure 12. ***We encourage a continuum perspective for VIE science whereby these***
systems are studied across broad ranges of key controlling variables without regard for
what names may be attached to a given studied place and time. *Two potential axes are*
topographic slope and inundation return interval. Points represent approximate locations of
where each VIE type may lie. Each VIE type spans a range of slopes and inundation return
intervals, but we do not define these ranges as the continuum perspective is based on how
study systems fall across the environmental space represented here, rather than within specific
nomenclature. Two priority research directions are greenhouse gas (GHG) fluxes and biological
diversity, and the arrows represent possible hypotheses that could be evaluated with cross-VIE
studies. We propose that knowledge and models that are transferable across VIEs can be
achieved through evaluation of such hypotheses across broad environmental extents tied to key
environmental variables, such as slope and return interval. Credit: Nathan Johnson.

1138
1139

Acknowledgements

1152   **References**
1153

1154   Abbott, B. W., K. Bishop, J. P. Zarnetske, C. Minaudo, F. S. Chapin, S. Krause, D. M. Hannah,

1155   L. Conner, D. Ellison, S. E. Godsey, S. Plont, J. Marçais, T. Kolbe, A. Huebner, R. J.

1156   Frei, T. Hampton, S. Gu, M. Buhman, S. Sara Sayedi, O. Ursache, M. Chapin, K. D.

1157   Henderson, and G. Pinay. 2019. Human domination of the global water cycle absent

1158   from depictions and perceptions. Nature Geoscience 12:533–540.

1159   Adler, P. B., E. P. White, W. K. Lauenroth, D. M. Kaufman, A. Rassweiler, and J. A. Rusak.

1160   2005. Evidence for a General Species-Time-Area Relationship. Ecology 86:2032–2039.

1161   Åhlén, I., J. Thorslund, P. Hambäck, G. Destouni, and J. Jarsjö. 2022. Wetland position in the

1162   landscape: Impact on water storage and flood buffering. Ecohydrology 15.

1163   Allen, D. C., T. Datry, K. S. Boersma, M. T. Bogan, A. J. Boulton, D. Bruno, M. H. Busch, K. H.

1164   Costigan, W. K. Dodds, K. M. Fritz, S. E. Godsey, J. B. Jones, T. Kaletova, S. K. Kampf,

1165   M. C. Mims, T. M. Neeson, J. D. Olden, A. V. Pastor, N. L. Poff, B. L. Ruddell, A. Ruhi,

1166   G. Singer, P. Vezza, A. S. Ward, and M. Zimmer. 2020. River ecosystem conceptual

1167   models and non-perennial rivers: A critical review. WIREs. Water 7:e1473.

1168   Anderson, M. G., and T. P. Burt. 1978. The role of topography in controlling throughflow

1169   generation. Earth Surface Processes 3:331–344.

1170   Angle, J. C., T. H. Morin, L. M. Solden, A. B. Narrowe, G. J. Smith, M. A. Borton, C. Rey-

1171   Sanchez, R. A. Daly, G. Mirfenderesgi, D. W. Hoyt, W. J. Riley, C. S. Miller, G. Bohrer,

1172   and K. C. Wrighton. 2017. Methanogenesis in oxygenated soils is a substantial fraction

1173   of wetland methane emissions. Nature Communications 8:1567.

1174   Arce, M. I., C. Mendoza-Lera, M. Almagro, N. Catalán, A. M. Romaní, E. Martí, R. Gómez, S.

1175   Bernal, A. Foulquier, M. Mutz, R. Marcé, A. Zoppini, G. Gionchetta, G. Weigelhofer, R.

1176   Del Campo, C. T. Robinson, A. Gilmer, M. Rulik, B. Obrador, O. Shumilova, S.

1177   Zlatanović, S. Arnon, P. Baldrian, G. Singer, T. Datry, N. Skoulikidis, B. Tietjen, and D.

1178   Von Schiller. 2019. A conceptual framework for understanding the biogeochemistry of

1179   dry riverbeds through the lens of soil science. Earth-Science Reviews 188:441–453.

1180   Arrigo, K. R., G. L. Van Dijken, M. A. Cameron, J. Van Der Grient, L. M. Wedding, L. Hazen, J.

1181   Leape, G. Leonard, A. Merkl, F. Micheli, M. M. Mills, S. Monismith, N. T. Ouellette, A.

1182   Zivian, M. Levi, and R. M. Bailey. 2020. Synergistic interactions among growing

1183   stressors increase risk to an Arctic ecosystem. Nature Communications 11:6255.

1184   Arscott, D. B., K. Tockner, D. Van Der Nat, and J. V. Ward. 2002. Aquatic habitat dynamics

1185   along a braided Alpine river ecosystem (Tagliamento River, Northeast Italy). Ecosystems

1186   5:0802–0814.

1187   Atchley, A. L., S. L. Painter, D. R. Harp, E. T. Coon, C. J. Wilson, A. K. Liljedahl, and V. E.

1188   Romanovsky. 2015. Using field observations to inform thermal hydrology models of

1189   permafrost dynamics with ATS (v0.83). Geoscientific Model Development 8:2701–2722.

1190   Bam, E. K. P., A. M. Ireson, G. Kamp, and J. M. Hendry. 2020. Ephemeral ponds: Are they the

1191   dominant source of depression-focused groundwater recharge? Water Resources

1192   Research 56.

1193   Beckingham, B., T. Callahan, and V. Vulava. 2019. Stormwater Ponds in the Southeastern U.S.

1194   Coastal Plain: Hydrogeology, Contaminant Fate, and the Need for a Social-Ecological

1195   Framework. Frontiers in Environmental Science 7:1–14.

1196   Belyea, L. R., and A. J. Baird. 2006. Beyond "The limits to peat bog growth: cross-scale

1197   feedback in peatland development. Ecological Monographs 76:299–322.

1198   Benstead, J. P., and D. S. Leigh. 2012. An expanded role for river networks. Nature Geoscience

1199   5:678–679.

1200 Bernhardt, E. S., J. R. Blaszczak, C. D. Ficken, M. L. Fork, K. E. Kaiser, and E. C. Seybold.

1201   2017. Control points in ecosystems: Moving beyond the hot spot hot moment concept.

1202   Ecosystems 20:665–682.

1203 Bernhardt, E. S., P. Savoy, M. J. Vlah, A. P. Appling, L. E. Koenig, R. O. Hall, M. Arroita, J. R.

1204   Blaszczak, A. M. Carter, M. Cohen, J. W. Harvey, J. B. Heffernan, A. M. Helton, J. D.

1205   Hosen, L. Kirk, W. H. McDowell, E. H. Stanley, C. B. Yackulic, and N. B. Grimm. 2022.

1206   Light and flow regimes regulate the metabolism of rivers. Proceedings of the National

1207   Academy of Sciences 119:e2121976119.

1208 Bertolini, C., and J. da Mosto. 2021. Restoring for the climate: a review of coastal wetland

1209   restoration research in the last 30 years. Restoration Ecology 29:e13438.

1210 Betson, R. P., and J. B. Marius. 1969. Source Areas of Storm Runoff. Water Resources

1211   Research 5:574–582.

1212 Bettez, N. D., and P. M. Groffman. 2012. Denitrification potential in stormwater control

1213   structures and natural riparian zones in an urban landscape. Environmental Science and

1214   Technology 46:10909–10917.

1215 Bevacqua, E., M. I. Vousdoukas, G. Zappa, K. Hodges, T. G. Shepherd, D. Maraun, L.

1216   Mentaschi, and L. Feyen. 2020. More meteorological events that drive compound

1217   coastal flooding are projected under climate change. Communications Earth &

1218   Environment 1:47.

1219 Biancamaria, S., D. P. Lettenmaier, and T. M. Pavelsky. 2016. The SWOT Mission and its

1220   capabilities for land hydrology. Surveys in Geophysics 37:307–337.

1221 Bie, W., T. Fei, X. Liu, H. Liu, and G. Wu. 2020. Small water bodies mapped from Sentinel-2

1222   MSI (MultiSpectral Imager) imagery with higher accuracy. International Journal of

1223   Remote Sensing 41:7912–7930.

1224 Blaurock, K., P. Garthen, B. S. Gilfedder, J. H. Fleckenstein, S. Peiffer, and L. Hopp. 2021.

1225   Elucidating sources and pathways of dissolved organic carbon in a small, forested

1226   catchment: A qualitative assessment of stream, soil and shallow groundwater. other,

1227   pico.

1228 Bloom, A. A., K. W. Bowman, M. Lee, A. J. Turner, R. Schroeder, J. R. Worden, R. Weidner, K.

1229   C. McDonald, and D. J. Jacob. 2017. A global wetland methane emissions and

1230   uncertainty dataset for atmospheric chemical transport models (WetCHARTs version

1231   1.0). Geoscientific Model Development 10:2141–2156.

1232 Bloom, A. A., P. I. Palmer, A. Fraser, D. S. Reay, and C. Frankenberg. 2010. Large-scale

1233   controls of methanogenesis inferred from methane and gravity spaceborne data.

1234   Science 327:322–325.

1235 Bogaard, T. A., and R. Greco. 2016. Landslide hydrology: from hydrology to pore pressure.

1236   WIREs Water 3:439–459.

1237 Bogan, M. T., E. T. Chester, T. Datry, A. L. Murphy, B. J. Robson, A. Ruhi, R. Stubbington, and

1238   J. E. Whitney. 2017a. Resistance, Resilience, and Community Recovery in Intermittent

1239   Rivers and Ephemeral Streams. Pages 349–376 Intermittent Rivers and Ephemeral

1240   Streams. Elsevier.

1241 Bogan, M. T., E. T. Chester, T. Datry, A. L. Murphy, B. J. Robson, A. Ruhi, R. Stubbington, and

1242   J. E. Whitney. 2017b. Resistance, Resilience, and Community Recovery in Intermittent

1243   Rivers and Ephemeral Streams. Pages 349–376 Intermittent Rivers and Ephemeral

1244   Streams. Elsevier.

1245 Bogard, M. J., B. A. Bergamaschi, D. E. Butman, F. Anderson, S. H. Knox, and L. Windham-

1246   Myers. 2020. Hydrologic export is a major component of coastal wetland carbon

1247   budgets. Global Biogeochemical Cycles 34.

1248 Bonada, N., M. Rieradevall, and N. Prat. 2007. Macroinvertebrate community structure and

1249   biological traits related to flow permanence in a Mediterranean river network.

1250   Hydrobiologia 589:91–106.

1251   Borch, T., R. Kretzchmar, A. Kappler, P. Van Cappellen, M. Ginder-Vogel, and K. Campbell.

1252   2010. Biogeochemical redox processes and their impact on contaminant dynamics.

1253   Environmental Science & Technology 44:15–23.

1254   Bornette, G., C. Amoros, H. Piegay, J. Tachet, and T. Hein. 1998. Ecological complexity of

1255   wetlands within a river landscape. Biological Conservation 85:35–45.

1256   Brantley, S. L., M. I. Lebedeva, V. N. Balashov, K. Singha, P. L. Sullivan, and G. Stinchcomb.

1257   2017. Toward a conceptual model relating chemical reaction fronts to water flow paths in

1258   hills. Geomorphology 277:100–117.

1259   Braswell, A. E., and J. B. Heffernan. 2019. Coastal wetland distributions: Delineating domains of

1260   macroscale drivers and local feedbacks. Ecosystems 22:1256–1270.

1261   Braswell, A. E., S. Leyk, D. S. Connor, and J. H. Uhl. 2022. Creeping disaster along the U.S.

1262   coastline: Understanding exposure to sea level rise and hurricanes through historical

1263   development. PLOS ONE 17:e0269741.

1264   Brazier, R. E., A. Puttock, H. A. Graham, R. E. Auster, K. H. Davies, and C. M. L. Brown. 2021.

1265   Beaver: Nature's ecosystem engineers. WIREs Water 8.

1266   Brendonck, L., T. Pinceel, and R. Ortells. 2017. Dormancy and dispersal as mediators of

1267   zooplankton population and community dynamics along a hydrological disturbance

1268   gradient in inland temporary pools. Hydrobiologia 796:201–222.

1269   Brinson, M. 1993. A Hydrogeomorphic classification for wetlands. Technical Report, U.S. Army

1270   Corps of Engineers, Washington, DC.

1271   Brooks, R. T. 2004. Weather-related effects on woodland vernal pool hydrology and

1272   hydroperiod. Wetlands 24:104–114.

1273   Burt, T. P., and W. T. Swank. 2010. Hursh CR and Brater EF (1941) Separating storm-

1274   hydrographs from small drainage-areas into surface- and subsurface-flow. Transactions,

1275   American Geophysical Union 22: 863-871. Progress in Physical Geography: Earth and

1276   Environment 34:719–726.

1277   Busch, M. H., K. H. Costigan, K. M. Fritz, T. Datry, C. A. Krabbenhoft, J. C. Hammond, M.

1278   Zimmer, J. D. Olden, R. M. Burrows, W. K. Dodds, K. S. Boersma, M. Shanafield, S. K.

1279   Kampf, M. C. Mims, M. T. Bogan, A. S. Ward, M. Perez Rocha, S. Godsey, G. H. Allen,

1280   J. R. Blaszczak, C. N. Jones, and D. C. Allen. 2020. What's in a name? Patterns, trends,

1281   and suggestions for defining non-perennial rivers and streams. Water 12:1980.

1282   Buszka, T. T., and D. M. Reeves. 2021. Pathways and timescales associated with nitrogen

1283   transport from septic systems in coastal aquifers intersected by canals. Hydrogeology

1284   Journal 29:1953–1964.

1285   Calhoun, A. J. K., D. M. Mushet, K. P. Bell, D. Boix, J. A. Fitzsimons, and F. Isselin-Nondedeu.

1286   2017. Temporary wetlands: challenges and solutions to conserving a 'disappearing'

1287   ecosystem. Biological Conservation 211:3–11.

1288   Cantelon, J. A., J. A. Guimond, C. E. Robinson, H. A. Michael, and B. L. Kurylyk. 2022. Vertical

1289   saltwater intrusion in coastal aquifers driven by episodic flooding: A review. Water

1290   Resources Research 58:e2022WR032614.

1291   Capps, K. A., R. Rancatti, N. Tomczyk, T. B. Parr, A. J. K. Calhoun, and M. Hunter. 2014.

1292   Biogeochemical hotspots in forested landscapes: The role of vernal pools in

1293   denitrification and organic matter processing. Ecosystems 17:1455–1468.

1294   Casanova, M. T., and M. A. Brock. 2000. How do depth, duration and frequency of flooding

1295   influence the establishment of wetland plant communities? Plant Ecology 147:237–250.

1296   Castaldelli, G., E. Soana, E. Racchetti, F. Vincenzi, E. A. Fano, and M. Bartoli. 2015. Vegetated

1297   canals mitigate nitrogen surplus in agricultural watersheds. Agriculture, Ecosystems &

1298   Environment 212:253–262.

1299   Castañeda-Moya, E., V. H. Rivera-Monroy, R. M. Chambers, X. Zhao, L. Lamb-Wotton, A.

1300   Gorsky, E. E. Gaiser, T. G. Troxler, J. S. Kominoski, and M. Hiatt. 2020. Hurricanes

1301   fertilize mangrove forests in the Gulf of Mexico (Florida Everglades, USA). Proceedings

1302   of the National Academy of Sciences 117:4831–4841.

1303   Cawley, K. M., Y. Yamashita, N. Maie, and R. Jaffé. 2014. Using optical properties to quantify

1304   fringe mangrove inputs to the dissolved organic matter (DOM) pool in a subtropical

1305   estuary. Estuaries and Coasts 37:399–410.

1306   Chambers, L. G., H. E. Steinmuller, and J. L. Breithaupt. 2019. Toward a mechanistic

1307   understanding of "peat collapse" and its potential contribution to coastal wetland loss.

1308   Ecology 100.

1309   Chapin, T. P., A. S. Todd, and M. P. Zeigler. 2014. Robust, low-cost data loggers for stream

1310   temperature, flow intermittency, and relative conductivity monitoring. Water Resources

1311   Research 50:6542–6548.

1312   Chen, B., and D. H. Wise. 1999. Bottom-up limitation of predaceous arthropods in a detritus-

1313   based terrestrial food web. Ecology 80:761–772.

1314   Cheng, F. Y., J. Park, M. Kumar, and N. B. Basu. 2023. Disconnectivity matters: the outsized

1315   role of small ephemeral wetlands in landscape-scale nutrient retention. Environmental

1316   Research Letters 18:024018.

1317   Choularton, T. W., and S. J. Perry. 1986. A model of the orographic enhancement of snowfall by

1318   the seeder-feeder mechanism. Quarterly Journal of the Royal Meteorological Society

1319   112:335–345.

1320   Clark, K. E., M. A. Torres, A. J. West, R. G. Hilton, M. New, A. B. Horwath, J. B. Fisher, J. M.

1321   Rapp, A. Robles Caceres, and Y. Malhi. 2014. The hydrological regime of a forested

1322   tropical Andean catchment. Hydrology and Earth System Sciences 18:5377–5397.

1323   Clifford, C., and J. Heffernan. 2018. Artificial aquatic ecosystems. Water 10:1096.

1324   Colbert, A. J., and B. J. Soden. 2012. Climatological variations in North Atlantic tropical cyclone

1325   tracks. Journal of Climate 25:657–673.

1326   Coles, A. E., B. G. McConkey, and J. J. McDonnell. 2017. Climate change impacts on hillslope

1327   runoff on the northern Great Plains, 1962–2013. Journal of Hydrology 550:538–548.

1328 Colmer, T. D. 2003. Long-distance transport of gases in plants: A perspective on internal
1329   aeration and radial oxygen loss from roots: Gas transport in plants. Plant, Cell &
1330   Environment 26:17–36.
1331 Connolly, R. M. 2003. Differences in trophodynamics of commercially important fish between
1332   artificial waterways and natural coastal wetlands. Estuarine, Coastal and Shelf Science
1333   58:929–936.
1334 Convention on wetlands of international importance espeically as waterfowl habitat. 1994, July
1335   13. . United Nations Educational, Scientific and Cultural Organization.
1336 Cooley, S., L. Smith, L. Stepan, and J. Mascaro. 2017. Tracking dynamic northern surface water
1337   changes with high-frequency planet CubeSat imagery. Remote Sensing 9:1306.
1338 Coon, E. T., J. D. Moulton, E. Kikinzon, M. Berndt, G. Manzini, R. Garimella, K. Lipnikov, and S.
1339   L. Painter. 2020. Coupling surface flow and subsurface flow in complex soil structures
1340   using mimetic finite differences. Advances in Water Resources 144:103701.
1341 Corti, R., and T. Datry. 2012. Invertebrates and sestonic matter in an advancing wetted front
1342   travelling down a dry river bed (Albarine, France). Freshwater Science 31:1187–1201.
1343 Costigan, K. H., M. D. Daniels, and W. K. Dodds. 2015. Fundamental spatial and temporal
1344   disconnections in the hydrology of an intermittent prairie headwater network. Journal of
1345   Hydrology 522:305–316.
1346 Costigan, K. H., K. L. Jaeger, C. W. Goss, K. M. Fritz, and P. C. Goebel. 2016. Understanding
1347   controls on flow permanence in intermittent rivers to aid ecological research: integrating
1348   meteorology, geology and land cover: Integrating Science to Understand Flow
1349   Intermittence. Ecohydrology 9:1141–1153.
1350 Costigan, K. H., M. J. Kennard, C. Leigh, E. Sauquet, T. Datry, and A. J. Boulton. 2017. Flow
1351   regimes in intermittent rivers and ephemeral streams. Pages 51–78 Intermittent Rivers
1352   and Ephemeral Streams. Elsevier.

1353   Cowardin, L. M., and F. C. Golet. 1995. US Fish and Wildlife Service 1979 wetland

1354   classification: A review. Vegetatio 118:139–152.

1355   Crook, D. A., D. J. Buckle, J. R. Morrongiello, Q. A. Allsop, W. Baldwin, T. M. Saunders, and M.

1356   M. Douglas. 2020. Tracking the resource pulse: Movement responses of fish to dynamic

1357   floodplain habitat in a tropical river. Journal of Animal Ecology 89:795–807.

1358   Crotty, S. M., C. Ortals, T. M. Pettengill, L. Shi, M. Olabarrieta, M. A. Joyce, A. H. Altieri, E.

1359   Morrison, T. S. Bianchi, C. Craft, M. D. Bertness, and C. Angelini. 2020. Sea-level rise

1360   and the emergence of a keystone grazer alter the geomorphic evolution and ecology of

1361   southeast US salt marshes. Proceedings of the National Academy of Sciences

1362   117:17891–17902.

1363   Crump, B. C., L. M. Fine, C. S. Fortunato, L. Herfort, J. A. Needoba, S. Murdock, and F. G.

1364   Prahl. 2017. Quantity and quality of particulate organic matter controls bacterial

1365   production in the Columbia River estuary. Limnology and Oceanography 62:2713–2731.

1366   Cubley, E. S., D. J. Cooper, and D. M. Merritt. 2023. Are riparian vegetation flow response

1367   guilds transferable between rivers? Freshwater Biology 68:406–424.

1368   Culley, S., S. Noble, A. Yates, M. Timbs, S. Westra, H. R. Maier, M. Giuliani, and A. Castelletti.

1369   2016. A bottom-up approach to identifying the maximum operational adaptive capacity of

1370   water resource systems to a changing climate. Water Resources Research 52:6751–

1371   6768.

1372   Dang, C., E. M. Morrissey, S. C. Neubauer, and R. B. Franklin. 2019. Novel microbial

1373   community composition and carbon biogeochemistry emerge over time following

1374   saltwater intrusion in wetlands. Global Change Biology 25:549–561.

1375   Daniel, J., and R. C. Rooney. 2021. Wetland hydroperiod predicts community structure, but not

1376   the magnitude of cross-community congruence. Scientific Reports 11:429.

1377   Datry, T., A. J. Boulton, N. Bonada, K. Fritz, C. Leigh, E. Sauquet, K. Tockner, B. Hugueny, and

1378   C. N. Dahm. 2018a. Flow intermittence and ecosystem services in rivers of the

1379   Anthropocene. Journal of Applied Ecology 55:353–364.

1380   Datry, T., A. Foulquier, R. Corti, D. von Schiller, K. Tockner, C. Mendoza-Lera, J. C. Clément,

1381   M. O. Gessner, M. Moleón, R. Stubbington, B. Gücker, R. Albariño, D. C. Allen, F.

1382   Altermatt, M. I. Arce, S. Arnon, D. Banas, A. Banegas-Medina, E. Beller, M. L.

1383   Blanchette, J. F. Blanco-Libreros, J. J. Blessing, I. G. Boëchat, K. S. Boersma, M. T.

1384   Bogan, N. Bonada, N. R. Bond, K. C. Brintrup Barría, A. Bruder, R. M. Burrows, T.

1385   Cancellario, C. Canhoto, S. M. Carlson, S. Cauvy-Frauníe, N. Cid, M. Danger, B. de

1386   Freitas Terra, A. M. De Girolamo, E. de La Barra, R. del Campo, V. D. Diaz-Villanueva,

1387   F. Dyer, A. Elosegi, E. Faye, C. Febria, B. Four, S. Gafny, S. D. Ghate, R. Gómez, L.

1388   Gómez-Gener, M. a. S. Graça, S. Guareschi, F. Hoppeler, J. L. Hwan, J. I. Jones, S.

1389   Kubheka, A. Laini, S. D. Langhans, C. Leigh, C. J. Little, S. Lorenz, J. C. Marshall, E.

1390   Martín, A. R. McIntosh, E. I. Meyer, M. Miliša, M. C. Mlambo, M. Morais, N. Moya, P. M.

1391   Negus, D. K. Niyogi, A. Papatheodoulou, I. Pardo, P. Pařil, S. U. Pauls, V. Pešić, M.

1392   Polášek, C. T. Robinson, P. Rodríguez-Lozano, R. J. Rolls, M. M. Sánchez-Montoya, A.

1393   Savić, O. Shumilova, K. R. Sridhar, A. L. Steward, R. Storey, A. Taleb, A. Uzan, R.

1394   Vander Vorste, N. J. Waltham, C. Woelfle-Erskine, D. Zak, C. Zarfl, and A. Zoppini.

1395   2018b. A global analysis of terrestrial plant litter dynamics in non-perennial waterways.

1396   Nature Geoscience 11:497–503.

1397   Datry, T., A. Foulquier, R. Corti, D. Von Schiller, K. Tockner, C. Mendoza-Lera, J. C. Clément,

1398   M. O. Gessner, M. Moleón, R. Stubbington, B. Gücker, R. Albariño, D. C. Allen, F.

1399   Altermatt, M. I. Arce, S. Arnon, D. Banas, A. Banegas-Medina, E. Beller, M. L.

1400   Blanchette, J. F. Blanco-Libreros, J. J. Blessing, I. G. Boëchat, K. S. Boersma, M. T.

1401   Bogan, N. Bonada, N. R. Bond, K. C. Brintrup Barría, A. Bruder, R. M. Burrows, T.

1402   Cancellario, C. Canhoto, S. M. Carlson, S. Cauvy-Frauníe, N. Cid, M. Danger, B. De

1403   Freitas Terra, A. M. De Girolamo, E. De La Barra, R. Del Campo, V. D. Diaz-Villanueva,

1404   F. Dyer, A. Elosegi, E. Faye, C. Febria, B. Four, S. Gafny, S. D. Ghate, R. Gómez, L.

1405   Gómez-Gener, M. A. S. Graça, S. Guareschi, F. Hoppeler, J. L. Hwan, J. I. Jones, S.

1406   Kubheka, A. Laini, S. D. Langhans, C. Leigh, C. J. Little, S. Lorenz, J. C. Marshall, E.

1407   Martín, A. R. McIntosh, E. I. Meyer, M. Miliša, M. C. Mlambo, M. Morais, N. Moya, P. M.

1408   Negus, D. K. Niyogi, A. Papatheodoulou, I. Pardo, P. Pařil, S. U. Pauls, V. Pešić, M.

1409   Polášek, C. T. Robinson, P. Rodríguez-Lozano, R. J. Rolls, M. M. Sánchez-Montoya, A.

1410   Savić, O. Shumilova, K. R. Sridhar, A. L. Steward, R. Storey, A. Taleb, A. Uzan, R.

1411   Vander Vorste, N. J. Waltham, C. Woelfle-Erskine, D. Zak, C. Zarfl, and A. Zoppini.

1412   2018c. A global analysis of terrestrial plant litter dynamics in non-perennial waterways.

1413   Nature Geoscience 11:497–503.

1414 Datry, T., and S. T. Larned. 2008. River flow controls ecological processes and invertebrate

1415   assemblages in subsurface flowpaths of an ephemeral river reach. Canadian Journal of

1416   Fisheries and Aquatic Sciences 65:1532–1544.

1417 Datry, T., A. Truchy, J. D. Olden, M. H. Busch, R. Stubbington, W. K. Dodds, S. Zipper, S. Yu,

1418   M. L. Messager, J. D. Tonkin, K. E. Kaiser, J. C. Hammond, E. K. Moody, R. M.

1419   Burrows, R. Sarremejane, A. G. DelVecchia, M. L. Fork, C. J. Little, R. H. Walker, A. W.

1420   Walters, and D. Allen. 2023. Causes, responses, and implications of anthropogenic

1421   versus natural flow intermittence in river networks. BioScience 73:9–22.

1422 Davidson, EriC. A., E. Belk, and R. D. Boone. 1998. Soil water content and temperature as

1423   independent or confounded factors controlling soil respiration in a temperate mixed

1424   hardwood forest. Global Change Biology 4:217–227.

1425 Davidson, N. C., E. Fluet-Chouinard, and C. M. Finlayson. 2018. Global extent and distribution

1426   of wetlands: trends and issues. Marine and Freshwater Research 69:620.

1427   Davidson, T. A., A. W. Mackay, P. Wolski, R. Mazebedi, M. Murray-Hudson, and M. Todd. 2012.

1428   Seasonal and spatial hydrological variability drives aquatic biodiversity in a flood-pulsed,

1429   sub-tropical wetland. Freshwater Biology 57:1253–1265.

1430   Davis, C. A., D. Dvorett, and J. R. Bidwell. 2013. Hydrogeomorphic classification and functional

1431   assessment. Pages 29–68 *in* J. T. Anderson and C. A. Davis, editors. Wetland

1432   Techniques: Volume 3: Applications and Management. Springer Netherlands, Dordrecht.

1433   De Sassi, C., O. T. Lewis, and J. M. Tylianakis. 2012. Plant-mediated and nonadditive effects of

1434   two global change drivers on an insect herbivore community. Ecology 93:1892–1901.

1435   De Vries, M. E., J. Rodenburg, B. V. Bado, A. Sow, P. A. Leffelaar, and K. E. Giller. 2010. Rice

1436   production with less irrigation water is possible in a Sahelian environment. Field Crops

1437   Research 116:154–164.

1438   Del Campo, R., R. Corti, and G. Singer. 2021. Flow intermittence alters carbon processing in

1439   rivers through chemical diversification of leaf litter. Limnology and Oceanography Letters

1440   6:232–242.

1441   Della Rocca, F., L. Vignoli, and M. A. Bologna. 2005. The reproductive biology of Salamandrina

1442   terdigitata (Caudata, Salamandridae). The Herpetological Journal 15:273–278.

1443   DelVecchia, A. G., M. Shanafield, M. A. Zimmer, M. H. Busch, C. A. Krabbenhoft, R.

1444   Stubbington, K. E. Kaiser, R. M. Burrows, J. Hosen, T. Datry, S. K. Kampf, S. C. Zipper,

1445   K. Fritz, K. Costigan, and D. C. Allen. 2022. Reconceptualizing the hyporheic zone for

1446   nonperennial rivers and streams. Freshwater Science 41:167–182.

1447   Dietze, M. C., C. Averill, J. Foster, and K. Wheeler. 2017. Ecological Forecasting. Princeton

1448   University Press.

1449   Dietze, M. C., A. Fox, L. M. Beck-Johnson, J. L. Betancourt, M. B. Hooten, C. S. Jarnevich, T.

1450   H. Keitt, M. A. Kenney, C. M. Laney, L. G. Larsen, H. W. Loescher, C. K. Lunch, B. C.

1451   Pijanowski, J. T. Randerson, E. K. Read, A. T. Tredennick, R. Vargas, K. C. Weathers,

1452   and E. P. White. 2018. Iterative near-term ecological forecasting: Needs, opportunities,

1453   and challenges. Proceedings of the National Academy of Sciences 115:1424–1432.

1454 van Dijk, G., A. J. P. Smolders, R. Loeb, A. Bout, J. G. M. Roelofs, and L. P. M. Lamers. 2015.

1455   Salinization of coastal freshwater wetlands; effects of constant versus fluctuating salinity

1456   on sediment biogeochemistry. Biogeochemistry 126:71–84.

1457 Dissanayake, P., J. Brown, P. Wisse, and H. Karunarathna. 2015. Effects of storm clustering on

1458   beach/dune evolution. Marine Geology 370:63–75.

1459 Döll, P., and H. M. Schmied. 2012. How is the impact of climate change on river flow regimes

1460   related to the impact on mean annual runoff? A global-scale analysis. Environmental

1461   Research Letters 7:014037.

1462 Du, J., J. Shen, Y. J. Zhang, F. Ye, Z. Liu, Z. Wang, Y. P. Wang, X. Yu, M. Sisson, and H. V.

1463   Wang. 2018. Tidal response to sea-level rise in different types of estuaries: The

1464   importance of length, bathymetry, and geometry. Geophysical Research Letters 45:227–

1465   235.

1466 Dube, K., G. Nhamo, and D. Chikodzi. 2021. Flooding trends and their impacts on coastal

1467   communities of Western Cape Province, South Africa. Geojournal:1–16.

1468 Ekici, A., H. Lee, D. M. Lawrence, S. C. Swenson, and C. Prigent. 2019. Ground subsidence

1469   effects on simulating dynamic high-latitude surface inundation under permafrost thaw

1470   using CLM5. Geoscientific Model Development 12:5291–5300.

1471 Elberling, B. B., G. M. Kovács, H. F. E. Hansen, R. Fensholt, P. Ambus, X. Tong, D. Gominski,

1472   C. W. Mueller, D. M. N. Poultney, and S. Oehmcke. 2023. High nitrous oxide emissions

1473   from temporary flooded depressions within croplands. Communications Earth &

1474   Environment 4:463.

1475 Ensign, S. H., and G. B. Noe. 2018. Tidal extension and sea-level rise: recommendations for a

1476   research agenda. Frontiers in Ecology and the Environment 16:37–43.

1477 Eppinga, M. B., M. Rietkerk, W. Borren, E. D. Lapshina, W. Bleuten, and M. J. Wassen. 2008.

1478   Regular Surface Patterning of Peatlands: Confronting Theory with Field Data.

1479   Ecosystems 11:520–536.

1480 Fagherazzi, S., M. L. Kirwan, S. M. Mudd, G. R. Guntenspergen, S. Temmerman, A. D'Alpaos,

1481   J. Van De Koppel, J. M. Rybczyk, E. Reyes, C. Craft, and J. Clough. 2012. Numerical

1482   models of salt marsh evolution: Ecological, geomorphic, and climatic factors. Reviews of

1483   Geophysics 50:RG1002.

1484 Fan, Y., M. Clark, D. M. Lawrence, S. Swenson, L. E. Band, S. L. Brantley, P. D. Brooks, W. E.

1485   Dietrich, A. Flores, G. Grant, J. W. Kirchner, D. S. Mackay, J. J. McDonnell, P. C. D.

1486   Milly, P. L. Sullivan, C. Tague, H. Ajami, N. Chaney, A. Hartmann, P. Hazenberg, J.

1487   McNamara, J. Pelletier, J. Perket, E. Rouholahnejad-Freund, T. Wagener, X. Zeng, E.

1488   Beighley, J. Buzan, M. Huang, B. Livneh, B. P. Mohanty, B. Nijssen, M. Safeeq, C.

1489   Shen, W. Verseveld, J. Volk, and D. Yamazaki. 2019. Hillslope hydrology in global

1490   change research and earth system modeling. Water Resources Research 55:1737–

1491   1772.

1492 Fan, Y., and G. Miguez-Macho. 2011. A simple hydrologic framework for simulating wetlands in

1493   climate and earth system models. Climate Dynamics 37:253–278.

1494 Fatichi, S., E. R. Vivoni, F. L. Ogden, V. Y. Ivanov, B. Mirus, D. Gochis, C. W. Downer, M.

1495   Camporese, J. H. Davison, B. Ebel, N. Jones, J. Kim, G. Mascaro, R. Niswonger, P.

1496   Restrepo, R. Rigon, C. Shen, M. Sulis, and D. Tarboton. 2016. An overview of current

1497   applications, challenges, and future trends in distributed process-based models in

1498   hydrology. Journal of Hydrology 537:45–60.

1499 Finlayson, C. M., and A. G. Van Der Valk, editors. 1995. Classification and Inventory of the

1500   World's Wetlands. Springer Netherlands, Dordrecht.

1501 Fisher, J. B., B. Lee, A. J. Purdy, G. H. Halverson, M. B. Dohlen, K. Cawse-Nicholson, A. Wang,

1502   R. G. Anderson, B. Aragon, M. A. Arain, D. D. Baldocchi, J. M. Baker, H. Barral, C. J.

1503   Bernacchi, C. Bernhofer, S. C. Biraud, G. Bohrer, N. Brunsell, B. Cappelaere, S. Castro-

1504   Contreras, J. Chun, B. J. Conrad, E. Cremonese, J. Demarty, A. R. Desai, A. De Ligne,

1505   L. Foltýnová, M. L. Goulden, T. J. Griffis, T. Grünwald, M. S. Johnson, M. Kang, D.

1506   Kelbe, N. Kowalska, J. Lim, I. Maïnassara, M. F. McCabe, J. E. C. Missik, B. P.

1507   Mohanty, C. E. Moore, L. Morillas, R. Morrison, J. W. Munger, G. Posse, A. D.

1508   Richardson, E. S. Russell, Y. Ryu, A. Sanchez-Azofeifa, M. Schmidt, E. Schwartz, I.

1509   Sharp, L. Šigut, Y. Tang, G. Hulley, M. Anderson, C. Hain, A. French, E. Wood, and S.

1510   Hook. 2020. ECOSTRESS: NASA's next generation mission to measure

1511   evapotranspiration from the international space station. Water Resources Research 56.

1512   Florencio, M., R. Fernández-Zamudio, M. Lozano, and C. Díaz-Paniagua. 2020. Interannual

1513   variation in filling season affects zooplankton diversity in Mediterranean temporary

1514   ponds. Hydrobiologia 847:1195–1205.

1515   Fortesa, J., G. F. Ricci, J. García-Comendador, F. Gentile, J. Estrany, E. Sauquet, T. Datry, and

1516   A. M. De Girolamo. 2021. Analysing hydrological and sediment transport regime in two

1517   Mediterranean intermittent rivers. CATENA 196:104865.

1518   Fournier, R. J., G. De Mendoza, R. Sarremejane, and A. Ruhi. 2023. Isolation controls

1519   reestablishment mechanisms and post-drying community structure in an intermittent

1520   stream. Ecology 104:e3911.

1521   Fredrickson, L., and T. S. Taylor. 1982. Management of seasonally flooded impoundments for

1522   wildlife. Resource Publication 148, U.S. Fish and Wildlife Service.

1523   Fryirs, K., and G. Brierley. 2022. Assemblages of geomorphic units: A building block approach

1524   to analysis and interpretation of river character, behaviour, condition and recovery. Earth

1525   Surface Processes and Landforms 47:92–108.

1526   Gallant, A. 2015. The challenges of remote monitoring of wetlands. Remote Sensing 7:10938–

1527   10950.

1528 Garayburu-Caruso, V. A., R. E. Danczak, J. C. Stegen, L. Renteria, M. Mccall, A. E. Goldman,

1529   R. K. Chu, J. Toyoda, C. T. Resch, J. M. Torgeson, J. Wells, S. Fansler, S. Kumar, and

1530   E. B. Graham. 2020. Using community science to reveal the global chemogeography of

1531   river metabolomes. Metabolites 10:518.

1532 Gates, J. B., P. M. Chittaro, and K. B. Veggerby. 2020. Standard operating procedures for

1533   measuring bulk stable isotope values of nitrogen and carbon in marine biota by isotope

1534   ratio mass spectrometry (IRMS).

1535 Gendreau, K. L., V. Buxton, C. E. Moore, and M. Mims. 2021. Temperature loggers capture

1536   intraregional variation of inundation timing for intermittent ponds. preprint, Hydrology.

1537 Gittman, R. K., F. J. Fodrie, A. M. Popowich, D. A. Keller, J. F. Bruno, C. A. Currin, C. H.

1538   Peterson, and M. F. Piehler. 2015. Engineering away our natural defenses: an analysis

1539   of shoreline hardening in the US. Frontiers in Ecology and the Environment 13:301–307.

1540 Gleason, J. E., and R. C. Rooney. 2018. Pond permanence is a key determinant of aquatic

1541   macroinvertebrate community structure in wetlands. Freshwater Biology 63:264–277.

1542 Goldman, A. E., S. R. Emani, L. C. Pérez-Angel, J. A. Rodríguez-Ramos, and J. C. Stegen.

1543   2022. Integrated, coordinated, open, and networked (ICON) science to advance the

1544   geosciences: Introduction and synthesis of a special collection of commentary articles.

1545   Earth and Space Science 9:e2021EA002099.

1546 Goldman, A. E., E. B. Graham, A. R. Crump, D. W. Kennedy, E. B. Romero, C. G. Anderson, K.

1547   L. Dana, C. T. Resch, J. K. Fredrickson, and J. C. Stegen. 2017. Biogeochemical cycling

1548   at the aquatic–terrestrial interface is linked to parafluvial hyporheic zone inundation

1549   history. Biogeosciences 14:4229–4241.

1550 Gómez-Gener, L., A. R. Siebers, M. I. Arce, S. Arnon, S. Bernal, R. Bolpagni, T. Datry, G.

1551   Gionchetta, H.-P. Grossart, C. Mendoza-Lera, V. Pohl, U. Risse-Buhl, O. Shumilova, O.

1552   Tzoraki, D. Von Schiller, A. Weigand, G. Weigelhofer, D. Zak, and A. Zoppini. 2021.

1553   Towards an improved understanding of biogeochemical processes across surface-

1554   groundwater interactions in intermittent rivers and ephemeral streams. Earth-Science

1555   Reviews 220:103724.

1556   González, E., A. A. Sher, E. Tabacchi, A. Masip, and M. Poulin. 2015. Restoration of riparian

1557   vegetation: A global review of implementation and evaluation approaches in the

1558   international, peer-reviewed literature. Journal of Environmental Management 158:85–

1559   94.

1560   Guimond, J. A., and H. A. Michael. 2021. Effects of marsh migration on flooding, saltwater

1561   intrusion, and crop yield in coastal agricultural land subject to storm surge inundation.

1562   Water Resources Research 57.

1563   Hale, R. L., L. Turnbull, S. R. Earl, D. L. Childers, and N. B. Grimm. 2015. Stormwater

1564   infrastructure controls runoff and dissolved material export from arid urban watersheds.

1565   Ecosystems 18:62–75.

1566   Hammond, J. C., M. Zimmer, M. Shanafield, K. Kaiser, S. E. Godsey, M. C. Mims, S. C. Zipper,

1567   R. M. Burrows, S. K. Kampf, W. Dodds, C. N. Jones, C. A. Krabbenhoft, K. S. Boersma,

1568   T. Datry, J. D. Olden, G. H. Allen, A. N. Price, K. Costigan, R. Hale, A. S. Ward, and D.

1569   C. Allen. 2021. Spatial patterns and drivers of nonperennial flow regimes in the

1570   contiguous United States. Geophysical Research Letters 48:e2020GL090794.

1571   Hanson, P. J., J. S. Riggs, W. R. Nettles, J. R. Phillips, M. B. Krassovski, L. A. Hook, L. Gu, A.

1572   D. Richardson, D. M. Aubrecht, D. M. Ricciuto, J. M. Warren, and C. Barbier. 2017.

1573   Attaining whole-ecosystem warming using air and deep-soil heating methods with an

1574   elevated CO_2 atmosphere. Biogeosciences 14:861–883.

1575   Hayashi, M., G. Van Der Kamp, and D. O. Rosenberry. 2016. Hydrology of prairie wetlands:

1576   Understanding the integrated surface-water and groundwater processes. Wetlands

1577   36:237–254.

1578   Herbert, E. R., J. Schubauer-Berigan, and C. B. Craft. 2018. Differential effects of chronic and

1579   acute simulated seawater intrusion on tidal freshwater marsh carbon cycling.

1580   Biogeochemistry 138:137–154.

1581   Herndon, E. M., A. L. Dere, P. L. Sullivan, D. Norris, B. Reynolds, and S. L. Brantley. 2015.

1582   Landscape heterogeneity drives contrasting concentration–discharge relationships in

1583   shale headwater catchments. Hydrology and Earth System Sciences 19:3333–3347.

1584   Herndon, E. M., G. Steinhoefel, A. L. D. Dere, and P. L. Sullivan. 2018. Perennial flow through

1585   convergent hillslopes explains chemodynamic solute behavior in a shale headwater

1586   catchment. Chemical Geology 493:413–425.

1587   Herzon, I., and J. Helenius. 2008. Agricultural drainage ditches, their biological importance and

1588   functioning. Biological Conservation 141:1171–1183.

1589   Hill, M. J., H. M. Greaves, C. D. Sayer, C. Hassall, M. Milin, V. S. Milner, L. Marazzi, R. Hall, L.

1590   R. Harper, I. Thornhill, R. Walton, J. Biggs, N. Ewald, A. Law, N. Willby, J. C. White, R.

1591   A. Briers, K. L. Mathers, M. J. Jeffries, and P. J. Wood. 2021. Pond ecology and

1592   conservation: research priorities and knowledge gaps. Ecosphere 12:e03853.

1593   Hill, M. J., C. Hassall, B. Oertli, L. Fahrig, B. J. Robson, J. Biggs, M. J. Samways, N. Usio, N.

1594   Takamura, J. Krishnaswamy, and P. J. Wood. 2018. New policy directions for global

1595   pond conservation. Conservation Letters 11:e12447.

1596   Hinkel, J., D. Lincke, A. T. Vafeidis, M. Perrette, R. J. Nicholls, R. S. J. Tol, B. Marzeion, X.

1597   Fettweis, C. Ionescu, and A. Levermann. 2014. Coastal flood damage and adaptation

1598   costs under 21st century sea-level rise. Proceedings of the National Academy of

1599   Sciences 111:3292–3297.

1600   Hinshaw, S. E., C. Tatariw, N. Flournoy, A. Kleinhuizen, C. Taylor, P. A. Sobecky, and B.

1601   Mortazavi. 2017. Vegetation loss decreases salt marsh denitrification capacity:

1602   Implications for marsh erosion. Environmental Science & Technology 51:8245–8253.

1603   Hladyz, S., S. C. Watkins, K. L. Whitworth, and D. S. Baldwin. 2011. Flows and hypoxic

1604   blackwater events in managed ephemeral river channels. Journal of Hydrology 401:117–

1605   125.

1606   Hofmeister, K. L., S. L. Eggert, B. J. Palik, D. Morley, E. Creighton, M. Rye, and R. K. Kolka.

1607   2022. The identification, mapping, and management of seasonal ponds in forests of the

1608   Great Lakes Region. Wetlands 42:9.

1609   Hondula, K. L., B. DeVries, C. N. Jones, and M. A. Palmer. 2021a. Effects of Using High

1610   Resolution Satellite-Based Inundation Time Series to Estimate Methane Fluxes From

1611   Forested Wetlands. Geophysical Research Letters 48:e2021GL092556.

1612   Hondula, K. L., C. N. Jones, and M. A. Palmer. 2021b. Effects of seasonal inundation on

1613   methane fluxes from forested freshwater wetlands. Environmental Research Letters

1614   16:084016.

1615   Hooley-Underwood, Z. E., S. B. Stevens, N. R. Salinas, and K. G. Thompson. 2019. An

1616   intermittent stream supports extensive spawning of large-river native fishes.

1617   Transactions of the American Fisheries Society 148:426–441.

1618   Hopple, A. M., K. O. Doro, V. L. Bailey, B. Bond-Lamberty, N. McDowell, K. A. Morris, A. Myers-

1619   Pigg, S. C. Pennington, P. Regier, R. Rich, A. Sengupta, R. Smith, J. Stegen, N. D.

1620   Ward, S. C. Woodard, and J. P. Megonigal. 2023. Attaining freshwater and estuarine-

1621   water soil saturation in an ecosystem-scale coastal flooding experiment. Environmental

1622   Monitoring and Assessment 195:425.

1623   Hopple, A. M., S. C. Pennington, J. P. Megonigal, V. Bailey, and B. Bond-Lamberty. 2022.

1624   Disturbance legacies regulate coastal forest soil stability to changing salinity and

1625   inundation: A soil transplant experiment. Soil Biology and Biochemistry 169:108675.

1626   Houser, C., and S. Hamilton. 2009. Sensitivity of post-hurricane beach and dune recovery to

1627   event frequency. Earth Surface Processes and Landforms 34:613–628.

1628   Huang, C., C. Gascuel-Odoux, and S. Cros-Cayot. 2002. Hillslope topographic and hydrologic

1629   effects on overland flow and erosion. CATENA 46:177–188.

1630   Huang, W., K. Wang, C. Ye, W. C. Hockaday, G. Wang, and S. J. Hall. 2021. High carbon

1631   losses from oxygen-limited soils challenge biogeochemical theory and model

1632   assumptions. Global Change Biology 27:6166–6180.

1633   Ivory, S. J., M. M. McGlue, S. Spera, A. Silva, and I. Bergier. 2019. Vegetation, rainfall, and

1634   pulsing hydrology in the Pantanal, the world's largest tropical wetland. Environmental

1635   Research Letters 14:124017.

1636   Jarecke, K. M., T. D. Loecke, and A. J. Burgin. 2016. Coupled soil oxygen and greenhouse gas

1637   dynamics under variable hydrology. Soil Biology and Biochemistry 95:164–172.

1638   Jeffries, M. 2008. The spatial and temporal heterogeneity of macrophyte communities in thirty

1639   small, temporary ponds over a period of ten years. Ecography 31:765–775.

1640   Jones, C. N., G. R. Evenson, D. L. McLaughlin, M. K. Vanderhoof, M. W. Lang, G. W. McCarty,

1641   H. E. Golden, C. R. Lane, and L. C. Alexander. 2018. Estimating restorable wetland

1642   water storage at landscape scales. Hydrological Processes 32:305–313.

1643   Jones, J. 2019. Improved automated detection of subpixel-scale inundation: Revised dynamic

1644   surface water extent (DSWE) partial surface water tests. Remote Sensing 11:374.

1645   Junk, W., P. Bayley, and R. Sparks. 1989. The flood pulse concept in river-floodplain systems.

1646   Page Can. Spec. Public Fish. Aquat. Sci.

1647   Kaushal, S. S., J. E. Reimer, P. M. Mayer, R. R. Shatkay, C. M. Maas, W. D. Nguyen, W. L.

1648   Boger, A. M. Yaculak, T. R. Doody, M. J. Pennino, N. W. Bailey, J. G. Galella, A.

1649   Weingrad, D. C. Collison, K. L. Wood, S. Haq, T. A. Newcomer-Johnson, S. Duan, and

1650   K. T. Belt. 2022. Freshwater salinization syndrome alters retention and release of

1651   chemical cocktails along flowpaths: From stormwater management to urban

1652   streams. Freshwater Science 41:420–441.

1653   Kirkby, M., L. Bracken, and S. Reaney. 2002. The influence of land use, soils and topography

1654   on the delivery of hillslope runoff to channels in SE Spain. Earth Surface Processes and

1655   Landforms 27:1459–1473.

1656   Kirwan, M. L., and K. B. Gedan. 2019. Sea-level driven land conversion and the formation of

1657   ghost forests. Nature Climate Change 9:450–457.

1658   Kneitel, J. M. 2014. Inundation timing, more than duration, affects the community structure of

1659   California vernal pool mesocosms. Hydrobiologia 732:71–83.

1660   Kollet, S. J., and R. M. Maxwell. 2006. Integrated surface–groundwater flow modeling: A free-

1661   surface overland flow boundary condition in a parallel groundwater flow model.

1662   Advances in Water Resources 29:945–958.

1663   Konapala, G., A. K. Mishra, Y. Wada, and M. E. Mann. 2020. Climate change will affect global

1664   water availability through compounding changes in seasonal precipitation and

1665   evaporation. Nature Communications 11:3044.

1666   Koschorreck, M., A. S. Downing, J. Hejzlar, R. Marcé, A. Laas, W. G. Arndt, P. S. Keller, A. J. P.

1667   Smolders, G. van Dijk, and S. Kosten. 2020. Hidden treasures: Human-made aquatic

1668   ecosystems harbour unexplored opportunities. Ambio 49:531–540.

1669   Krabbenhoft, C. A., G. H. Allen, P. Lin, S. E. Godsey, D. C. Allen, R. M. Burrows, A. G.

1670   DelVecchia, K. M. Fritz, M. Shanafield, A. J. Burgin, M. A. Zimmer, T. Datry, W. K.

1671   Dodds, C. N. Jones, M. C. Mims, C. Franklin, J. C. Hammond, S. Zipper, A. S. Ward, K.

1672   H. Costigan, H. E. Beck, and J. D. Olden. 2022. Assessing placement bias of the global

1673   river gauge network. Nature Sustainability 5:586–592.

1674   Kundel, D., S. Meyer, H. Birkhofer, A. Fliessbach, P. Mäder, S. Scheu, M. van Kleunen, and K.

1675   Birkhofer. 2018. Design and manual to construct rainout-shelters for climate shange

1676   experiments in agroecosystems. Frontiers in Environmental Science 6.

1677   Ladau, J., and E. A. Eloe-Fadrosh. 2019. Spatial, temporal, and phylogenetic scales of microbial

1678   ecology. Trends in Microbiology 27:662–669.

1679 Lalli, K., S. Soenen, J. B. Fisher, J. McGlinchy, T. Kleynhans, R. Eon, and L. M. Moreau. 2022.

1680   VanZyl-1: demonstrating SmallSat measurement capabilities for land surface

1681   temperature and evapotranspiration. Page 8 *in* C. D. Norton and S. R. Babu, editors.

1682   CubeSats and SmallSats for Remote Sensing VI. SPIE, San Diego, United States.

1683 Lane, C. R., and E. D'Amico. 2016. Identification of putative geographically isolated wetlands of

1684   the conterminous United States. JAWRA Journal of the American Water Resources

1685   Association 52:705–722.

1686 Lane, K., K. Charles-Guzman, K. Wheeler, Z. Abid, N. Graber, and T. Matte. 2013. Health

1687   effects of coastal storms and flooding in urban areas: A review and vulnerability

1688   assessment. Journal of Environmental and Public Health 2013:1–13.

1689 Laronne, J. B., and L. Reid. 1993. Very high rates of bedload sediment transport by ephemeral

1690   desert rivers. Nature 366:148–150.

1691 Larsen, L., N. Aumen, C. Bernhardt, V. Engel, T. Givnish, S. Hagerthey, J. Harvey, L. Leonard,

1692   P. McCormick, C. Mcvoy, G. Noe, M. Nungesser, K. Rutchey, F. Sklar, T. Troxler, J.

1693   Volin, and D. Willard. 2011. Recent and historic drivers of landscape change in the

1694   Everglades Ridge, slough, and tree island mosaic. Critical Reviews in Environmental

1695   Science and Technology 41:344–381.

1696 Lei, Y., C. Liu, L. Zhang, and S. Luo. 2016. How smallholder farmers adapt to agricultural

1697   drought in a changing climate: A case study in southern China. Land Use Policy 55:300–

1698   308.

1699 Li, L., K. Maher, A. Navarre-Sitchler, J. Druhan, C. Meile, C. Lawrence, J. Moore, J. Perdrial, P.

1700   Sullivan, A. Thompson, L. Jin, E. W. Bolton, S. L. Brantley, W. E. Dietrich, K. U. Mayer,

1701   C. I. Steefel, A. Valocchi, J. Zachara, B. Kocar, J. Mcintosh, B. M. Tutolo, M. Kumar, E.

1702   Sonnenthal, C. Bao, and J. Beisman. 2017. Expanding the role of reactive transport

1703   models in critical zone processes. Earth-Science Reviews 165:280–301.

1704   Li, L., P. L. Sullivan, P. Benettin, O. A. Cirpka, K. Bishop, S. L. Brantley, J. L. A. Knapp, I.

1705   Meerveld, A. Rinaldo, J. Seibert, H. Wen, and J. W. Kirchner. 2021. Toward catchment

1706   hydro-biogeochemical theories. WIREs Water 8.

1707   Li, S., G. Wang, C. Zhu, J. Lu, W. Ullah, D. F. T. Hagan, G. Kattel, and J. Peng. 2022a.

1708   Attribution of global evapotranspiration trends based on the Budyko framework.

1709   Hydrology and Earth System Sciences 26:3691–3707.

1710   Li, Z., S. Gao, M. Chen, J. J. Gourley, and Y. Hong. 2022b. Spatiotemporal characteristics of

1711   US floods: Current status and forecast under a future warmer climate. Earth's Future

1712   10:e2022EF002700.

1713   Liberato, M. L. R., J. G. Pinto, R. M. Trigo, P. Ludwig, P. Ordóñez, D. Yuen, and I. F. Trigo.

1714   2013. Explosive development of winter storm Xynthia over the subtropical North Atlantic

1715   Ocean. Natural Hazards and Earth System Sciences 13:2239–2251.

1716   Lisenby, P. E., S. Tooth, and T. J. Ralph. 2019. Product vs. process? The role of

1717   geomorphology in wetland characterization. Science of The Total Environment 663:980–

1718   991.

1719   Londe, D. W., D. Dvorett, C. A. Davis, S. R. Loss, and E. P. Robertson. 2022a. Inundation of

1720   depressional wetlands declines under a changing climate. Climatic Change 172:27.

1721   Londe, D. W., D. Dvorett, C. A. Davis, S. R. Loss, and E. P. Robertson. 2022b. Inundation of

1722   depressional wetlands declines under a changing climate. Climatic Change 172:27.

1723   Lovelock, C. E., and R. Reef. 2020. Variable impacts of climate change on blue carbon. One

1724   Earth 3:195–211.

1725   Lugo, A. E. 2008. Visible and invisible effects of hurricanes on forest ecosystems: an

1726   international review. Austral Ecology 33:368–398.

1727   Luijendijk, A., G. Hagenaars, R. Ranasinghe, F. Baart, G. Donchyts, and S. Aarninkhof. 2018.

1728   The state of the world's beaches. Scientific Reports 8:6641.

1729   Mahecha, M. D., M. Reichstein, N. Carvalhais, G. Lasslop, H. Lange, S. I. Seneviratne, R.

1730   Vargas, C. Ammann, M. A. Arain, A. Cescatti, I. A. Janssens, M. Migliavacca, L.

1731   Montagnani, and A. D. Richardson. 2010. Global convergence in the temperature

1732   sensitivity of respiration at ecosystem level. Science 329:838–840.

1733   Mandishona, E., and J. Knight. 2022. Inland wetlands in Africa: A review of their typologies and

1734   ecosystem services. Progress in Physical Geography: Earth and Environment 46:547–

1735   565.

1736   Marton, J. M., I. F. Creed, D. B. Lewis, C. R. Lane, N. B. Basu, M. J. Cohen, and C. B. Craft.

1737   2015. Geographically isolated wetlands are important biogeochemical reactors on the

1738   landscape. BioScience 65:408–418.

1739   Matthews, J. 2010. Anthropogenic climate change impacts on ponds: a thermal mass

1740   perspective. BioRisk 5:193–209.

1741   Maul, G. A., and I. W. Duedall. 2019. Demography of coastal populations. Pages 692–700 *in* C.

1742   W. Finkl and C. Makowski, editors. Encyclopedia of Coastal Science. Springer

1743   International Publishing, Cham.

1744   McCarthy, J. K., J. M. Dwyer, and K. Mokany. 2019. A regional-scale assessment of using

1745   metabolic scaling theory to predict ecosystem properties. Proceedings of the Royal

1746   Society B: Biological Sciences 286:20192221.

1747   McClain, M. E., E. W. Boyer, C. L. Dent, S. E. Gergel, N. B. Grimm, P. M. Groffman, S. C. Hart,

1748   J. W. Harvey, C. A. Johnston, E. Mayorga, W. H. McDowell, and G. Pinay. 2003.

1749   Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic

1750   ecosystems. Ecosystems 6:301–312.

1751   McDaniel, P. A., M. P. Regan, E. Brooks, J. Boll, S. Barndt, A. Falen, S. K. Young, and J. E.

1752   Hammel. 2008. Linking fragipans, perched water tables, and catchment-scale

1753   hydrological processes. CATENA 73:166–173.

1754   McDonnell, J. J. 2009. Hewlett, J.D. and Hibbert, A.R. 1967: Factors affecting the response of

1755   small watersheds to precipitation in humid areas. In Sopper, W.E. and Lull, H.W.,

1756   editors, Forest hydrology, New York: Pergamon Press, 275—90. Progress in Physical

1757   Geography: Earth and Environment 33:288–293.

1758   McDowell, N. G., M. Ball, B. Bond-Lamberty, M. L. Kirwan, K. W. Krauss, J. P. Megonigal, M.

1759   Mencuccini, N. D. Ward, M. N. Weintraub, and V. Bailey. 2022. Processes and

1760   mechanisms of coastal woody-plant mortality. Global Change Biology 28:5881–5900.

1761   Mcleod, E., G. L. Chmura, S. Bouillon, R. Salm, M. Björk, C. M. Duarte, C. E. Lovelock, W. H.

1762   Schlesinger, and B. R. Silliman. 2011. A blueprint for blue carbon: toward an improved

1763   understanding of the role of vegetated coastal habitats in sequestering CO_2. Frontiers in

1764   Ecology and the Environment 9:552–560.

1765   McVicar, T. R., T. G. Van Niel, L. Li, M. F. Hutchinson, X. Mu, and Z. Liu. 2007. Spatially

1766   distributing monthly reference evapotranspiration and pan evaporation considering

1767   topographic influences. Journal of Hydrology 338:196–220.

1768   Melton, J. R., R. Wania, E. L. Hodson, B. Poulter, B. Ringeval, R. Spahni, T. Bohn, C. A. Avis,

1769   D. J. Beerling, G. Chen, A. V. Eliseev, S. N. Denisov, P. O. Hopcroft, D. P. Lettenmaier,

1770   W. J. Riley, J. S. Singarayer, Z. M. Subin, H. Tian, S. Zürcher, V. Brovkin, P. M. Van

1771   Bodegom, T. Kleinen, Z. C. Yu, and J. O. Kaplan. 2013. Present state of global wetland

1772   extent and wetland methane modelling: conclusions from a model inter-comparison

1773   project (WETCHIMP). Biogeosciences 10:753–788.

1774   Merritt, D. M., and E. E. Wohl. 2002. Processes governing hydrochory along rivers: Hydraulics,

1775   hydrology and dispersal phenology. Ecological Applications 12:1071–1087.

1776   Mertes, L. A. K. 2011. Inland flood hazards: Human, riparian, and aquatic communities. Pages

1777   145–166 Inundation hydrology. Cambridge University Press, Cambridge, UK.

1778 Messager, M. L., B. Lehner, C. Cockburn, N. Lamouroux, H. Pella, T. Snelder, K. Tockner, T.

1779   Trautmann, C. Watt, and T. Datry. 2021. Global prevalence of non-perennial rivers and

1780   streams. Nature 594:391–397.

1781 Mikac, S., A. Zmegac, T. Domagoj, P. Vinko, M. Orsanic, and I. Anic. 2018. Drought-induced

1782   shift in tree response to climate in floodplain forests of Southeastern Europe. Scientific

1783   Reports 8:16495.

1784 Molins, S., D. Svyatsky, Z. Xu, E. T. Coon, and J. D. Moulton. 2022. A multicomponent reactive

1785   transport model for integrated surface-subsurface hydrology problems. Water Resources

1786   Research 58:e2022WR032074.

1787 Moomaw, W. R., G. L. Chmura, G. T. Davies, C. M. Finlayson, B. A. Middleton, S. M. Natali, J.

1788   E. Perry, N. Roulet, and A. E. Sutton-Grier. 2018. Wetlands In a changing climate:

1789   Science, policy and management. Wetlands 38:183–205.

1790 Morrissey, E. M., and R. B. Franklin. 2015. Evolutionary history influences the salinity

1791   preference of bacterial taxa in wetland soils. Frontiers in Microbiology 6.

1792 Murray, N. J., P. Bunting, R. F. Canto, L. Hilarides, E. V. Kennedy, R. M. Lucas, M. B. Lyons, A.

1793   Navarro, C. M. Roelfsema, A. Rosenqvist, M. D. Spalding, M. Toor, and T. A.

1794   Worthington. 2022a. coastTrain: A global feference library for coastal ecosystems.

1795   Remote Sensing 14:5766.

1796 Murray, N. J., T. A. Worthington, P. Bunting, S. Duce, V. Hagger, C. E. Lovelock, R. Lucas, M. I.

1797   Saunders, M. Sheaves, M. Spalding, N. J. Waltham, and M. B. Lyons. 2022b. High-

1798   resolution mapping of losses and gains of Earth's tidal wetlands. Science 376:744–749.

1799 Nanson, G., and J. Croke. 1992. A genetic classification of floodplains. Faculty of Science,

1800   Medicine and Health - Papers: part A:459–486.

1801 Nelson, T. M., C. Streten, K. S. Gibb, and A. A. Chariton. 2015. Saltwater intrusion history

1802   shapes the response of bacterial communities upon rehydration. Science of The Total

1803   Environment 502:143–148.

1804   Neubauer, S. C., and J. P. Megonigal. 2015. Moving beyond global warming potentials to
1805   quantify the climatic role of ecosystems. Ecosystems 18:1000–1013.
1806   Ode, P. R., A. E. Fetscher, and L. B. Busse. 2016. Standard operating procedures for the
1807   collection of field data for bioassessments of California wadeable streams: Benthic
1808   macroinvertebrates, algae, and physical habitat. Page 80. California State Water
1809   Resources Control Board Surface Water Ambient Monitoring Program (SWAMP)
1810   Bioassessment SOP 004.
1811   O'Mara, K., J. M. Olley, B. Fry, and M. Burford. 2019. Catchment soils supply ammonium to the
1812   coastal zone - Flood impacts on nutrient flux in estuaries. Science of The Total
1813   Environment 654:583–592.
1814   O'Meara, T. A., J. R. Hillman, and S. F. Thrush. 2017. Rising tides, cumulative impacts and
1815   cascading changes to estuarine ecosystem functions. Scientific Reports 7:10218.
1816   Palmer, M. A., and K. L. Hondula. 2014. Restoration as Mitigation: Analysis of Stream Mitigation
1817   for Coal Mining Impacts in Southern Appalachia. Environmental Science & Technology
1818   48:10552–10560.
1819   Palmer, M. A., K. L. Hondula, and B. J. Koch. 2014. Ecological restoration of streams and rivers:
1820   Shifting strategies and shifting goals. Annual Review of Ecology, Evolution, and
1821   Systematics 45:247–269.
1822   Palta, M. M., J. G. Ehrenfeld, and P. M. Groffman. 2014. "Hotspots" and "Hot Moments" of
1823   Denitrification in Urban Brownfield Wetlands. Ecosystems 17:1121–1137.
1824   Palta, M. M., N. B. Grimm, and P. M. Groffman. 2017. "Accidental" urban wetlands: Ecosystem
1825   functions in unexpected places. Frontiers in Ecology and the Environment 15:248–256.
1826   Pan, J., Y. Liu, X. Zhong, R. M. Lampayan, G. R. Singleton, N. Huang, K. Liang, B. Peng, and
1827   K. Tian. 2017. Grain yield, water productivity and nitrogen use efficiency of rice under
1828   different water management and fertilizer-N inputs in South China. Agricultural Water
1829   Management 184:191–200.

1830   Pascolini-Campbell, M., J. B. Fisher, and J. T. Reager. 2021. GRACE-FO and ECOSTRESS

1831   synergies constrain fine-scale impacts on the water balance. Geophysical Research

1832   Letters 48.

1833   Patel, K. F., K. A. Rod, J. Zheng, P. J. Regier, F. Machado-Silva, B. Bond-Lamberty, X. Chen,

1834   D. Day, K. O. Doro, M. Kaufman, M. Kovach, N. McDowell, S. A. McKever, P. J.

1835   Megonigal, C. G. Norris, T. O'Meara, R. Rich, P. Thornton, K. M. Kemner, N. D. Ward,

1836   M. N. Weintraub, and V. L. Bailey. 2023. Time to anoxia: Observations and predictions

1837   of oxygen drawdown following coastal flood events.

1838   Patel, K. F., C. Tatariw, J. D. MacRae, T. Ohno, S. J. Nelson, and I. J. Fernandez. 2020.

1839   Snowmelt periods as hot moments for soil N dynamics: a case study in Maine, USA.

1840   Environmental Monitoring and Assessment 192:777.

1841   Patel, N., S. Gahlaud, A. Saxena, B. Thakur, N. Bharti, A. Dabhi, R. Bhushan, and R. Agnihotri.

1842   2022. Revised chronology and stable isotopic (carbon and nitrogen) characterization of

1843   Lahuradewa lake sediment (Ganga-plain, India): Insights into biogeochemistry leading to

1844   peat formation in the lake. Journal of the Palaeontological Society of India Volume

1845   67(1):113–125.

1846   Peacock, M., J. Audet, D. Bastviken, M. N. Futter, V. Gauci, A. Grinham, J. A. Harrison, M. S.

1847   Kent, S. Kosten, C. E. Lovelock, A. J. Veraart, and C. D. Evans. 2021. Global

1848   importance of methane emissions from drainage ditches and canals. Environmental

1849   Research Letters 16.

1850   Pedersen, O., M. Sauter, T. D. Colmer, and M. Nakazono. 2021. Regulation of root adaptive

1851   anatomical and morphological traits during low soil oxygen. New Phytologist 229:42–49.

1852   Pekel, J.-F., A. Cottam, N. Gorelick, and A. S. Belward. 2016. High-resolution mapping of global

1853   surface water and its long-term changes. Nature 540:418–422.

1854   Peng, S., X. Lin, R. L. Thompson, Y. Xi, G. Liu, D. Hauglustaine, X. Lan, B. Poulter, M.

1855   Ramonet, M. Saunois, Y. Yin, Z. Zhang, B. Zheng, and P. Ciais. 2022. Wetland emission

1856   and atmospheric sink changes explain methane growth in 2020. Nature 612:477–482.

1857   Peruccacci, S., M. T. Brunetti, S. L. Gariano, M. Melillo, M. Rossi, and F. Guzzetti. 2017.

1858   Rainfall thresholds for possible landslide occurrence in Italy. Geomorphology 290:39–57.

1859   Pezeshki, S. R., and R. D. DeLaune. 2012. Soil oxidation-reduction in wetlands and Its impact

1860   on plant functioning. Biology 1:196–221.

1861   Pickering, M. D., K. J. Horsburgh, J. R. Blundell, J. J.-M. Hirschi, R. J. Nicholls, M. Verlaan, and

1862   N. C. Wells. 2017. The impact of future sea-level rise on the global tides. Continental

1863   Shelf Research 142:50–68.

1864   Plum, N. 2005. Terrestrial invertebrates in flooded grassland: A literature review. Wetlands

1865   25:721–737.

1866   Pool, S., F. Francés, A. Garcia-Prats, M. Pulido-Velazquez, C. Sanchis-Ibor, M. Schirmer, H.

1867   Yang, and J. Jiménez-Martínez. 2021. From flood to drip irrigation under climate change:

1868   Impacts on evapotranspiration and groundwater recharge in the mediterranean region of

1869   Valencia (Spain). Earth's Future 9:e2020EF001859.

1870   Popper, K. R. 2014. Conjectures and refutations: the growth of scientific knowledge. Repr.

1871   Routledge, London.

1872   Price, A. N., C. N. Jones, J. C. Hammond, M. A. Zimmer, and S. C. Zipper. 2021. The drying

1873   regimes of non-perennial rivers and streams. Geophysical Research Letters

1874   48:e2021GL093298.

1875   Quinn, J. D., P. M. Reed, M. Giuliani, A. Castelletti, J. W. Oyler, and R. E. Nicholas. 2018.

1876   Exploring how changing monsoonal dynamics and human pressures challenge

1877   multireservoir management for flood protection, hydropower production, and agricultural

1878   water supply. Water Resources Research 54:4638–4662.

1879   Rameshwaran, P., V. A. Bell, H. N. Davies, and A. L. Kay. 2021. How might climate change

1880   affect river flows across West Africa? Climatic Change 169:21.

1881   Rasmussen, T. C., J. B. Deemy, and S. L. Long. 2016. Wetland Hydrology. Pages 1–16 *in* C. M.

1882   Finlayson, M. Everard, K. Irvine, R. J. McInnes, B. A. Middleton, A. A. Van Dam, and N.

1883   C. Davidson, editors. The Wetland Book. Springer Netherlands, Dordrecht.

1884   Regier, P., N. D. Ward, J. Indivero, C. Wiese Moore, M. Norwood, and A. Myers-Pigg. 2021.

1885   Biogeochemical control points of connectivity between a tidal creek and its floodplain.

1886   Limnology and Oceanography Letters 6:134–142.

1887   Reichstein, M., G. Camps-Valls, B. Stevens, M. Jung, J. Denzler, N. Carvalhais, and Prabhat.

1888   2019. Deep learning and process understanding for data-driven Earth system science.

1889   Nature 566:195–204.

1890   Reis, V., V. Hermoso, S. K. Hamilton, D. Ward, E. Fluet-Chouinard, B. Lehner, and S. Linke.

1891   2017. A global assessment of inland wetland conservation status. BioScience 67:523–

1892   533.

1893   Reisinger, A. J., P. M. Groffman, and E. J. Rosi-Marshall. 2016. Nitrogen cycling process rates

1894   across urban ecosystems. FEMS Microbiology Ecology 92:fiw198.

1895   Renwick, W., R. Sleezer, R. Buddemeier, and S. Smith. 2006. Small artificial ponds in the

1896   United States: Impacts on sedimentation and carbon budget. Pages 738–744

1897   Proceedings of the Eighth Federal Interagency Sedimentation Conference.

1898   Resetarits, W. J. 1996. Oviposition site choice and life history evolution. American Zoologist

1899   36:205–215.

1900   Reverey, F., L. Ganzert, G. Lischeid, A. Ulrich, K. Premke, and H.-P. Grossart. 2018. Dry-wet

1901   cycles of kettle hole sediments leave a microbial and biogeochemical legacy. Science of

1902   The Total Environment 627:985–996.

1903   Richardson, D. C., M. A. Holgerson, M. J. Farragher, K. K. Hoffman, K. B. S. King, M. B.

1904   Alfonso, M. R. Andersen, K. S. Cheruveil, K. A. Coleman, M. J. Farruggia, R. L.

1905   Fernandez, K. L. Hondula, G. A. López Moreira Mazacotte, K. Paul, B. L. Peierls, J. S.

1906   Rabaey, S. Sadro, M. L. Sánchez, R. L. Smyth, and J. N. Sweetman. 2022a. A

1907   functional definition to distinguish ponds from lakes and wetlands. Scientific Reports

1908   12:10472.

1909 Richardson, D. C., M. A. Holgerson, M. J. Farragher, K. K. Hoffman, K. B. S. King, M. B.

1910   Alfonso, M. R. Andersen, K. S. Cheruveil, K. A. Coleman, M. J. Farruggia, R. L.

1911   Fernandez, K. L. Hondula, G. A. López Moreira Mazacotte, K. Paul, B. L. Peierls, J. S.

1912   Rabaey, S. Sadro, M. L. Sánchez, R. L. Smyth, and J. N. Sweetman. 2022b. A

1913   functional definition to distinguish ponds from lakes and wetlands. Scientific Reports

1914   12:10472.

1915 Richey, A. S., B. F. Thomas, M. Lo, J. T. Reager, J. S. Famiglietti, K. Voss, S. Swenson, and M.

1916   Rodell. 2015. Quantifying renewable groundwater stress with GRACE. Water Resources

1917   Research 51:5217–5238.

1918 Ripley, B. J., and M. A. Simovich. 2009. Species richness on islands in time: Variation in

1919   ephemeral pond crustacean communities in relation to habitat duration and size.

1920   Hydrobiologia 617:181–196.

1921 Robinson, C. T., K. Tockner, and J. V. Ward. 2002. The fauna of dynamic riverine landscapes:

1922   Fauna of riverine landscapes. Freshwater Biology 47:661–677.

1923 Rosado, J., M. Morais, and K. Tockner. 2015. Mass dispersal of terrestrial organisms during first

1924   flush events in a temporary stream: Mass dispersal of terrestrial organisms. River

1925   Research and Applications 31:912–917.

1926 Rosentreter, J. A., A. V. Borges, B. R. Deemer, M. A. Holgerson, S. Liu, C. Song, J. Melack, P.

1927   A. Raymond, C. M. Duarte, G. H. Allen, D. Olefeldt, B. Poulter, T. I. Battin, and B. D.

1928   Eyre. 2021. Half of global methane emissions come from highly variable aquatic

1929   ecosystem sources. Nature Geoscience 14:225–230.

1930   Ruel, J. J., and M. P. Ayres. 1999. Jensen's inequality predicts effects of environmental

1931   variation. Trends in Ecology & Evolution 14:361–366.

1932   Rullens, V., S. Mangan, F. Stephenson, D. E. Clark, R. H. Bulmer, A. Berthelsen, J. Crawshaw,

1933   R. V. Gladstone-Gallagher, S. Thomas, J. I. Ellis, and C. A. Pilditch. 2022.

1934   Understanding the consequences of sea level rise: the ecological implications of losing

1935   intertidal habitat. New Zealand Journal of Marine and Freshwater Research 56:353–370.

1936   Saadat, S., J. Frankenberger, L. Bowling, and S. Ale. 2020. Evaluation of surface ponding and

1937   runoff generation in a seasonally frozen drained agricultural field. Journal of Hydrology

1938   588:124985.

1939   Saltarelli, W. A., D. G. F. Cunha, A. Freixa, N. Perujo, J. C. López-Doval, V. Acuña, and S.

1940   Sabater. 2022. Nutrient stream attenuation is altered by the duration and frequency of

1941   flow intermittency. Ecohydrology 15:e2351.

1942   Sarremejane, R., H. Mykrä, N. Bonada, J. Aroviita, and T. Muotka. 2017. Habitat connectivity

1943   and dispersal ability drive the assembly mechanisms of macroinvertebrate communities

1944   in river networks. Freshwater Biology 62.

1945   Sarremejane, R., R. Stubbington, J. England, C. E. M. Sefton, M. Eastman, S. Parry, and A.

1946   Ruhi. 2021. Drought effects on invertebrate metapopulation dynamics and quasi-

1947   extinction risk in an intermittent river network. Global Change Biology 27:4024–4039.

1948   Schaffer-Smith, D., S. W. Myint, R. L. Muenich, D. Tong, and J. E. DeMeester. 2020. Repeated

1949   hurricanes reveal risks and opportunities for social-ecological resilience to flooding and

1950   water quality problems. Environmental Science & Technology 54:7194–7204.

1951   von Schiller, D., T. Datry, R. Corti, A. Foulquier, K. Tockner, R. Marcé, G. García-Baquero, I.

1952   Odriozola, B. Obrador, A. Elosegi, C. Mendoza-Lera, M. O. Gessner, R. Stubbington, R.

1953   Albariño, D. C. Allen, F. Altermatt, M. I. Arce, S. Arnon, D. Banas, A. Banegas-Medina,

1954   E. Beller, M. L. Blanchette, J. F. Blanco-Libreros, J. Blessing, I. G. Boëchat, K. S.

1955   Boersma, M. T. Bogan, N. Bonada, N. R. Bond, K. Brintrup, A. Bruder, R. M. Burrows, T.

1956   Cancellario, S. M. Carlson, S. Cauvy-Frauníe, N. Cid, M. Danger, B. de Freitas Terra, A.

1957   Dehedin, A. M. De Girolamo, R. del Campo, V. Díaz-Villanueva, C. P. Duerdoth, F. Dyer,

1958   E. Faye, C. Febria, R. Figueroa, B. Four, S. Gafny, R. Gómez, L. Gómez-Gener, M. a. S.

1959   Graça, S. Guareschi, B. Gücker, F. Hoppeler, J. L. Hwan, S. Kubheka, A. Laini, S. D.

1960   Langhans, C. Leigh, C. J. Little, S. Lorenz, J. Marshall, E. J. Martín, A. McIntosh, E. I.

1961   Meyer, M. Miliša, M. C. Mlambo, M. Moleón, M. Morais, P. Negus, D. Niyogi, A.

1962   Papatheodoulou, I. Pardo, P. Pařil, V. Pešić, C. Piscart, M. Polášek, P. Rodríguez-

1963   Lozano, R. J. Rolls, M. M. Sánchez-Montoya, A. Savić, O. Shumilova, A. Steward, A.

1964   Taleb, A. Uzan, R. Vander Vorste, N. Waltham, C. Woelfle-Erskine, D. Zak, C. Zarfl, and

1965   A. Zoppini. 2019. Sediment respiration pulses in intermittent rivers and ephemeral

1966   streams. Global Biogeochemical Cycles 33:1251–1263.

1967 Schimel, J. P. 2018. Life in dry soils: Effects of drought on soil microbial communities and

1968   processes. Annual Review of Ecology, Evolution, and Systematics 49:409–432.

1969 Schlesinger, W. H., and E. S. Bernhardt. 2020. The atmosphere. Pages 51–97

1970   Biogeochemistry. Elsevier.

1971 Schumann, G. J.-P., and D. K. Moller. 2015. Microwave remote sensing of flood inundation.

1972   Physics and Chemistry of the Earth, Parts A/B/C 83–84:84–95.

1973 Scientific Investigations Report. 2015. . Scientific Investigations Report.

1974 Secretariat, R. 2016. An Introduction to the Convention on Wetlands (previously The Ramsar

1975   Convention Manual). 7th edition.

1976 Semeniuk, C. A., and V. Semeniuk. 1995. A geomorphic approach to global classification for

1977   inland wetlands. Pages 103–124 Advances in Vegetation Science.

1978 Semeniuk, C., and V. Semeniuk. 2011. A comprehensive classification of inland wetlands of

1979   Western Australia using the geomorphic-hydrologic approach. Journal of the Royal

1980   Society of Western Australia 94:449–464.

1981   Shi, X., P. E. Thornton, D. M. Ricciuto, P. J. Hanson, J. Mao, S. D. Sebestyen, N. A. Griffiths,

1982   and G. Bisht. 2015. Representing northern peatland microtopography and hydrology

1983   within the community land model. Biogeosciences 12:6463–6477.

1984   Shumilova, O., D. Zak, T. Datry, D. von Schiller, R. Corti, A. Foulquier, B. Obrador, K. Tockner,

1985   D. C. Allan, F. Altermatt, M. I. Arce, S. Arnon, D. Banas, A. Banegas-Medina, E. Beller,

1986   M. L. Blanchette, J. F. Blanco-Libreros, J. Blessing, I. G. Boëchat, K. Boersma, M. T.

1987   Bogan, N. Bonada, N. R. Bond, K. Brintrup, A. Bruder, R. Burrows, T. Cancellario, S. M.

1988   Carlson, S. Cauvy-Fraunié, N. Cid, M. Danger, B. de Freitas Terra, A. M. D. Girolamo,

1989   R. del Campo, F. Dyer, A. Elosegi, E. Faye, C. Febria, R. Figueroa, B. Four, M. O.

1990   Gessner, P. Gnohossou, R. G. Cerezo, L. Gomez-Gener, M. A. S. Graça, S. Guareschi,

1991   B. Gücker, J. L. Hwan, S. Kubheka, S. D. Langhans, C. Leigh, C. J. Little, S. Lorenz, J.

1992   Marshall, A. McIntosh, C. Mendoza-Lera, E. I. Meyer, M. Miliša, M. C. Mlambo, M.

1993   Moleón, P. Negus, D. Niyogi, A. Papatheodoulou, I. Pardo, P. Paril, V. Pešić, P.

1994   Rodriguez-Lozano, R. J. Rolls, M. M. Sanchez-Montoya, A. Savić, A. Steward, R.

1995   Stubbington, A. Taleb, R. V. Vorste, N. Waltham, A. Zoppini, and C. Zarfl. 2019.

1996   Simulating rewetting events in intermittent rivers and ephemeral streams: A global

1997   analysis of leached nutrients and organic matter. Global Change Biology 25:1591–1611.

1998   Siebert, S., F. T. Portmann, and P. Döll. 2010. Global patterns of cropland use intensity.

1999   Remote Sensing 2:1625–1643.

2000   Siev, S., E. C. Paringit, C. Yoshimura, and S. Hul. 2019. Modelling inundation patterns and

2001   sediment dynamics in the extensive floodplain along the Tonle Sap River. River

2002   Research and Applications 35:1387–1401.

2003   Smith, A. P., B. Bond-Lamberty, B. W. Benscoter, M. M. Tfaily, C. R. Hinkle, C. Liu, and V. L.

2004   Bailey. 2017. Shifts in pore connectivity from precipitation versus groundwater rewetting

2005   increases soil carbon loss after drought. Nature Communications 8:1335.

2006   Smith, J. A. M., K. J. Rossner, and D. P. Duran. 2021. New opportunities for conservation of a

2007   rare tiger beetle on developed barrier island beaches. Journal of Insect Conservation

2008   25:733–745.

2009   Smyth, A. R., T. D. Loecke, T. E. Franz, and A. J. Burgin. 2019. Using high-frequency soil

2010   oxygen sensors to predict greenhouse gas emissions from wetlands. Soil Biology and

2011   Biochemistry 128:182–192.

2012   Song, X., X. Chen, J. Stegen, G. Hammond, H. Song, H. Dai, E. Graham, and J. M. Zachara.

2013   2018. Drought Conditions Maximize the Impact of High-Frequency Flow Variations on

2014   Thermal Regimes and Biogeochemical Function in the Hyporheic Zone. Water

2015   Resources Research 54:7361–7382.

2016   Soupir, M. L., S. Mostaghimi, and C. E. Mitchem, Jr. 2009. A comparative study of stream-

2017   gaging techniques for low-flow measurements in two Virginia tributaries. JAWRA Journal

2018   of the American Water Resources Association 45:110–122.

2019   Speir, S. L., J. L. Tank, and U. H. Mahl. 2020. Quantifying denitrification following floodplain

2020   restoration via the two-stage ditch in an agricultural watershed. Ecological Engineering

2021   155:105945.

2022   Stallins, J. A., and A. J. Parker. 2003. The influence of complex systems interactions on barrier

2023   island dune vegetation pattern and process. Annals of the Association of American

2024   Geographers 93:13–29.

2025   Stanford, J. A., M. S. Lorang, and F. R. Hauer. 2005. The shifting habitat mosaic of river

2026   ecosystems. SIL Proceedings, 1922-2010 29:123–136.

2027   Stanley, E. H., S. M. Powers, N. R. Lottig, I. Buffam, and J. T. Crawford. 2012. Contemporary

2028   changes in dissolved organic carbon (DOC) in human-dominated rivers: is there a role

2029   for DOC management? Freshwater Biology 57:26–42.

2030   Stewart, B., J. B. Shanley, J. W. Kirchner, D. Norris, T. Adler, C. Bristol, A. A. Harpold, J. N.

2031   Perdrial, D. M. Rizzo, G. Sterle, K. L. Underwood, H. Wen, and L. Li. 2022. Streams as

2032   mirrors: Reading subsurface water chemistry from stream chemistry. Water Resources

2033   Research 58.

2034 Sullivan, S. M. P., M. C. Rains, and A. D. Rodewald. 2019. The proposed change to the

2035   definition of "waters of the United States" flouts sound science. PNAS, 116:11558-

2036   11561.

2037 Sun, Z., L. Sandoval, R. Crystal-Ornelas, S. M. Mousavi, J. Wang, C. Lin, N. Cristea, D. Tong,

2038   W. H. Carande, X. Ma, Y. Rao, J. A. Bednar, A. Tan, J. Wang, S. Purushotham, T. E.

2039   Gill, J. Chastang, D. Howard, B. Holt, C. Gangodagamage, P. Zhao, P. Rivas, Z.

2040   Chester, J. Orduz, and A. John. 2022. A review of Earth artificial intelligence. Computers

2041   & Geosciences 159:105034.

2042 Svensson, J. R., M. Lindegarth, P. R. Jonsson, and H. Pavia. 2012. Disturbance–diversity

2043   models: what do they really predict and how are they tested? Proceedings of the Royal

2044   Society B: Biological Sciences 279:2163–2170.

2045 Sweet, W., J. Park, J. Marra, C. Zervas, and S. Gill. 2014. Sea level rise and nuisance flood

2046   frequency changes around the United States.

2047 Tagestad, J., N. D. Ward, D. Butman, and J. Stegen. 2021. Small streams dominate US tidal

2048   reaches and will be disproportionately impacted by sea-level rise. Science of The Total

2049   Environment 753:141944.

2050 Thomas, M. A., B. B. Mirus, and J. B. Smith. 2020. Hillslopes in humid-tropical climates aren't

2051   always wet: Implications for hydrologic response and landslide initiation in Puerto Rico.

2052   Hydrological Processes 34:4307–4318.

2053 Tiner, R. W. 2013. Tidal wetlands primer: An introduction to their ecology, natural history, status,

2054   and conservation. University of Massachusetts Press, Amherst.

2055 Tiner, R. W. 2017. Wetland indicators: A guide to wetland identification, delineation,

2056   classification, and mapping. Second edition. Taylor & Francis, Boca Raton.

2057   Tromp-van Meerveld, H. J., and J. J. McDonnell. 2006. Threshold relations in subsurface

2058   stormflow: 2. The fill and spill hypothesis: Threshold flow relations. Water Resources

2059   Research 42.

2060   Tweedley, J. 2016. The contrasting ecology of temperate macrotidal and microtidal estuaries.

2061   U.S. Geological Survey. 2017. Cottonwood Lake Study Area - Aerial Imagery: U.S. Geological

2062   Survey data release, https://doi.org/10.5066/F7DZ06GR.

2063   Valett, H. M., M. A. Baker, J. A. Morrice, C. S. Crawford, M. C. Molles Jr., C. N. Dahm, D. L.

2064   Moyer, J. R. Thibault, and L. M. Ellis. 2005. Biogeochemical and metabolic responses to

2065   the flood pulse in a semiarid floodplain. Ecology 86:220–234.

2066   Van Meerveld, H. J. I., E. Sauquet, F. Gallart, C. Sefton, J. Seibert, and K. Bishop. 2020. Aqua

2067   temporaria incognita. Hydrological Processes 34:5704–5711.

2068   VanZomeren, C. M., J. F. Berkowitz, C. D. Piercy, and J. R. White. 2018. Restoring a degraded

2069   marsh using thin layer sediment placement: Short term effects on soil physical and

2070   biogeochemical properties. Ecological Engineering 120:61–67.

2071   Venterink, H. O., N. M. Pieterse, J. D. M. Belgers, M. J. Wassen, and P. C. De Ruiter. 2002. N,

2072   P, and K budgets along nutrient availability and productivity gradients in wetlands.

2073   Ecological Applications 12:1010–1026.

2074   Vorste, R. V., R. Corti, A. Sagouis, and T. Datry. 2016. Invertebrate communities in gravel-bed,

2075   braided rivers are highly resilient to flow intermittence. Freshwater Science 35:164–177.

2076   Waltham, N. J., and R. M. Connolly. 2011. Global extent and distribution of artificial, residential

2077   waterways in estuaries. Estuarine, Coastal and Shelf Science 94:192–197.

2078   Wang, X., W. Wang, and C. Tong. 2016. A review on impact of typhoons and hurricanes on

2079   coastal wetland ecosystems. Acta Ecologica Sinica 36:23–29.

2080   Wantzen, K., C. Alves, S. Badiane, R. Bala, M. Blettler, M. Callisto, Y. Cao, M. Kolb, G. Kondolf,

2081   M. Leite, D. Macedo, O. Mahdi, M. Neves, M. Peralta, V. Rotgé, G. Rueda-Delgado, A.

2082   Scharager, A. Serra-Llobet, J.-L. Yengué, and A. Zingraff-Hamed. 2019. Urban stream

2083   and wetland restoration in the Global South—A DPSIR analysis. Sustainability 11:4975.

2084   Ward, J. V., K. Tockner, D. B. Arscott, and C. Claret. 2002. Riverine landscape diversity.

2085   Freshwater Biology 47:517–539.

2086   Ward, J. V., K. Tockner, and F. Schiemer. 1999. Biodiversity of floodplain river ecosystems:

2087   ecotones and connectivity1. Regulated Rivers: Research & Management 15:125–139.

2088   Ward, N. D., J. P. Megonigal, B. Bond-Lamberty, V. L. Bailey, D. Butman, E. A. Canuel, H.

2089   Diefenderfer, N. K. Ganju, M. A. Goñi, E. B. Graham, C. S. Hopkinson, T. Khangaonkar,

2090   J. A. Langley, N. G. McDowell, A. N. Myers-Pigg, R. B. Neumann, C. L. Osburn, R. M.

2091   Price, J. Rowland, A. Sengupta, M. Simard, P. E. Thornton, M. Tzortziou, R. Vargas, P.

2092   B. Weisenhorn, and L. Windham-Myers. 2020. Representing the function and sensitivity

2093   of coastal interfaces in Earth system models. Nature Communications 11:2458.

2094   Watts, J. D., J. S. Kimball, A. Bartsch, and K. C. McDonald. 2014. Surface water inundation in

2095   the boreal-Arctic: potential impacts on regional methane emissions. Environmental

2096   Research Letters 9:075001.

2097   Weird Bristol [@WeirdBristol] With a difference of 15-metres/49-foot between high and low tide,

2098   the River Avon has the second largest tidal range in the world. Only the Bay of Fundy in

2099   Canada has a higher tide, with an average of 16.8 metres/55-foot. #Bristol,

2100   https://twitter.com/WeirdBristol/status/1015732213730758658; July 7, 2018.

2101   Wen, H., J. Perdrial, B. W. Abbott, S. Bernal, R. Dupas, S. E. Godsey, A. Harpold, D. Rizzo, K.

2102   Underwood, T. Adler, G. Sterle, and L. Li. 2020. Temperature controls production but

2103   hydrology regulates export of dissolved organic carbon at the catchment scale.

2104   Hydrology and Earth System Sciences 24:945–966.

2105   Weyman, D. R. 1973. Measurements of the downslope flow of water in a soil. Journal of

2106   Hydrology 20:267–288.

2107   Whitworth, K. L., J. L. Kerr, L. M. Mosley, J. Conallin, L. Hardwick, and D. S. Baldwin. 2013.

2108   Options for managing hypoxic blackwater in river systems: case studies and framework.

2109   Environmental Management 52:837–850.

2110   Wierzbicki, G., P. Ostrowski, and T. Falkowski. 2020. Applying floodplain geomorphology to

2111   flood management (The Lower Vistula River upstream from Plock, Poland). Open

2112   Geosciences 12:1003–1016.

2113   Williams, D. D. 2006. The biology of temporary waters. Oxford University Press, Oxford ; New

2114   York.

2115   Wittenberg, H. 1999. Baseflow recession and recharge as nonlinear storage processes.

2116   Hydrological Processes 13:715–726.

2117   Wohl, E. 2021. An integrative conceptualization of floodplain storage. Reviews of Geophysics

2118   59.

2119   Wollheim, W. M., T. K. Harms, A. L. Robison, L. E. Koenig, A. M. Helton, C. Song, W. B.

2120   Bowden, and J. C. Finlay. 2022. Superlinear scaling of riverine biogeochemical function

2121   with watershed size. Nature Communications 13:1230.

2122   Wu, B., F. Tian, M. Nabil, J. Bofana, Y. Lu, A. Elnashar, A. N. Beyene, M. Zhang, H. Zeng, and

2123   W. Zhu. 2023. Mapping global maximum irrigation extent at 30m resolution using the

2124   irrigation performances under drought stress. Global Environmental Change 79:102652.

2125   Wu, R., X. Chen, G. Hammond, G. Bisht, X. Song, M. Huang, G.-Y. Niu, and T. Ferre. 2021.

2126   Coupling surface flow with high-performance subsurface reactive flow and transport

2127   code PFLOTRAN. Environmental Modelling & Software 137:104959.

2128   Xiao, D., Y. Shi, S. L. Brantley, B. Forsythe, R. DiBiase, K. Davis, and L. Li. 2019. Streamflow

2129   Generation From Catchments of Contrasting Lithologies: The Role of Soil Properties,

2130   Topography, and Catchment Size. Water Resources Research 55:9234–9257.

2131   Xie, D., C. Schwarz, M. Z. M. Brückner, M. G. Kleinhans, D. H. Urrego, Z. Zhou, and B. Van

2132   Maanen. 2020. Mangrove diversity loss under sea-level rise triggered by bio-

2133   morphodynamic feedbacks and anthropogenic pressures. Environmental Research

2134   Letters 15:114033.

2135 Xin, P., A. Wilson, C. Shen, Z. Ge, K. B. Moffett, I. R. Santos, X. Chen, X. Xu, Y. Y. Y. Yau, W.

2136   Moore, L. Li, and D. A. Barry. 2022. Surface water and groundwater interactions in salt

2137   marshes and their impact on plant ecology and coastal biogeochemistry. Reviews of

2138   Geophysics 60:e2021RG000740.

2139 Zedler, P. H. 2003. Vernal pools and the concept of "isolated wetlands." Wetlands 23:597–607.

2140 Zhang, Y. S., W. R. Cioffi, R. Cope, P. Daleo, E. Heywood, C. Hoyt, C. S. Smith, and B. R.

2141   Silliman. 2018. A Global Synthesis Reveals Gaps in Coastal Habitat Restoration

2142   Research. Sustainability 10:1040.

2143 Zhang, Z., E. Fluet-Chouinard, K. Jensen, K. McDonald, G. Hugelius, T. Gumbricht, M. Carroll,

2144   C. Prigent, A. Bartsch, and B. Poulter. 2021. Development of the global dataset of

2145   Wetland Area and Dynamics for Methane Modeling (WAD2M). Earth System Science

2146   Data 13:2001–2023.

2147 Zhang, Z., N. E. Zimmermann, A. Stenke, X. Li, E. L. Hodson, G. Zhu, C. Huang, and B.

2148   Poulter. 2017. Emerging role of wetland methane emissions in driving 21st century

2149   climate change. Proceedings of the National Academy of Sciences 114:9647–9652.

2150 Zhao, Y., X. Wang, S. Jiang, J. Xiao, J. Li, X. Zhou, H. Liu, Z. Hao, and K. Wang. 2022. Soil

2151   development mediates precipitation control on plant productivity and diversity in alpine

2152   grasslands. Geoderma 412:115721.

2153 Zhi, W., and L. Li. 2020. The shallow and deep hypothesis: Subsurface vertical chemical

2154   contrasts shape nitrate export patterns from different land uses. Environmental Science

2155   & Technology 54:11915–11928.

2156 Zimmer, M. A., A. J. Burgin, K. Kaiser, and J. Hosen. 2022. The unknown biogeochemical

2157   impacts of drying rivers and streams. Nature Communications 13:7213.

2158   Zimmer, M. A., K. E. Kaiser, J. R. Blaszczak, S. C. Zipper, J. C. Hammond, K. M. Fritz, K. H.

2159   Costigan, J. Hosen, S. E. Godsey, G. H. Allen, S. Kampf, R. M. Burrows, C. A.

2160   Krabbenhoft, W. Dodds, R. Hale, J. D. Olden, M. Shanafield, A. G. DelVecchia, A. S.

2161   Ward, M. C. Mims, T. Datry, M. T. Bogan, K. S. Boersma, M. H. Busch, C. N. Jones, A.

2162   J. Burgin, and D. C. Allen. 2020. Zero or not? Causes and consequences of zero-flow

2163   stream gage readings. WIREs Water 7.

2164   Zimmer, M. A., and B. L. McGlynn. 2017. Ephemeral and intermittent runoff generation

2165   processes in a low relief, highly weathered catchment. Water Resources Research

2166   53:7055–7077.

2167   Zipper, S. C., J. C. Hammond, M. Shanafield, M. Zimmer, T. Datry, C. N. Jones, K. E. Kaiser, S.

2168   E. Godsey, R. M. Burrows, J. R. Blaszczak, M. H. Busch, A. N. Price, K. S. Boersma, A.

2169   S. Ward, K. Costigan, G. H. Allen, C. A. Krabbenhoft, W. K. Dodds, M. C. Mims, J. D.

2170   Olden, S. K. Kampf, A. J. Burgin, and D. C. Allen. 2021. Pervasive changes in stream

2171   intermittency across the United States. Environmental Research Letters 16:084033.

2172

2173