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Focused Flows to Maintain Natural Nursery Habitats

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Abstract: Regulatory standards for environmental flows to estuaries are not common, but they are required in Texas. This has led to adoption of complex freshwater inflow regimes that reflect seasonal and yearly fluctuations that vary geographically throughout the state. The flow regimes are based on dilution of saline water with fresh water in whole systems. Because the estuaries are large lagoons, large volumes of fresh water are required to meet standards. However, this volume of water is not available during dry periods. We present a new concept, focused flows, for lower flow volumes that would maintain the ecological health of the upper reaches of estuaries during droughts. The concept is based on maintaining ecological integrity of nursery habitats, which is an important ecological function of estuaries. These focused flows would protect nursery habitats during droughts and allow estuaries to recover more quickly when the hydrology returns to average or higher flow periods. This approach could be applied globally where increasing water infrastructure and deficits are a concern or increasing aridity due to climate change is reducing river flows to coasts.

Keywords: environmental flow, freshwater inflow, focused flows, hydrology, nursery habitats, management, protection

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Terms used in paper

Acronym/Initialism	Descriptive Name
ac-ft	acre-feet
ha	hectare
HB	house bill
m^3	cubic meters
NOAA	National Oceanic and Atmospheric Administration
psu	practical salinity unit
s	second
SAC	Science Advisory Committee
SB	Senate Bill
y	year

INTRODUCTION

While nearly every political jurisdiction on Earth has some kind of laws, rules, or regulations that protect water quality, very few jurisdictions have such protections for water quantity. Yet rivers that do not flow are hardly river habitats at all, and the dilution of sea water with fresh water defines estuary habitats. Scientists and managers of freshwater ecosystems have long recognized the importance of flowing water in the environment to define aquatic habitats, and that management of flow rates is important to protect freshwater species (Ward and Stanford 1979; Postel et al. 1996; Richter et al. 1997). The importance of natural flow regimes, which acknowledge the dynamic nature of the timing and flow of rivers instead of just a minimum flow rate, is now recognized as a critical management approach (Poff et al. 1997). Recently, the field of hydroecology (or ecohydrology) has arisen to examine the relationship among environmental flow regimes, ecological responses, and potential management applications (Wood et al. 2008).

Estuary habitats are different from river and stream habitats. Flow rates in flowing freshwater riverine environments define instream habitats, maintain riparian and floodplain communities, influence habitat quality, and transport matter and materials downstream (Bain et al. 1988). This is not true in estuaries. In estuaries, freshwater inflow from rivers and streams delivers nutrients and sediments and dilutes sea water from the coastal ocean; thus, environmental flow is a driver of estuarine condition and ecological responses to the varying estuarine conditions (Alber 2002). The importance of salinity in defining estuary conditions also has a long history since first described by Pritchard (1952, 1967). The role of nutrients and sediments in shaping estuarine productivity and habitats along salinity gradients from the river to the sea is also well known (Day et al. 1989). Early studies of estuaries demonstrated that they provide nursery habitats, which support fish and shellfish fishery species, and these nurseries are primarily located in marshes and near river mouths (Gunter 1967; Weinstein 1979).

While it has been firmly established that estuaries are complex ecosystems with high spatial and temporal variability (which influences food webs, habitat complexity, and ecosystem productivity characteristics), early attempts to address management of freshwater inflows focused on flow rates alone. This was true in many regions (Adams 2014). For example, in Texas, United States, the primary approach to identifying freshwater inflow needs was a model of fisheries harvest that was driven by freshwater inflow rates (Longley 1994; Powell et al. 2002). In Florida, United States, a percent of flow approach has been used in some estuaries (Flannery et al. 2002). In South Africa, static volumes were used to set inflow criteria (Adams et al. 2002). In other cases, the flow required to maintain a downstream salinity value was used, as in San Francisco Bay, California (Jassby et al. 1995; Kimmerer 2002a), Georgia, United States, estuaries (Alber and Flory 2002), and Swan River Estuary, Western Australia (Kurup et al. 1998). These condition approaches to define inflow needs were replaced by more mechanistic and holistic approaches over time (Adams 2014).

However, one consequence of these whole-estuary approaches to identify inflow needs is that very large volumes of fresh

Table 1. Estuary and river basin characteristics on the Texas coast. Estuary inflow and river flows are in 10^3 acre-feet/year (ac-ft/y), estuary volume is in 10^3 ac-ft, and flushing rate (i.e., volume/surface inflow) is in days.

Estuary characteristics [a]					**River basin characteristics** [b]			
Estuary	Volume	Surface inflow	Inflow balance	Flushing rate	**River basin**	Naturalized flows at outlet	Regulated flows at outlet	Percent regulated flow
Sabine-Neches	492	13,866	13,919	13	Sabine	6,633	6,192	93%
					Neches	6,224	5,572	90%
Trinity-San Jacinto	2,108	11,120	11,241	69	Trinity	6,630	4,829	73%
					San Jacinto	2270	1,119	49%
Lavaca-Colorado	1,798	3,528	3,242	186	Colorado	3,119	1,908	61%
					Lavaca	860	806	94%
Guadalupe	564	2,455	2,270	84	Guadalupe & San Antonio	2,220	2,063	93%
Mission-Aransas	702	490	280	522				
Nueces	964	587	262	599	Nueces	648	440	68%
Laguna Madre	414	705	-595	215	Rio-Grande	1,100	75	7%

[a] Montagna et al. 2011
[b] Wurbs and Zhang 2014

water are required to dilute salinity in whole-bay and estuary systems or to maintain a salt wedge in the downstream area near the inlet or pass where sea water and fresh water are mixing. These large volumes impose a problem for those resource managers setting inflow standards or others attempting to restore hydrology to ensure estuary functions. The problem is that the large volumes of fresh water may no longer be available. The reality is that there are about 16.7 million reservoirs larger than 0.01 hectare (ha; 0.08 acre-feet [ac-ft]) in the world (Lehner et al. 2011), and one-sixth of the river flow in the world is now captured behind these dams (Hanasaki et al. 2006), which is severely restricting fresh water and sediment flow to the coasts (Tessler et al. 2018). In addition to land-use change, climate change will also alter water availability. Aridity is increasing worldwide because of climate change (Berdugo et al. 2020). This is particularly true in the southwestern region of North America where extreme droughts can extend many years (Seager et al. 2007). So, the problem is: How will we ever hydrologically restore estuaries if large volumes of water are no longer available in rivers and streams or are already allocated?

TEXAS ESTUARIES

There are 10 major river basins and nine coastal basins in Texas that provide freshwater inflow to seven major receiving estuaries, which range from hydrologically positive in the northeast to negative in the southwest (Montagna et al. 2011; Table 1). Water supply diversions are less than natural flows in every Texas river basin except for the Rio Grande in the southwest (Wurbs and Zhang 2014; Table 1). However, on average, regulated flows at the outlet of the river basins to the estuaries is 81% of the naturalized flows at the outlet, meaning that much environmental water is still reaching bays and estuaries. Reduced inflow may already be a problem in the southernmost, hydrologically neutral and negative estuaries, where water is already naturally scarce. An example of this is the Nueces River, where flushing rates are very slow and regulated flows are much reduced from naturalized flows (Table 1).

Since the mid-1980s, the state of Texas has struggled with the issue of how to secure freshwater inflows to estuaries sufficient to keep them healthy and productive while also meeting the myriad of human demands on that limited resource. Because of these legislative mandates (1985 House Bill [HB] 2, 1997 Senate Bill [SB] 1, and 2007 SB 3), Texas has led the world in efforts to characterize environmental water and especially freshwater inflows as the basis of making rational, science-based decisions about water allocation and management to assure healthy and productive bays and estuaries. Much of that early work was synthesized in the seminal book Freshwater Inflows to Texas Bays and Estuaries (Longley 1994). A fundamental tenet of those early studies was a focus on recreationally and commercially important shellfish species (i.e., crabs, shrimp, and oysters), and finfish (i.e., black drum, flounder, red drum, and spotted seatrout). That focus generated two significant constraints on efforts to produce a model that would predict the required inflows, both in quantity and timing to meet the legislative mandate (Powell et al. 2002). The models necessarily had to encompass an entire bay system because of

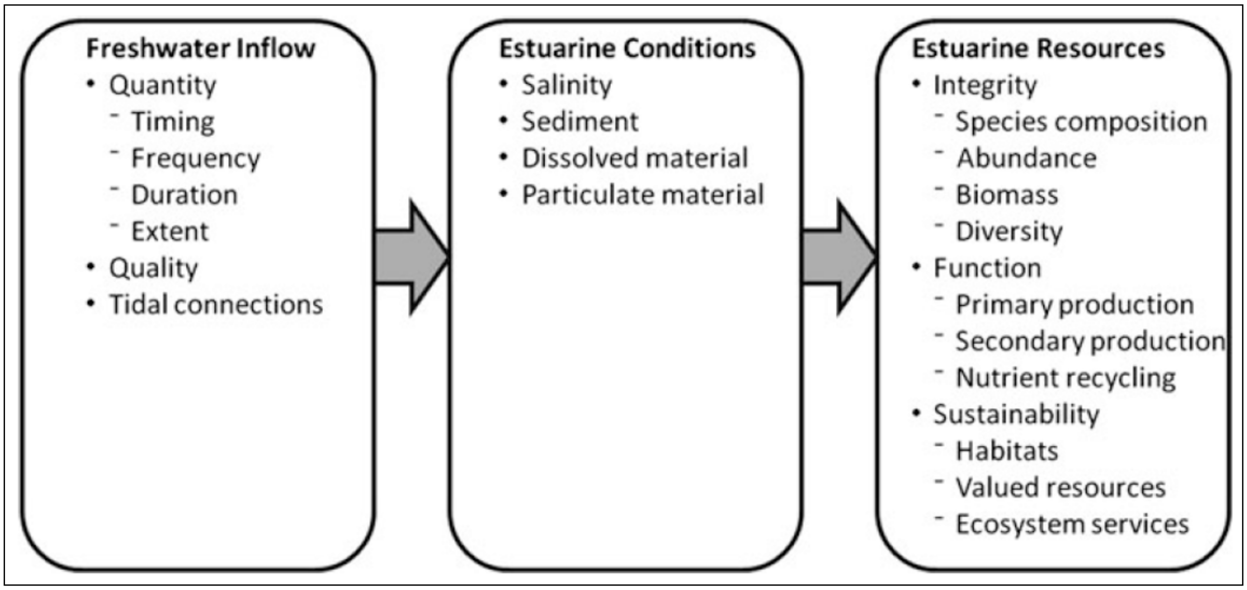

Figure 1. The domino theory conceptual model of freshwater inflow effects on estuary ecosystems (based on Alber 2002; Brandes et al. 2009; Palmer et al. 2011; Montagna et al. 2013).

these species' mobility (only oysters remained a fixed community). The focus on the entire bay meant models had to predict the effect of changing conditions over large areas and relate those changes to the adult stages of the target species. Such complexities made the margins of error in the models large and difficult to resolve.

These scientific constraints created two significant political impediments to securing environmental flows for estuaries. The large margins of error in the models made it necessary to provide a range of inflows with differing biological impacts rather than more specific recommendations. While that may be a scientifically reasonable approach, detractors seized on that as an uncertainty to discredit the recommendations. Second, and more importantly, because the focus of the effort was on entire bay systems, the quantities of water needed to meet legislative mandates was in the hundreds of thousands (even millions) of acre-feet, and that high volume proved to be politically, economically, and hydrologically impossible to secure.

As described above, the state of Texas started with a conceptual model of direct effects of flow on harvestable species (Matsumoto et al. 1994). The conceptual model was that "fisheries' production may be considered a measure of an estuary's overall health," and the mathematical approach was essentially a regression between inflow and harvest (Matsumoto et al. 1994, page 700). The strengths and weaknesses of the method have been described in detail by the Texas Environmental Flows Science Advisory Committee (SAC; Brandes et al. 2009, pages 33-37). The main problem is that harvest is an economic factor driven by pricing and fishery regulation, not an ecological factor, and that finfish and shellfish need food to grow and habitat to live in. There is not a simple harvest = flow relationship. The original idea was a species-based management approach. The problem with species management is related to the problem with the direct relationship approach, in that species live in a complex environmental setting, and what is good for one species may be bad for another. Modern environmental management usually takes an ecosystem-based approach where habitat and environmental quality is managed for the benefit of the full complement of species. The idea that evolved was that inflow has an indirect effect on bays and estuaries and is best managed by an ecosystem-based approach focused on habitats.

Role of fresh water in estuaries

While it is recognized that freshwater inflow has indirect effects in estuaries (i.e., inflow affects water quality conditions, and water condition affects habitat quality), the idea was first formalized into a management strategy by Alber (2002). The Alber conceptual model was based on a quantitative model of the cumulative impacts on ecosystem processes as a function of changes in freshwater, sediment, and nutrient inflows created by Sklar and Browder (1998). The indirect approach was adopted by SAC to provide guidance to all science and stakeholder teams responsible for making inflow recommendations to the Texas Commission on Environmental Quality, the agency responsible for setting environmental flow standards in Texas (Brandes et al. 2009). The conceptual model developed by these earlier efforts was refined by Palmer et al. (2011) and Montagna et al. (2013) and named the domino theory (Figure 1).

The conceptual model is called the domino theory because there is a domino effect where inflow drives water quality conditions, and living estuarine resources respond to the water quality conditions that drive habitat quality. Recent numerical modeling approaches use this idea to integrate the delivery of nutrients to the estuary that drives primary production, which in turn drives secondary production (Montagna and Li 2010; Kim and Montagna 2009, 2012).

Ultimately, biological resources in estuaries are affected more by salinity solely by flow, because salinity is the most important water quality component regulating community structure (Van Diggelen and Montagna 2016). Salinity is affected by inflow, but there are complexities because of the interactions between tides and geomorphology. Consequently, all salinity-flow relationships are characterized by very high variance or scatter, especially in the low flow end of the spectrum. Because of the links among flow, salinity, and biology, all the resource-based approaches are multi-step and essentially run the domino theory backwards. First, the resource to be protected is identified. Second, the salinity range or requirements of that resource are identified in both space and time. Third, the flow regime needed to support the required distribution of salinity is identified.

It is impossible to manage freshwater inflow without a policy framework and an adaptive management process, both of which have evolved over time in Texas. After a drought in the 1950s, the Texas Water Planning Act was passed by the Texas State Legislature in 1957. This act was amended over the next 10 years and led to the creation of a Texas water plan that was adopted in 1969 and called for 13.5 million ac-ft of freshwater inflows annually to Texas bays and estuaries. Estuarine monitoring programs to inform state water planning and permitting decisions were enacted in legislation in 1985 (HB 2) and 1987 (SB 683; Longley 1994; Powell et al. 2002). A major change occurred in 2007 when the Texas Legislature passed SB 3, which requires that new water permits contain, to the extent possible, a set aside for an environmental flow regime (Montagna et al. 2013). Complex inflow regimes were adopted for stream locations throughout Texas river basins that include provision for subsistence, base, and pulse flows during each of the four seasons (winter, spring, summer, and fall; Opdyke et al. 2014). Altogether, these volumes are large (millions of ac-ft/year [y] or billions of cubic meters [m^3]/y) because they are based on diluting whole estuary systems.

Freshwater inflow needs

There are two issues that make identification of freshwater inflow needs problematic: 1) a large amount of fresh water is needed to maintain ecological integrity, which is dependent on salinity gradients from the river to the sea in the entire estuary, and 2) water in the upstream basins can be allocated to a high degree during droughts. Thus, finding water quantities necessary to resolve these problems is going to be a challenge.

The state of Texas creates a new water plan every 5 years (Texas Water Development Board 2017), which provides the following facts. Human water demand in 2017 was 18.4 million ac-ft/y (22 billion m^3/y), but water supply during a drought is only 15.2 million ac-ft (19 billion m^3/y). This data shows that during droughts, there are insufficient supplies to meet human needs, let alone environmental needs. Worse, it is projected that by 2070 annual water demand will increase 17% and annual water supply will decrease by 11%, which will considerably widen the shortfall during droughts. It is obvious that fresh water is currently over-allocated to meet current demands during droughts.

Where will the water come from to meet environmental needs and standards when it is most needed for human uses, i.e., during droughts? With so little water available and such large volumes necessary to maintain estuarine conditions, it appears that Texas estuaries are at great risk. The arid parts of Texas are already characterized by water scarcity, and this risk increases with climate change (Ward 2011).

Inflow creates different salinity zone habitats within bays (Montagna et al. 1996, and thus the critical need is to characterize within bay dynamics, not bay-wide dynamics. In addition, we now know that minimal inflow during dry times would minimize a bay system from degrading during droughts (Palmer and Montagna 2015; Montagna et al. 2017).

Advances in estuarine science have demonstrated that there are zones within bay systems. The critical zones are the estuarine habitats that are the natural nurseries for estuaries (Deegan and Day 1984) that support connectivity with the coastal sea (Vasconcelos et al. 2011). These zones have also been called refuges, or refugia, because this is a place where estuarine-dependent species can seek refuge during times of stress (Boesch and Turner 1984). Often these nursery habitats are associated with edges of vegetated habitats near freshwater sources, such as mangroves (Nagelkerken et al. 2008), marshes (Boesch and Turner 1984), or areas near river mouths (McCambridge and Alden 1984; Zimmerman and Minello 1984; Kimmerer 2002b; Fernández-Delgado et al. 2007). The key paradigms have been that estuaries are nurseries, many species are estuarine dependent, and freshwater inflow influences habitat (Able 2005). Thus, salinity gradients define habitat utilization in Texas estuaries (Zimmerman et al. 1990; Montagna et al. 2013).

Water resources in Texas are driven by spatial and temporal variability, and most flow occurs during floods separated by periods of low to moderate flows (Wurbs 2021). Thus, periods of higher inflow will occur after low-flow periods. So, if we maintain a natural nursery, this will enable the bay to recolonize more rapidly when higher flow periods resume, and we can ensure that we "maintain the productivity, extent, and persistence of key aquatic habitats" over the long-term as required by 2007's SB 3. These two developments (drought regimes and refuges) provide a basis for a new goal: to determine how much fresh water is needed during dry times to maintain natural nurseries (i.e., refugia).

The areas near river mouths are smaller and shallower, and thus have much smaller volumes of water. Therefore, these areas need much less water to maintain an estuarine salinity zone that would maintain these natural nurseries. A model of the Nueces Delta marsh predicts reductions in plant cover in both drought and moderate conditions, and marsh plant coverage increases only during wet conditions (Montagna et al. 2017). The delta marshes near river mouths are typically composed of a community of marsh plants, such as *Batis maritima, Distichlis spicata, Monanthcloe littoralis, Salicornia virginica, Borrichia frutescens,* and *Spartina alterniflora* (Montagna et al. 2017). These marshes are distinct from fringing marshes that are composed of only *Spartina alterniflora* and occur throughout the bay systems, including the primary bays. Focused flows will not affect fringing marsh habitat in primary bays.

ONE POTENTIAL SOLUTION: FOCUSED FLOWS

The issue of adequate freshwater inflows to maintain estuaries was first raised in the 1960s (Copeland 1966). There have been at least four compilations or reviews on this topic since then: Cross and Williams (1981), Dyer and Orth (1994), Montagna et al. (2002a), and Acreman et al. (2014). So there is quite a bit known about the importance of freshwater inflow to estuaries and the science used to identify environmental flow needs of estuaries (Brandes et al. 2011; Montagna et al. 2013; Adams 2014).

Small scale hydrological restoration projects have demonstrated that measurable environmental benefits can be derived from relatively small amounts of water delivered strategically into the upper ends of Texas estuaries. For example, construction of two dams in the Nueces River watershed and an ensuing drought reduced flow to the Nueces Estuary and overbanking from the Nueces River to Rincon Bayou, which feeds the Nueces Delta marsh (Ward et al. 2002). This led to higher salinities and a reverse estuary where salinity was higher at the mouth of the river than downstream in the bay (Palmer et al. 2002). In 1995, an overflow channel was cut into the bank of the Nueces River to increase the frequency of flow into Rincon Bayou and the marsh. This solution led to higher abundance and diversity of intertidal vegetation (Alexander and Dunton 2002) and benthic communities (Montagna et al. 2002b). Additionally, a pipeline was built to move fresh water directly into the marsh in 2009, and the pumping was able to maintain salinities at less than 35 practical salinity units (psu) during droughts (Del Rosario and Montagna 2018). It was also determined that inflow volumes as low 0.41 m^3/second (29 ac-ft/day) would maintain optimal salinity and water depth for infauna and epifauna communities (Montagna et al. 2018). Water depth is an important factor because focused flows would be delivered to shallow upland marshes and bayous. In Rincon Bayou, which is a good example of an area that requires focused flows, maintaining the ecological health of the marsh would require maintaining salinity between 6 and 18 psu and a minimum water depth between 0.2 meters to 0.3 meters (Montagna et al. 2018).

Flows that create and sustain natural nurseries can accelerate recovery of estuaries, perhaps by years, following the end of droughts. A more rapid recovery of these productive systems has both economic and ecological benefits. Thus, a small amount of water delivered to strategic areas of the estuary during droughts can have great ecosystem and human benefits. These areas are nursery habitats, which are also of lower overall volumes and thus require less fresh water to dilute salt water. Therefore only thousands, rather than hundreds of thousands, of acre-feet of fresh water would be necessary. Small volumes of freshwater inflow could be focused on these nursery habitats at critical times, hence the name of this strategy is "focused flows."

Focused flows are likely not adequate to sustain ecosystem health and productivity for whole estuarine systems, and they cannot substitute for environmental flows that sustain fisheries or ecosystem services beyond drought mitigation. However, focused flows do provide significantly more ecosystem value than a requirement to meet minimum water quality standards, and it has been shown that the public places high value on the impact of freshwater inflow (Yoskowitz and Montagna 2009).

The concept of focused flows could be a more palatable political goal for securing environmental water than what has been attempted in the past. It is a strategy that many stakeholders would likely agree to because it does not force the false choice between securing water to serve people versus the environment. These focused flows may be the only viable option in systems where water is mostly allocated, or restoration is a desirable environmental goal.

The focused flows concept also has economic benefits. Payment for conservation and restoration activities that have public benefits can be provided from the public sector, public-private partnerships, or private social impact investing (Alix-Garcia et al. 2018; Holl and Howarth 2000; Pascal et al. 2018). Also, focused flows could be secured through market-based approaches (i.e., purchasing permanent rights, spot market transactions, or options contracts) because smaller volumes of water are more likely to be available than larger volumes. It has been suggested that a water market in Texas could encourage water conservation (Vaca et al. 2019). Focused flows from water transactions could also be created by mitigation or restoration actions, or a permanent water right. Part of the economic value generated by a more rapid recovery from extreme droughts using a focused flow regime—where natural nurseries are maintained—can be calculated by the increase in the rate of recovery of habitat and infauna and epifauna communities (Montagna et al. 2018; Montagna et al. 2017) and commercially and recreationally important fish recovery (Lellis-Dibble et al. 2008; Brown et al. 2018). Thus, focused flows is an economically useful strategy for restoration projects.

Should a focused flows program be adopted, there will be many new questions that will need to be answered with research, as well as engineering challenges to be met. To design a focused flow regime, it will be necessary to know details about the species present at a specific location, their seasonal dynamics, and the optimal salinity and depth ranges to support the habitat requirements of the species present. It will be necessary to identify valued ecosystem components that would benefit from the focused flows. Mechanisms to deliver water will also have to be resolved. For example, a pipeline was built to transport water around the saltwater barrier (i.e., the Calallen Dam) on the Nueces River to deliver water directly to Rincon Bayou (Montagna et al. 2009). So some kind of conveyance, such as a pipeline or ditch, may be required to deliver water directly to where it might provide the most benefits. Water might be required from storage, return flows, or aquifer storage and recovery, which will provide additional engineering challenges.

Additionally, a focused flow program will likely require some monitoring to determine if the project is working as designed. While the benefit is primarily for maintaining nursery habitat function for biological resources, it will be expensive to monitor the target species utilizing the habitat. However, a minimal monitoring program is inexpensive and should measure habitat characteristics, such as salinity and water elevation, to ensure the habitat design requirements are being met.

The general public expects environmental programs to benefit society (Kulin et al. 2019) and will support them when they are perceived as fair and effective. The focused flows concept provides a science-based approach that meets this desire and in doing so facilitates governmental agencies in meeting regulatory requirements related to water allocations. A focused flow program could also be a means to engage non-governmental organizations more productively (Bennett et al. 2018) to create projects and apply for funding to restore hydrological functioning of estuaries. Water markets have successfully been used to address conservation issues in freshwater systems (Garrick et al. 2009). Focused flows expand those market possibilities to estuarine systems, providing both government agencies and conservation organizations with new cost-effective means to meet both regulatory and environmental needs.

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