# Small artificial impoundments have big implications for hydrology and freshwater biodiversity

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**Headwater streams are critical for freshwater ecosystems. Global and continental studies consistently show major dams as dominant sources of hydrological stress threatening biodiversity in the world's major rivers, but cumulative impacts from small artificial impoundments (SAIs) concentrated in headwater streams have rarely been acknowledged. Using the Murray Darling River basin (Australia) and the Arkansas River basin (US) as case studies, we examined the hydrological impacts of SAIs. The extent of their influence is considerable, altering hydrology in 280–380% more waterways as compared to major dams. Hydrological impacts are concentrated in smaller streams (catchment area <100 km$^2$), raising concerns that the often diverse and highly endemic biota found in these systems may be under threat. Adjusting existing biodiversity planning and management approaches to address the cumulative effects of many small and widely distributed artificial impoundments presents a rapidly emerging challenge for ecologically sustainable water management.**

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In healthy river systems, headwater streams play a paramount role in maintaining hydrologic connectivity, harboring biodiversity, and supporting ecosystem integrity (Colvin *et al.* 2019). Despite this, debates continue over the implementation of policies and regulations seeking to protect these waters from burgeoning human enterprise. In one high-profile example, a 2015 update of the "Waters of the United States" (WOTUS) rule would have qualified both perennial and smaller non-perennial waterways in the US for water-quality protections (Marshall *et al.* 2018), but implementation of this update was halted in 2019 and further scaling back of the WOTUS definition was signed in 2020. Such regulatory actions in the US and elsewhere contrast with the large and growing body of scientific research supporting the social and ecological value of headwater streams (Meyer *et al.* 2003; Clarke *et al.* 2008; Colvin *et al.* 2019), as well as with the mounting threats to these ecosystems posed by climate change and regulating infrastructure, among other factors.

Past and planned construction of smaller scale dams is unprecedented. Recent estimates report that small- to medium-sized in-channel dams (approximately 82,891) vastly outnumber large dams around the world, and that hundreds of thousands of additional small hydropower plants may be installed to meet future energy demands (Couto and Olden 2018). Indeed, many more dams are likely to be built in coming decades due to increasing global demand for hydropower, reliable water supply, and food security (Zarfl *et al.* 2014). The widespread ecological damage and loss of important goods and services caused by large dams is well recognized (Sabater *et al.* 2018; Poff 2019; Tickner *et al.* 2020). One recent study concluded that close to two-thirds (63%) of major global waterways have greatly reduced connectivity due primarily to large in-channel dams and to a lesser extent by a range of other anthropogenic factors (such as urbanization and floodplain structures), while the remaining one-third (37%) are considered "free flowing" (Grill *et al.* 2019).

A conspicuous omission from global assessments of river regulation by dams (eg Nilsson *et al.* 2005; Zarfl *et al.* 2014; Grill *et al.* 2019) is that headwater streams – while not directly impacted by large in-stream dams – remain at risk from the impacts of smaller dams and artificial ponds within the catchment. These smaller, diffuse sources of hydrologic interception – referred to here as small artificial impoundments (SAIs) but also often called "farm ponds", "farm dams", or "small storages" (Panel 1; Figure 1) – have received far less recognition. Awareness of the impact of smaller dams and waterbodies on hydrology and biodiversity has emerged in recent years, including the cumulative effects of dams built to support hydropower production (Walter and Merritts 2008; Couto and Olden 2018; Couto *et al.* 2021) and agriculture practices (Downing 2008; Nathan and Lowe 2012).

The scope of SAI-related impacts is challenging to characterize at continental or global scales due to a lack of information about their number and locations in many regions (Januchowski-Hartley *et al.* 2020). Consequently, they are often excluded from investigations into how flow alteration affects freshwater ecosystems, with research and policy attention instead focusing on large in-channel structures and major water extractions. In so doing, such studies make an implicit assumption that the primary ecological impacts arise from the largest individual extractions or impoundments, rather

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**Panel 1. What are small artificial impoundments (SAIs)?**

The wide range of different terms for small waterbodies is a common source of confusion (Biggs *et al.* 2017). Small *natural* impoundments are usually called "ponds" or "lakes", whereas small *artificial* impoundments are called "farm ponds", "farm storages", "small storages", "tanks", "stock ponds", or "mill ponds", and are usually constructed with a low earthen bank across a watercourse or landscape depression.

Local differences may also exist. In Australia, small *artificial* impoundments are typically called "farm dams" (Nathan and Lowe 2012), but other terms, such as "floodplain storage", "catchment dam", or "runoff dam", are sometimes used to help identify the primary source of the water. In Europe, the term "small waterbodies" appears to be a more common label when referring to a wide range of features like storages, mill ponds, and ditches (Biggs *et al.* 2017).

In this paper, we adopted the term "small artificial impoundments" (SAIs) because it apparently is the most precise and least ambiguous term. SAIs included in our analysis ranged over 400-fold in size, from as little as 250 $m^2$ to more than 100,000 $m^2$. In our case study, SAIs are typically constructed for agricultural and livestock purposes, with a smaller number managed for hydropower, recreation, aquaculture, or potable supply. Some examples of SAIs from around the world highlighting their diversity of size and construction techniques are shown in Figure 1.

than considering the totality of hydrological stresses in operation, including those associated with the cumulative effects of SAIs.

We examined the relative role of SAIs and larger in-stream dams in causing hydrological stress throughout a catchment, and the challenges associated with the management, and supporting policy, of SAIs into the future. Impoundments of all types can affect upstream and downstream biodiversity through multiple pathways, for instance by altering habitat conditions (Agoramoorthy *et al.* 2016; Biggs *et al.* 2017), water quality (Ibrahim and Amir-Faryar 2018), and waterway connectivity (Barbarossa *et al.* 2020). Here, we focused on the threat to downstream biodiversity using a hydrological measure of the degree of impoundment. Two specific examples, one in Australia and the other in the US, were used to demonstrate how the risk to global biodiversity from hydrological alteration, particularly in headwater streams, continues to be underestimated through disregard of the widespread, growing number and cumulative impact of SAIs.

## Magnitude of hydrological stress

Global assessments of the impacts of in-stream dams have reported the "degree of regulation" (DoR), defined by the ratio of the total capacity of upstream storages with the average annual flow at a given location in the river network (Nilsson *et al.* 2005; Grill *et al.* 2019). DoR is a useful surrogate measure of the potential threat to biodiversity, with dam-induced flow changes shown to act synergistically with other impacts from dam modification (eg sediment flux, geomorphic alteration, floodplain disconnection, river corridor fragmentation; Poff *et al.* 2007; Grill *et al.* 2014). Although it is a simple metric and does not describe individual components of the flow regime, DoR provides a consistent quantitative measure of the *potential* for hydrological stress that can be readily mapped (Lehner *et al.* 2011; Grill *et al.* 2014).

To understand the role of SAIs in contributing to hydrological stress throughout a catchment, the DoR concept was applied to two case studies, the Murray Darling River basin in Australia and the Arkansas River basin in the US. These basins were selected as exemplars of the longstanding challenges facing global rivers subjected to SAIs. The Murray Darling basin is the largest river basin in Australia, covering more than 1 million $km^2$, supplying drinking water to more than 3 million people, and generating roughly 40% of Australia's total agricultural production. The Arkansas River basin, the second longest tributary of the Mississippi River, encompasses close to 0.5 million $km^2$, and supports substantial irrigated agricultural production.

The DoR was calculated for all reaches – defined as the segments between tributaries – in the river network for both case study basins, in the first instance considering only major in-stream dams, and then accounting for the presence of SAIs. To date, a threshold DoR value to identify impacted rivers has not been estimated with any confidence; however, a DoR value of 16.7% (Grill *et al.* 2019) has been adopted as a plausible threshold that facilitates comparisons with previous studies (see WebPanel 1 for more details).

Differences in DoR estimates are striking. In the Murray Darling River basin, when considering only major in-stream storages (Figure 2a, top), around 10% of reaches by

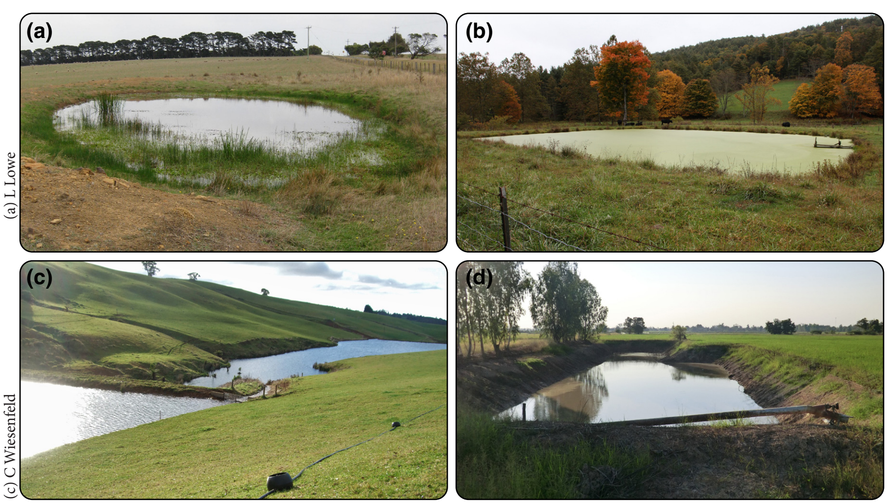




**Figure 1.** Examples of small artificial impoundments around the world: (a) Victoria, Australia; (b) Virginia, US; (c) Tasmania, Australia; (d) Kamphaeng Phet, Thailand.

length were flow impacted (Figure 2b, top). However, when SAIs are included, the proportion of impacted streams in the basin almost quadruples to 37%, with impacted streams represented across almost the entire basin. SAIs represent just 7% of total storage capacity, yet their influence increases the relative length of impacted waterways by 380% compared to the extent of impacts from large storages. Similarly, in the Arkansas River basin, 3.5% of reaches by length are impacted by major in-stream dams (Figure 2a, bottom), but when SAIs are included this proportion nearly triples to 9.7% (Figure 2b, bottom). In this basin SAIs represent a mere 0.03% of total storage capacity, yet they increase the relative length of impacted waterways by 280%. These differences are essentially practical in their origin: large dams are constructed on higher order streams to maximize yield, whereas SAIs are typically distributed across the landscape wherever landholders can and choose to build them.

Climate is an important driver of our results. Areas with mean annual rainfall greater than ~1000 mm have sufficiently high rates of runoff that the DoR rarely exceeds 16.7% even with high levels of SAI development. Conversely, areas with less than ~400 mm have such low runoff that even the presence of a small number of SAIs could result in high DoR estimates. However, these areas tend to have relatively low levels of SAI development, most likely because a combination of low runoff and high evaporation make open water impoundments impractical for most agricultural purposes.

A separate hydrological analysis revealed that the effects of SAIs on downstream flow regimes are broadly similar to the effects of large dams. Using one site in southeastern Australia as an example, the effect on downstream flow regime of a hypothetical large dam was compared to a large number of SAIs with the same aggregate capacity and aggregate upstream catchment area (Figure 3). The overall percentage reduction in annual flow was somewhat higher for SAIs than for a single large storage, but the net effect on flow exceedance and numbers of low flow days were very similar. Four additional sites modeled in the same way showed comparable results (see WebPanel 1 for modeling methods and results for other sites). In effect, if a large dam is considered a source of flow regulation, then SAIs must be viewed as a form of "distributed flow regulation".

## Spatial comparison of impacted streams with biodiversity

SAIs in both the Murray Darling River and Arkansas River basins primarily affected smaller streams and headwater streams. In some instances these streams may have higher conservation priority because they support greater numbers of threatened species than waterways affected by large dams alone. This is particularly important, as lower order streams typically compose the majority of waterways in a basin (Colvin *et al.* 2019), and widespread threats to freshwater biodiversity globally (Tickner *et al.* 2020) highlight the need to protect and restore these types of waterways.

Using the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (www.iucnredlist.org) as a key measure of biodiversity, we compared numbers of threatened species across waterways of different sizes (Figure 4; see WebPanel 1 for analysis details). In both basins, almost all waterways impacted by major dams have an upstream catchment area greater than 1000 $km^2$. In contrast, approximately half of streams impacted by SAIs have an upstream catchment area less than 100 $km^2$. For the Murray Darling River basin, the proportion of SAI-affected waterways with high numbers of threatened species is much greater for smaller (<100 $km^2$) than larger (>10,000 $km^2$) waterways (32% and 7% of waterways, respectively). For the Arkansas River basin, the trend is reversed (21% and 50% of waterways, respectively) due to lower order streams tending to occur in the upper catchment where there is lower rainfall (and therefore lower species counts); the inverse situation occurs in the Murray Darling basin. This underscores the need to consider how local climate and topography could lead to SAI-affected waterways having either higher or lower conservation priority.

## Management challenges

Efforts to restore biodiversity both upstream and downstream of large dams are ongoing worldwide. While these efforts are necessary to address the substantial environmental impacts

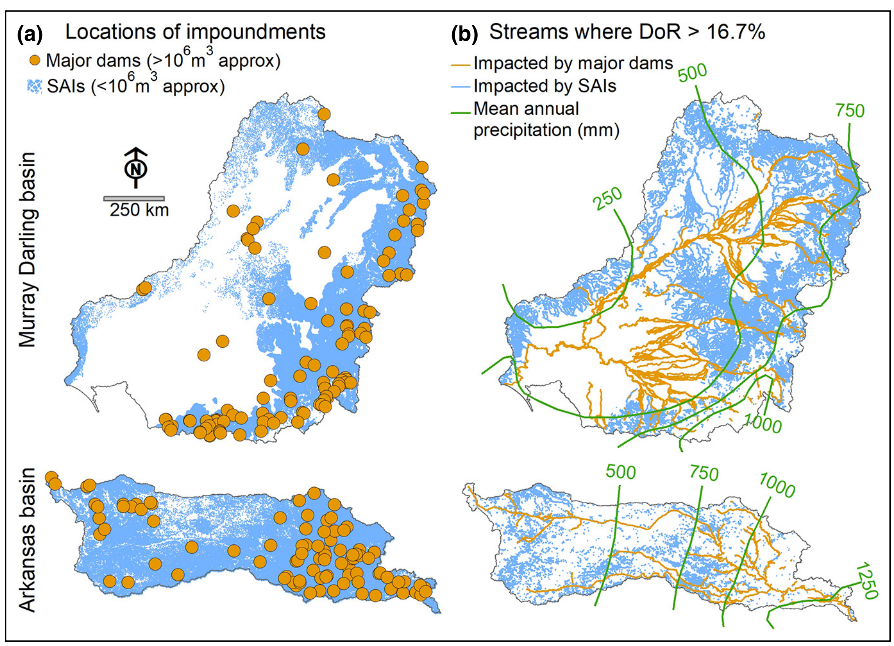


**Figure 2.** Impoundments and the downstream waterways in which they cause hydrologic stress. (a) Locations of major in-stream dams and small artificial impoundments (SAIs) in the Murray Darling River basin and Arkansas River basin. (b) Streams with a degree of regulation (DoR) greater than 16.7% in the Murray Darling River basin and Arkansas River basin. Precipitation data from WorldClim (Hijmans *et al.* 2005).

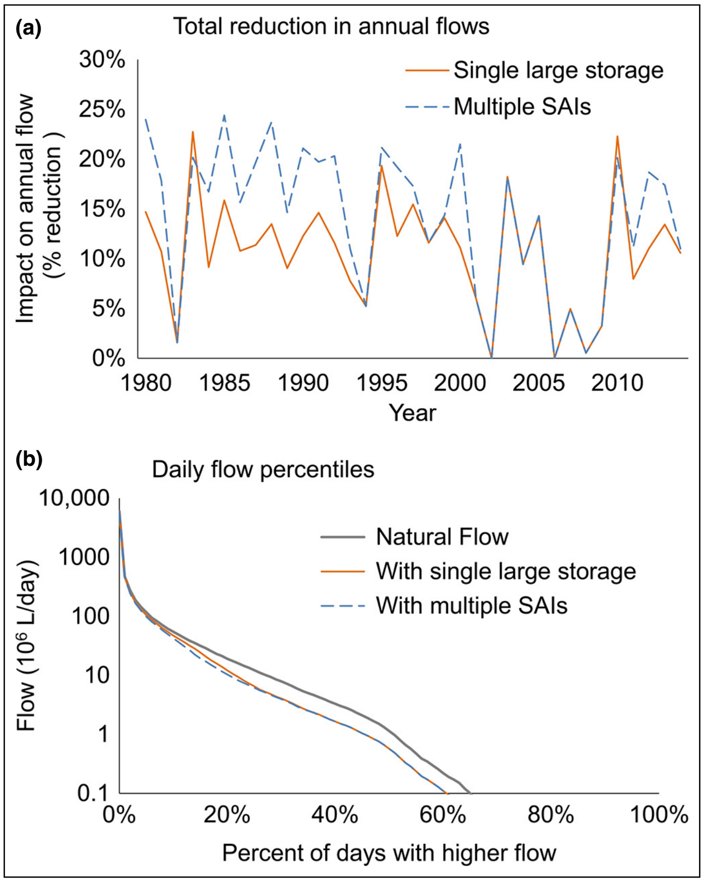


**Figure 3.** Comparison of impacts of a single large dam and multiple small dams, including impacts on (a) total annual flows from 1980 to 2014 and (b) daily flow percentiles. Note that in (b) the solid orange line is mostly hidden by the dashed blue line. In each scenario, streamflow from a single gauge location (above shows Mt Ida Creek, Australia, gauge 406226, catchment area 174 $km^2$) was used as a hypothetical "natural" flow, to which the hydrological impact of impoundments was applied. The single large dam was set to a capacity of 20% of mean annual flow (DoR = 20%) with an upstream watershed area 50% of the gauged catchment. The multiple small dams were set to capacities of 2500 $m^3$ each, with the same aggregate capacity and watershed area as the single large dam.

arising downstream from such structures (Tickner *et al.* 2020), our analysis suggests that river reaches downstream of large dams may potentially represent only a small fraction of all river reaches experiencing hydrologic stress. Catchment and waterway management agencies are already overstretched, and addressing the needs of the additional waterways impacted by SAIs is undoubtedly a major task.

## Challenges to current policy

While the impetus for controlling SAIs to minimize risks to biodiversity may be apparent in some areas, there may also be a complex policy mosaic and considerable local resistance. Historically, in most parts of the world, SAIs could be built with little regulation or consideration of potential environmental impacts, although some jurisdictions have in recent years introduced controls on the construction of new SAIs (Morris *et al.* 2019). Consequently, there is a tendency for many SAI owners to consider them a "right", and therefore any attempt to regulate or limit future development can be controversial (Horne *et al.* 2017). The large number of individual SAIs requires consultation and engagement with an equally large number of individual owners. In addition, because SAIs serve a variety of purposes (Nathan and Lowe 2012), they become entwined in a range of policy areas, including agricultural water supply (Wisser *et al.* 2010), essential domestic water supply, sediment control (Ibrahim and Amir-Faryar 2018), fire management, and provision of critical habitat and refuges (Agoramoorthy *et al.* 2016; Biggs *et al.* 2017).

## The dangers of cumulative impacts

When many individual landowners construct new SAIs, their individual impacts may be negligible but their cumulative impacts can give rise to "the tyranny of small decisions" (Kahn 1966). Crucially, we have demonstrated that the storage capacity of an impoundment is not a good indicator of its potential impact, and therefore a key challenge is to ensure that the cumulative impact of existing and future SAIs is considered alongside larger dams (Couto and Olden 2018; Couto *et al.* 2021), other current threats (such as extractions), and additional foreseeable future threats (such as climate change and land-use change).

## Incomplete understanding of the problem

Knowledge of the impacts of SAIs requires, at a minimum, spatial data identifying waterbodies as small as ~200 $m^2$. This information does not exist for much of the world (McManamay *et al.* 2018), although there are some exceptions, such as the US and several states in Australia. One of the highest resolution global datasets is HydroLAKES (Messager *et al.* 2016), which shows 1.42 million waterbodies; even this is insufficient, however, as the smallest identified features are around 10 ha in size, approximately the upper limit of SAIs. The scale of data processing required to capture large numbers of very small features from remote-sensing data makes generating new datasets a complex and expensive task.

## Insufficient modeling tools to account for impact and assess management actions

A further issue is the difficulty in demonstrating the benefits of any remedial actions over long implementation periods (Thompson *et al.* 2018). Although there exists a range of modeling tools for SAIs (Habets *et al.* 2018), adaptation of these tools will be required to track the impacts and benefits of any planned management intervention. There has been some success in this regard in Australia; for example, the Murray Darling Basin Plan (Australian Government 2012) includes SAIs in its annual accounting processes alongside major dams as part of the overall consumptive pool.

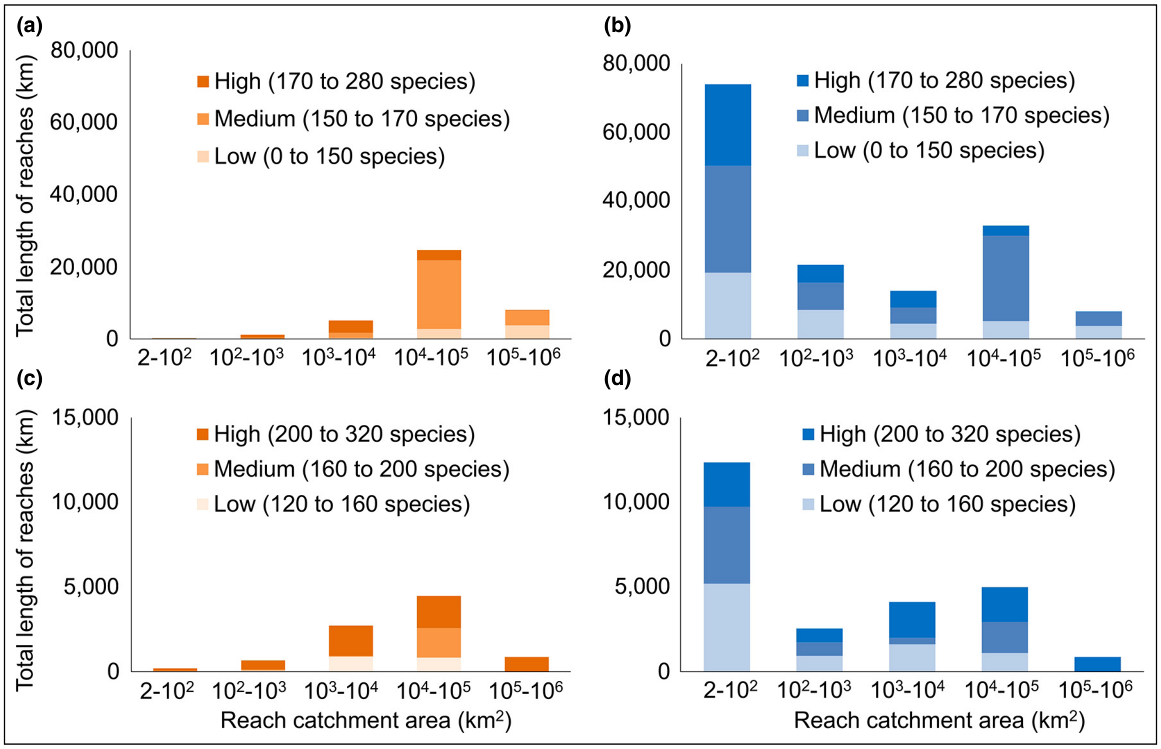


**Figure 4.** Total numbers of threatened freshwater species (International Union for Conservation of Nature Red List) in waterways affected (DoR > 16.7%) by large dams or large dams plus SAIs, aggregated by upstream catchment area and reach length. (a) Murray Darling River basin with large dams only; (b) Murray Darling River basin with large dams plus SAIs; (c) Arkansas River basin with large dams only; and (d) Arkansas River basin with large dams plus SAIs.

Considerable work has been undertaken to develop new water accounting and modeling approaches to make this possible (Srikanthan *et al.* 2015; Morden 2017).

## Moving forward

Many global and continental studies overlook the impacts of SAIs, making an implicit assumption that the biggest ecological impacts arise from the biggest extractions or impoundments. Here, we have highlighted the dangers of this assumption by demonstrating that while SAIs have relatively small capacity individually, their abundance and widespread distribution can result in substantial cumulative impacts. To exclude SAIs from assessments is to underestimate the risk posed to biodiversity in smaller and headwater streams that are paramount to freshwater integrity in healthy river systems (Colvin *et al.* 2019). In the future, substantial investment in the development of new information systems that catalog SAIs and implementation of environmental and hydrological monitoring is needed. Only with these data can SAIs be considered alongside other forms of anthropogenic extractions and held accountable for the hydrological impacts they generate.

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## Supporting Information

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