MANAGING FRESHWATER INFLOWS TO ESTUARIES: A METHODS GUIDE

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CONTRIBUTORS

The first five sections of this Guide draw on drafts prepared initially by Scott Nixon, Professor of Oceanography at the University of Rhode Island. Several people in Scott Nixon's lab worked to compile the comparative data that shaped what was initially termed a "Primer" on how estuaries function and respond to human pressures. This team included Betty Buckley, Robinson W. Fulweiler and Autumn Oczkowski.

The method offered for integrating science and addressing governance in the management of freshwater flows (Sections VI through IX) builds upon the five-step process applied and refined in many countries since 1990 by the Coastal Resources Center (CRC) at the University of Rhode Island. Paul Montagna of the University of Texas Marine Science Institute prepared a working paper on methods for assessing the impacts of changes to freshwater inflows. Discussions with the project's science advisors Alejandro Yanez-Arancibia, John Day, Björn Kjerfve, Scott Nixon and Charles Vörösmarty helped shape decisions at various points in the evolution of the project.

An initial version of the approach described in this Methods Guide was applied and refined at pilot sites in Mexico and the Dominican Republic by a multi-disciplinary team from CRC and The Nature Conservancy (TNC). The contributors include Leslie Bach, Mike Beck, Rafael Calderon, Maria Fernanda Cepeda, Tom Fitzhugh, Chuck DeCurtis, Andrea Erickson, Lynne Hale, Phil Kramer, Karin Krchnak, Cristina Lasch, Jeannette Mateo, Francisco Nuñez, Antonio Ortiz, Marie Claire Paiz, Don Robadue, Pam Rubinoff, Steve Schill, Jim Tobey, Nathan D. Vinhateiro, and Andy Warner. In the Dominican Republic, the staff of the Centro para la Conservación y Ecodesarrollo de la Bahía de Samana y su Entorno (CEBSE, Inc.) provided critical research and facilitation for the Samana Pilot area. In Mexico, this invaluable role was played by Pronatura, A.C. Rob Brumbaugh of TNC's Global Marine Initiative made contributions to the section on field methods.

Throughout this project, Sharon Murray and Richard Volk of the Water Team at the United States Agency for International Development (USAID) made many substantive contributions that have greatly improved the final version. The support provided by USAID's Dominican Republic and Mexico programs helped direct and guide the in-country pilot projects.

The authors acknowledge the hard work of the many contributors who have helped make this Guide a reality.

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I. INTRODUCTION

The management of freshwater and the management of estuaries have in most countries evolved as independent programs that operate with distinct mandates, authorities, policies and institutional structures. This Guide addresses the need to better integrate river and catchment (watershed) management with estuary management by combining important features of integrated coastal management (ICM) with integrated water resources management (IWRM) (**Box 1**). This approach recognizes that catchments, coastlines, estuaries and near-shore tidal waters are all elements of discrete, but closely coupled, ecosystems.

Such ecosystem-based management has emerged as a broadly accepted approach to managing natural resources and the environment. Traditionally, management efforts have been organized around particular sectors such as agriculture or tourism, resulting in distinct technical approaches and governance regimes for each use. The shift away from the management of individual resources to a systems approach is reflected in the work of international organizations ranging from the Intergovernmental Oceanographic Commission, to the Food and Agriculture Organization, to the United Nations Environment Program, to the Global Environment Facility. In 1997, the United Nations Commission on Sustainable Development found that:

> "The concept of integrated management of watersheds, river basins, estuaries and marine and coastal areas is now largely accepted in the United Nations system and in most countries as providing a comprehensive, ecosystem-based approach to sustainable development." (E/CN.17/1997/2/Add.16, 24 January 1997)

Ecosystem-based management recognizes that plant, animal and human communities are interdependent and interact with their physical environment to form distinct ecological units called ecosystems. These units typically cut across political and jurisdictional boundaries and are subject to multiple management systems. Ecosystem-based management has been defined to be:

> "…driven by explicit goals, executed by policies, protocols, and practices, and made adaptable by monitoring and research based on our best understanding of the ecological interactions and processes necessary to sustain ecosystem structure and function." (Christensen et al., 1996).

As expressions of ecosystem-based management, IWRM and ICM are rooted in three principles:

- An approach that fully recognizes the interconnected nature of living systems and human activity at the landscape scale.
- The practice of decentralized democratic governance that works to nest policies, laws and institutions into a tiered, internally consistent and mutually reinforcing planning and decision-making system.
- The application of sound science to the planning and decision-making process.

In this Guide, we use the broader term of IWRM to include ICM and advocate methods that address the competing needs of multiple users and stakeholders in a transparent, systematic and participatory manner. As used in this Guide, IWRM is a process and set of practices that address the issues posed by the allocation, use and conservation of freshwater from the headwaters of catchments to the seaward boundaries of estuaries. It addresses upstream and downstream users, terrestrial and aquatic systems, and surface and ground water sources in catchments and their associated and adjacent coastal and marine systems. This integration of catchment and coastal management has been promoted by the Global Program of Action (GPA) for the Protection of the Marine Environment from Land-based Activities administered by the United Nations Environment Program (UNEP). In this context, the term Integrated Coastal and River Basin Management is being used by UNEP (http://www.gpa.unep.org).

BOX 1: INTEGRATED WATER RESOURCES MANAGEMENT (IWRM)

Integrated Water Resources Management has been defined as "a process which promotes the co-ordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP, 2000). One of the key concepts embodied in IWRM is cross sectoral integration of different water uses including water for people, water for food, water for nature as well as water for other uses such as flood risk management, industry, hydropower and navigation (UCC-Water, 2006). The concept has been discussed and refined throughout the 2000s in major international conferences.

Making IWRM principles operational is a major challenge. This is recognized in the recent Millennium Ecosystem Assessment, (2005) that notes that the institutional arrangements currently in place to manage ecosystems are poorly designed to cope with the challenges of the temporal and spatial patterns of change. It remains difficult to assess the costs and benefits of ecosystem change, or to attribute costs and benefits among stakeholders. This is particularly true for estuarine systems, which are affected by often-distant decisions that produce changes to water flow and water quality.

To advance understanding of the dependence of estuarine health on adequate freshwater inflows and to spur greater institutional collaboration and integrated policymaking, this Methods Guide is designed to help answer the following questions:

- Why are estuaries important? What are the processes that enable estuaries to generate an extraordinarily rich set of goods and services of critical importance to coastal ecosystems and coastal people?
- What are the potential effects of changing freshwater inflows to estuaries?
- Are there robust, low-cost methods that can be used to explore the dynamics of problems associated with changes to freshwater inflows to estuaries?
- What policies and management processes are effective in guiding the integration of freshwater allocation and estuarine management?

The approach described here emphasizes low-cost techniques that will be useful to water managers and decision-makers striving to balance the many human needs for water with protection of the ecosystem goods and services provided by estuaries. This Guide is directed particularly at freshwater and coastal managers who need to understand and forecast the impacts of changes to the quantity, quality and timing of freshwater flows in small- and medium-sized catchments and estuaries in developing nations. It is tailored to the needs of an interdisciplinary team with limited funding and time, operating in settings where poverty prevails and governance institutions are often weak and unstable. In these situations, costly studies may not be an option.

The Guide offers the principles, questions and sequences of actions that can enhance understanding, dialogue and collaboration among all those involved in catchment, freshwater and coastal policy making and management. This will typically involve governmental officials at the national, regional and local levels; the communities, businesses and user groups whose livelihoods are linked to how freshwater is allocated and used; and non-governmental organizations and research organizations.

The approach described in this Guide focuses on the maintenance of adequate flows (i.e., quantity and timing) of water from catchments into estuaries. We recognize however, that in many instances, water quality issues are of equal or greater importance to estuarine and overall ecosystem health. These issues should be considered as being of paramount importance in any linked catchment-to-estuary management initiative.

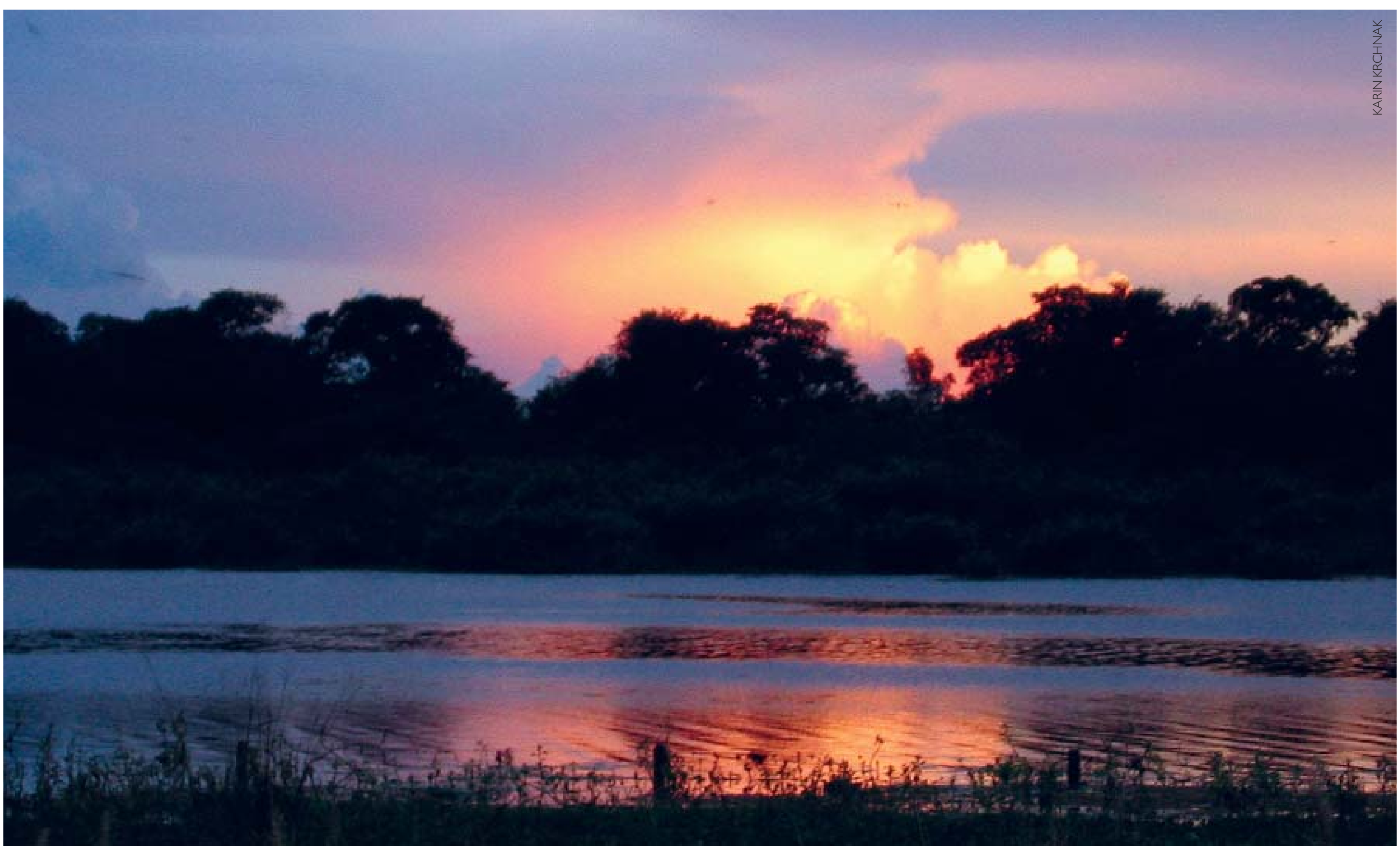
II. GLOBAL WATER SCARCITY

Our earth is a blue planet. Water covers about seven-tenths of its surface, but most of this is salty seawater. Only 3% of Earth's water is freshwater, and most of this freshwater is inaccessible—frozen in glaciers or at the polar ice caps or buried in inaccessible aquifers. A mere 0.03% of our global water supply is both accessible and suitable for human use (Bhandari, 2003). The scarcity of high quality freshwater is increasingly producing sectoral and transboundary conflicts both within and among countries.

An estimated 2.8 billion people—35% of the world's projected population by the year 2025—are expected to face serious shortages of freshwater in virtually every region of the globe. Half of the world's major cities are within 50 kilometers of the coast, and coastal population densities are 2.6 times greater than those in inland areas (Crossland et al., 2005). As coastal populations increase, debates, disputes and dilemmas over freshwater use become more frequent and more intense.

Climate change will accentuate shortages of freshwater in many parts of the world during the next 25 years, and make its seasonal availability more uncertain (Vörösmarty et al., 2000). The rising Earth's temperature is producing regional changes in precipitation and evaporation and accelerating sea-level rise that can salinize aquifers and surface water bodies along the coast. Thus, sea-level rise and climate change will aggravate water scarcity problems and pose considerable challenges to low-lying coastal communities.

The terrestrial water cycle has been significantly altered by the construction and operation of water engineering facilities. Dams, in particular, have fragmented and transformed the world's rivers. The last century saw a rapid increase in large dam building. By 1949 about 5,000 large dams had been constructed worldwide, three-quarters of them in industrialized countries. By the end of the 20th century, there were over 45,000 large dams in over 140 countries (World Commission on Dams, 2000; Vörösmarty and Sahagiann, 2000; Postel and Richter, 2003). Small dams have also proliferated. These engineering projects and the associated irrigation systems, diversions of freshwater from one catchment to another, flood control and increases in freshwater use are having major impacts on the functioning and qualities of catchments and their associated estuaries.



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BOX 2: TYPES OF ESTUARIES

There are several classification schemes for distinguishing among different types of estuaries. Two methods are most pertinent to this Guide.

Water Balance: Estuary ecosystems vary dramatically as a function of their water balance. This is the sum of the sources (additions) of freshwater to an estuary, minus the sum of the freshwater sinks (losses). There are many potential sources of freshwater to an estuary, including rivers, streams, groundwater, precipitation onto the estuary, and runoff. A primary freshwater sink is evaporation. *Positive estuaries* are those in which freshwater input exceeds freshwater loss (i.e., where the amount of water coming into the estuary from rain, runoff, rivers and groundwater exceeds the amount of water lost from the estuary as a result of outflow and evaporation). *Neutral estuaries* are where the sources and sinks are in balance. *Negative or inverse* estuaries are those systems in which water loss is greater than freshwater input. These estuaries are hypersaline. Some systems change seasonally. For instance, a given estuary may be positive during rainy seasons (when there is a large influx of freshwater from runoff and rain), and negative during dry seasons (at which time there is little or no input from rain and runoff, and a large loss due to evaporation). Human induced shifts, such as the diversion of waters from one catchment to another, may be expected to produce dramatic changes in the biota.

Geomorphology: The physical characteristics of the estuary, its shape, geologic material, topography, etc., are also important determinants of estuarine ecology. *River mouth estuaries* are usually perpendicular to the coastline. The sediments carried by rivers typically form deltas or groups of islands. In river mouth estuaries, salinity typically shows a strong gradient with freshwater at the estuary head, sometimes many kilometers from the coast, and progressively higher salinities that give rise to a mosaic of habitats extending down estuary to the open sea. Not all river mouths are estuaries. In the case of very large rivers, such as the Amazon, the volume of freshwater is so large that no seawater penetrates into the river mouth; instead, the mixing of freshwater with seawater occurs in the open sea. *Lagoonal estuaries* form where the inflow of fresh water is small. Lagoons are usually formed parallel to the coast and are in appearance more like a lake than a river. The more modest freshwater inflows may be limited to seasonal pulses, brought by rainfall. Salinity in a lagoon may be high throughout the basin in the dry season and low in the wet season. The patterns of mixing of fresh and seawater in a lagoonal estuary produce habitat zonations different from those seen in river mouth estuaries. Lagoons are typically uniformly shallow—usually only a few meters deep—and clear. As a result, light penetrates to the bottom, creating conditions where rooted plants can flourish. Many lagoons are therefore carpeted by seagrasses. As the water volume in lagoons is generally small, a modest change to freshwater inflow may have a significant impact on their ecology.

III. THE IMPORTANCE OF ESTUARIES

WHAT IS AN ESTUARY?

Estuaries are semi-enclosed coastal bodies of water which have a free connection with the open sea and within which sea water is measurably diluted with freshwater from land drainage (Pritchard, 1967). Estuaries may be classified in different ways (**Box 2**). At the simplest level, there are two types of estuaries—river mouth estuaries and lagoonal estuaries. Both provide important services to people.

Since the dawn of history, people have congregated along rivers, and in particular, at river mouths. Many estuaries are hubs of commerce and trade. As places of great beauty, estuaries strongly influence the high value of waterfront property and provide for a diversity of economically important recreational activities. They provide valuable open space in coastal towns and cities. The rich soils and abundant freshwater in the deltas of rivers make for some of the world's best farmland. Estuaries and their associated wetlands also serve as storm buffers that absorb wave energy and rising tidal waters during storms.

ESTUARIES ARE FOOD FACTORIES

Estuaries play a unique role in the functioning of life on this planet. They are also critical habitats to many species of fish, shellfish, birds and marine mammals. They are nurseries for many species of fish that are harvested in the open sea and are, therefore, important to the food security of many countries and regions. In temperate regions, some three-quarters of all commercially important marine fish depend upon estuaries at some stage in their life cycle. Estuaries therefore play a critical role in the generation of protein-rich fish and shellfish. In many parts of the world, communities living near estuaries depend upon them for their food and livelihoods.

At the base of all food chains are the plants that combine the energy in sunlight with carbon dioxide and nutrients to produce organic matter and oxygen. In estuaries, as in other aquatic systems, the bulk of the primary (plant) productivity is generated by microscopic floating plants known as phytoplankton. Estimates of the annual primary productivity of terrestrial and aquatic ecosystems (**Table 1**) demonstrate that estuaries are among the most productive (Schlesinger, 1997; O'Reilly et al., 1987; Nixon et al., 1986; Mann, 2000). Only intensively cultivated land, where the large volume of crops is made possible by the artificial application of fertilizers and the control of competitors and pests, matches the natural productivity of estuaries.

Estuaries also show by far the highest yields of secondary (animal) productivity (**Table 2**) compared to other aquatic systems and to non-cultivated systems (Nixon et al., 1986; Nixon, 1988). Temperate lakes commonly yield less than 10 kilograms per hectare per year of fish (Ryder et al.,1974; Schlesinger and Regier, 1982; Nixon, 1988). In contrast, intensively fished temperate estuaries commonly yield hundreds of kilograms of fish and shellfish each year from each hectare—a value matched by very few other ecosystems (Nixon, 1988). This high secondary productivity has attracted people to estuaries for thousands of years.

ESTUARIES ARE WASTE PROCESSORS

Estuaries have a high assimilative capacity—that is, the plants, animals and bacteria that are found there quickly break down and recycle organic matter, which leads to the very high productivity that is typical of estuaries. To some degree, the mixing and recycling of organic matter enables estuaries to absorb the human wastewater and byproducts of surrounding cities and towns. The same processes of aeration, microbial

Table 1. Comparison of Average Primary Production of Various Terrestrial and Marine Aquatic Systems Expressed as Annual Net Primary Production per Area of the Water or Land Surface (Grams of Carbon per Square Meter per Year)

†Terrestrial Ecosystems		Aquatic Ecosystems	
Freshwater wetlands	1300	**Rooted aquatic plants**	
Tropical wet forest	800	Seaweed beds*	1000
Temperate forest	650	Seagrass beds*	400
Boreal forest	430	Saltmarsh*	500
Tropical woodland/ savanna	450	**Phytoplankton production**	
Desert	80	Coastal upwelling areas*	420
Cultivated land	760	Estuarine plankton¥	400
		Continental shelves‡	305
		Georges Bank‡	360
		Open ocean*	130

† SCHLESINGER (1997)
‡ O'REILLY ET AL. (1987)
¥ NIXON ET AL. (1986)
* MANN (2000)

Table 2. Comparison of Average Secondary Production of Various Terrestrial and Aquatic Systems Expressed as Annual Yield of Animals per Area of the Water/Land Surface

Ecosystem type	Yield of animals (fresh weight) kg ha-1 yr-1
Estuaries	100-500
Ocean Upwelling	~250
Seas	30-60
Prime Fishing Grounds	~160
Coral reefs	5-50
Lakes	1-10
Non-agricultural terrestrial systems	0.5-50

NIXON ET AL., 1986; NIXON, 1988, RYDER ET AL.,1974; SCHLESINGER AND REGIER 1982.

processing of organic matter, and settling of residual organic material are the dominant features of modern municipal treatment plants. Because of this high "assimilative capacity," estuaries and their associated wetlands have been described as the kidneys of coastal ecosystems. Estuaries also serve as the buffer between terrestrial and oceanic systems, capturing and processing the many substances that flow from the land to the sea. The chemical behavior of many pollutants (such as heavy metals) changes when they meet seawater. They quickly interact with other substances and may become less biologically available and sink to the bottom where they are buried and removed from living systems. This change in chemistry has many implications for various human activities, such as dredging, because such disturbance of estuary sediments can remobilize buried pollutants and—especially if they are placed on the land and back into a freshwater system—make them biologically available again.

IV. FRESHWATER: THE LIFEBLOOD OF ESTUARIES

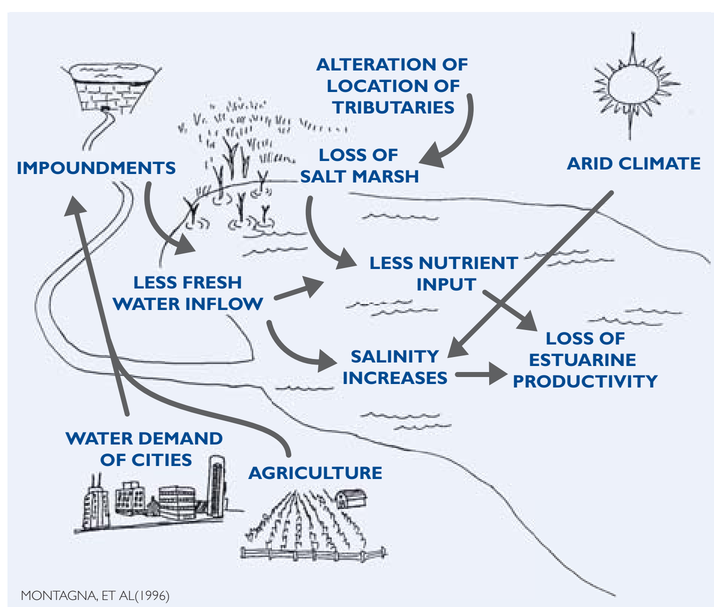
Freshwater is an estuary's lifeblood. The high-protein output of estuaries is the product of the inflow and mixing of freshwater in a unique combination of physical, chemical and biological functions working in unison to make estuaries extremely productive of plant and animal life (**Figure 1**).

Each estuary is at the "bottom" of a catchment and drains a land area tens to thousands of times larger than the estuary itself. The semi-enclosed shape of an estuary funnels and concentrates the freshwater flowing from this large landscape, and the sediments, nutrients, and other materials carried along with it. These processes are described below.

NUTRIENTS

Rivers carry into estuaries a variety of nutrients that are necessary for the growth of aquatic plants that in turn support aquatic animals. The nutrients most critical to plant productivity—nitrogen, phosphorus and silica—are carried to the estuary by freshwater inflows. Freshwater inflows also contribute to the productivity of estuaries by bringing dissolved gases and food to sessile estuarine plants and animals (i.e., plants and animals that remain fixed in place, generally rooted or otherwise attached to the bottom). This energy subsidy is important in sustaining intertidal marshes and mangrove forests as well as dense meadows of sea grasses and kelp beds. It is also critical for supporting many filter-feeding animals, such as oysters and clams.

Figure 1
Effects of Changing Freshwater Flows to Estuaries



BOX 3: EUTROPHICATION

Without nutrients, there can be no production of plants and animals. But with too much fertilization, tidal and wind mixing in an estuary can be overwhelmed and low oxygen conditions will result. Sewage and agricultural runoff, for example, may enrich estuarine waters with nitrogen, thereby increasing primary production. As the phytoplankton die, sink, and decompose oxygen depletion of bottom water can occur. Unless the bottom water is brought to the surface for aeration, the available oxygen can be consumed, resulting in many undesirable consequences. This process is known as eutrophication, and it severely reduces the values of many estuaries. Common adverse effects of eutrophication are: increased turbidity, loss of submerged aquatic vegetation such as seagrass, harmful algal blooms, and fish kills. The losses in the quality and functioning of an estuary due to eutrophication may result in losses to fisheries, declines in public health, reduction in the recreational value of estuarine waters, and decreases in the value of surrounding real estate.

These natural nutrient inputs are supplemented by the wastes of human populations that typically cluster around rivers and estuaries. The result is that the flow of nitrogen and phosphorus to estuaries is often higher per unit area than the amounts spread as fertilizer on the most intensively-farmed agricultural land (Nixon et al., 1986). The result is the same—very high primary productivity. Although the delivery of nutrients is vital to estuarine production, there is an upper limit to the level of nutrients necessary to sustain balanced production. Excessively high levels of nutrients associated with human activities on land—farming, exhaust emissions, wastewater from homes and businesses—cause eutrophication (**Box 3**), an increasingly pervasive problem in the world's estuaries.

SALINITY

The salinity of water at any geographic point in an estuary reflects the degree to which seawater entering at the mouth of the estuary has been diluted by freshwater inflows. Freshwater has 0 parts per thousand (ppt) of salts and full-strength seawater has about 35 ppt. Estuaries, therefore, generally have salinities that range between these values although some lagoons with very little freshwater input and very high evaporation rates can have even higher salinities—up to 40-45 ppt.

A characteristic of estuaries is a gradient in salinity, with lower salinities near the river head and higher salinities toward the ocean mouth. The salinity gradient plays a major role in determining the distribution of communities of plants, animals, and microorganisms within the estuary. Estuarine species and communities are well adapted to the variations in salinity related to tidal cycles and seasonal rainfall patterns. Relatively few species are adapted for the variable conditions found in estuaries, and as a result, estuaries are not biodiversity "hot spots" like rain forests or coral reefs. On the other hand, varying salinity reduces competition and disease, and this contributes to the high rates of productivity typical of estuarine species.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Another aspect of the salinity gradient and the associated habitats it creates is its role as a transitional habitat for species of fish such as salmon that pass through the estuary during their spawning migrations. These anadromous fish spawn in freshwater but migrate and grow to maturity in seawater. Estuaries enable them to readjust to tolerating low salinity as they swim upstream to spawn. The length and nature of salinity gradients are also important in the physiological adjustments that many larval or juvenile fish experience as they move from rivers out to the sea.

SEDIMENTS

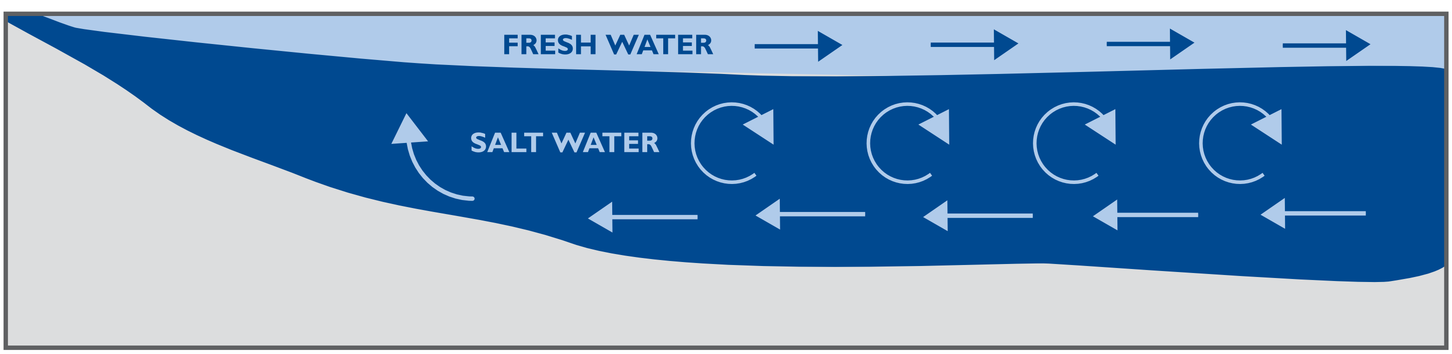
Because the shallows and shores of estuaries are protected from waves and strong currents, and because many estuaries receive large amounts of sediment from rivers and streams, extensive intertidal wetlands often form around their margins. Freshwater inflow carries sediments from the catchment into the estuary. These sediments build and stabilize inter-tidal wetlands, banks and shoals, and may also nourish beaches.

CIRCULATION AND MIXING

The manner in which water circulates in an estuary is unique. Inflowing low-salinity freshwater floats on top of denser seawater below. This low-salinity water flows seaward and a compensating bottom current of seawater flows back up into the estuary (**Figure 2**). This brings extraordinary benefits to planktonic and juvenile animals. Rather than being swept out to sea by surface currents, they are carried back into the protected, food-rich nursery once they sink towards the bottom. Estuarine circulation, therefore, plays a central role in making estuaries a nursery for a very large proportion of the marine fish consumed by people, by acting as a conveyor belt that retains plankton and juvenile animals within the estuary. Alteration of freshwater inflows can change the circulation pattern, thereby affecting organisms dependent upon the habitats shaped by that circulation.

In estuaries and other shallow areas, wind and tidal currents provide a lot of mechanical energy that mixes the water vertically as well as horizontally. This mixing helps to deliver food to sessile animals. Where such vertical mixing is weak or absent, as in lakes or the deep ocean, animals must expend much of their energy actively seeking food and cannot form dense colonies or reefs. The strong mixing of bottom water with surface water is one reason why estuaries contain densely packed beds of shellfish and high densities of other animals.

Figure 2
Typical Two-Layer Estuarine Circulation
Fresh, less dense water flows seaward over the denser landward flowing salty bottom water. Some of this salt water is entrained with the seaward flowing fresh water.

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V. THE IMPACTS OF ALTERING FRESHWATER INFLOWS ON ESTUARIES AND HUMAN COMMUNITIES

Humans influence the movement of water through the hydrologic cycle in a variety of ways. Water is withdrawn from rivers, lakes, and ground water aquifers for a myriad of uses. Water is stored in reservoirs to generate electricity, control floods, and provide water supply. Some portion of the water used in cities, farms, or industries may flow back to a river, but in many cases it returns in a different condition at a different time, or in a different part of the catchment. All of these human modifications to the hydrologic cycle affect the quantity, quality, and timing of water flows through rivers and into estuaries. Water managers face a difficult challenge in keeping track of these many uses of water and managing them to meet the diverse needs of society while maintaining the health and benefits of natural systems.

Complicated interconnections exist between the quality, quantity and timing of freshwater inflows and the health of estuaries. A small change in inflow may affect the fundamental functioning of an estuary, which in turn will have ramifications on the biota (animals and plants) and on human cultures dependent upon the estuary. The cascade of effects brought about by altered freshwater inflows is often unexpected because few people understand how these systems function, even though they may appreciate the value of the benefits they generate.

The complexity and small size of estuaries makes them particularly susceptible to human impacts. Once key habitats are lost, they are difficult or impossible to restore. The major issues posed by freshwater inflow management are described below. **Table 3** summarizes the effects of the most common types of alterations to freshwater inflows.

ALTERED QUANTITY AND TIMING OF FRESHWATER INFLOWS

Water development projects can alter the delivery of freshwater to estuaries in three ways (**Box 4**). In the majority of cases, the change is seen as a reduction of freshwater volume. Reducing freshwater inflows can reduce the effective size of an estuary, and amplify the impacts of pollution, overfishing and habitat destruction. Human interventions may also result in an increase to freshwater inflows, brought for example by trans-basin diversions of water, which can impact estuarine organisms adapted to the original flow and salinity conditions. Deforestation, the conversion of natural lands to agriculture, and poorly planned urban development can all cause an increase in freshwater inflows to estuaries when these land use changes result in a higher volume of stormwater runoff, with less going to groundwater recharge and evapotranspiration.

Also vitally important to the functioning of an estuary is the timing of freshwater inflows because estuarine organisms have evolved over long periods to particular regimes of freshwater inflow and associated biogeochemical conditions

Table 3. **The Potential Effects of Common Alterations to Freshwater Inflows to Estuaries**

TYPE OF CHANGE TO FRESHWATER INFLOW	POTENTIAL IMPACTS ON ESTUARY FUNCTIONS	POTENTIAL HUMAN IMPACTS
Water Quantity (Possible drivers of change in quantity include surface withdrawals and diversions, dams, groundwater use, and drought).		
Reduction in quantity (volume) of freshwater inflow.	• Increased salinity; die-offs of salinity-sensitive plants; introduction of predatory marine animals into the estuary; reductions in sessile shellfish populations; reductions in salinity-sensitive fish. • Reduction of natural nutrient inputs; reduced plant and animal productivity. • Reduced sediment recharge; loss of wetland habitat. • Less estuarine flushing; increased potential for eutrophication and other human-causes pollution impacts.	• Reduced harvests of economically important fish and shellfish. • Changes for estuary-dependent human populations including loss of livelihood for fishing communities. • Reduction in area of habitats with tourist appeal. • Reduction in recreational value of waters and in real-estate value of surrounding lands.
Increase in quantity (volume) of freshwater inflow.	• Reduced salinity; die-offs of salinity-sensitive plants; drastic reductions in sessile shellfish populations; reductions in salinity-sensitive fish. • Increase in nutrients and sediments • Reduction in spatial extent of important benthic habitats (e.g., seagrass beds).	• Reduced harvests of economically important fish and shellfish. • Changes for estuary-dependent human populations including loss of livelihood for fishing communities.
Altered pulsing (timing and volume of inflows).	• Destruction or degradation of habitats that are adapted to seasonal pulses of freshwater and seasonal changes in salinity. • Reductions in population of organisms adapted to seasonal pulses of freshwater.	• Reduced harvests of economically important fish and shellfish. • Changes for estuary-dependent human populations including loss of livelihood for fishing communities. • Reduction in area of habitats with tourist appeal.
Water Quality (Possible drivers of change in quality include agriculture, industrial activity, urbanization, pollution and dredging).		
Increased levels of nitrogen, phosphorus or silica in incoming waters.	• Eutrophication. • Anoxic or hypoxic waters.	• Die-offs of economically important fish. • Loss of recreational and tourist appeal of estuary (in terms of swimming, fishing, boating). • Reduction in real-estate value of lands surrounding foul-smelling waters.
Increased levels of chemical, heavy metals, or other toxic contaminants.	• Concentration of pollutants in the food chain. • Reduction in spatial extent of important ecological habitats. • Reduction in population of organisms unable to tolerate pollution loads.	• Die-offs of economically important fish. • Loss of recreational and tourist appeal of estuary (in terms of swimming, fishing, boating). • Reduction in real-estate value of lands surrounding waters. • Adverse human health effects (e.g., from ingestion of contaminated fish and shellfish).
Changes in basin morphology (as a result of dredging of sedimentation).	• Altered residence time of freshwater in the estuary; changed flushing time and longevity of pollutants in the system. • Change to water quality (especially if polluted sediments are disturbed and pollutants are mixed again into the water column). • Changes in sediment transport and deposition patterns within the estuary and to the coast.	• Die-offs of economically important fish. • Loss of recreational and tourist appeal of estuary (in terms of swimming, fishing, boating). • Reduction in real-estate value of lands surrounding waters. • Increased beach erosion.

BOX 4: ALTERATIONS TO FRESHWATER INFLOWS

Water development projects can alter the delivery of freshwater to estuaries in three ways:

Quantity. The total amount of freshwater flowing to the estuary may be changed. Reducing, and in some cases eliminating these flows is the result of surface water diversions upstream for human use or storage, over-abstraction of groundwater, or changes in land management and land cover that alters surface runoff patterns. Similarly, freshwater inflows may increase when urbanization reduces the absorption of rainwater into the ground and wetlands or when water from one catchment is transferred into another.

Pulsing. (timing and volume variability). River flows fluctuate seasonally, being higher during the "wet" season and lower during the "dry" season. Humans can influence freshwater pulsing by storing (and releasing) water behind dams for flood control, water supply for agriculture, drinking water, or the generation of electricity.

Quality. Human activities can be the source of significant levels of estuarine pollution. Both point and non-point sources of chemical contaminants, pathogens, or excess sediment and nutrients are of concern. The storage of water behind dams or use in power generation (hydroelectric or other) facilities also influences the chemistry and temperature of the water passing through them (Vörösmarty et al., 1997; Ittekkot et al., 2000; Nixon, 2003; Postel and Richter, 2003).

(Montagna et al., 2002). Land use changes, in particular the losses of wetlands and other areas that absorb and store groundwater, can alter a catchment's runoff behavior and increase seasonal variation. In these circumstances, dry season flows are usually reduced and rainy season inflows are amplified.

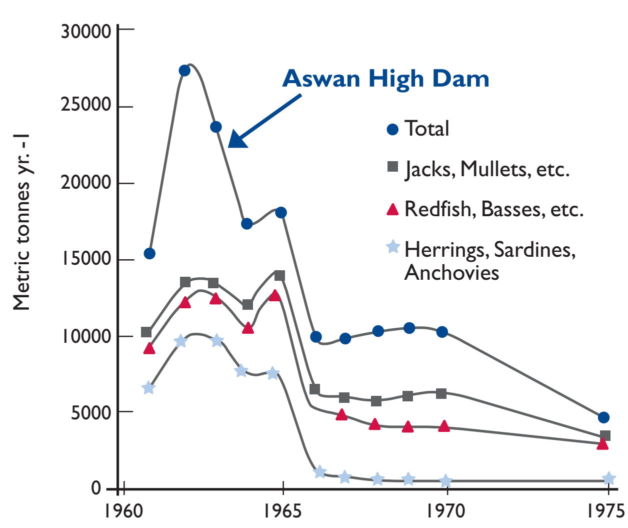
In many cases, upstream alterations to the volume and timing of freshwater inflows have resulted in catastrophic destruction of downstream habitats, losses of species and degradation of ecosystems adapted to a certain range of freshwater inflows. **Figure 3** depicts the decline in fish landings from Egypt's Mediterranean coast after the building of the Aswan High Dam. Similar impacts at smaller scales frequently go unrecorded. In many cases, small rivers and streams that flowed year-round a few decades ago now only flow in the rainy season. The impacts of such change are of great local importance to coastal communities, profoundly affecting the livelihoods of many people, most notably those who are most impoverished. These changes also affect the diets and nutritional health of people for whom fish and shellfish are no longer available. The cumulative impacts of these changes are often of national and regional importance.

IMPACTS ON MIXING AND SALINITY GRADIENTS

Freshwater inflows also play a key role in mixing estuarine waters. When freshwater inflows are depleted, salinity conditions can change markedly, leading to the disappearance of species dependent upon the lower-salinity conditions of estuaries. On the other hand, large inflows of freshwater, such as when an inter-basin transfer brings additional water into an estuary's catchment, can "put a lid" on the estuary that separates the saltier bottom waters from the atmosphere. The nutrients carried into the estuary by freshwater can, under conditions of reduced mixing, lead to low oxygen (hypoxia) or absence of oxygen (anoxia) in bottom waters. This, in turn, may result in the death of aquatic organisms and other undesirable consequences (Rabalais and Nixon, 2002). Mixing by the tides and wind usually prevents this from happening. However, when inputs of freshwater are very large and tidal currents are weak, or when there are prolonged periods with little or no wind, episodes of hypoxia or anoxia may occur.

Salinity gradients act as effective barriers to predators, parasites and diseases. This is especially important where estuaries function as nurseries for a variety of species. Species living in

Figure 3
The Fall in Fish Landings Immediately After the Construction of the Aswan High Dam



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BRIAN RICHTER

the fresh tidal portion of rivers and wetlands just above the reach of salt water may be especially sensitive to the higher salinities that result from upstream water diversions. For example, oysters and shrimp require low salinities to spawn successfully. Certain species of underwater grasses are adapted to salinities from 0-5 ppt. If habitats with suitable salinity are reduced or destroyed by changes in quantity or seasonality of freshwater inflow to an estuary, a drastic decline in the populations of these commercially viable species may be the result. Another, often unexpected result of a change in the salinity gradient is the intrusion of predators. Some parasites or predators that prey on oyster populations can become over-abundant if salinity variations created by pulses of freshwater inflows do not keep them in check.

IMPACTS ON THE RESIDENCE TIME OF WATER IN AN ESTUARY

The time that water spends within the estuary is known as the residence time, or flushing time. Residence time is a function of the volume of the estuary divided by the rate at which water is added from rivers or exchanged with the sea. Ecologists and managers are often very concerned with the flushing time of estuaries because systems with slow flushing are more susceptible to impacts from pollution. The flushing time or residence time of an estuary varies with the discharge of freshwater into the system and with changes to the physical shape of the estuary brought about, for example, by channel dredging.

As freshwater inflow increases, the flushing time decreases. Diverting freshwater from estuaries during times of seasonal low flow may dramatically increase the flushing time. Changes in the flushing time of an estuary may impact the ecology of the system in a variety of ways. For example, longer flushing times will increase the concentrations of anthropogenic pollutants, including pathogens. The two-layer circulation of water within the estuary may be weakened and reduce the inflows of offshore bottom water. If nuisance algal blooms intensify and oxygen concentrations decline, eutrophication may result. The proper functioning of estuarine ecosystems depends on the balance between inputs, residence time, and export.

If there is less flushing, the potential also exists for increases in the populations of pathogens that could increase the spread of human diseases. Fish and shellfish that have accumulated toxins from water may not be fit for human consumption. Waters polluted with wastes are not suitable for swimming or other forms of recreation. Any change that affects the aesthetics of an estuary can affect real estate values. Tourism downstream may also be severely affected by upstream changes in freshwater flow.

The typically slow exchange of waters with the sea in lagoonal estuaries makes them especially vulnerable to overloading with pollutants and their shallow, productive waters are easily over-fished. Their large benthic (bottom-dwelling) communities are also particularly sensitive to pollution and sedimentation because of the shallow depth typical of these estuaries. The exchange with the sea in lagoonal estuaries is likewise easily altered by human engineering projects. For example, to ease the passage of boats between the lagoon and the sea, and to speed the flushing of polluted water, channels are often dredged across lagoons and permanent inlets are constructed. These channels alter estuarine salinity, hydrology and ecology. The resulting losses in fisheries and accelerated sedimentation in the lagoon brought by strong currents flowing through the artificial inlets too often come as a surprise to both engineers and local communities.

IMPACTS ON SEDIMENT INFLOWS

Altering freshwater inflows to estuaries may change the sediment load carried into the estuary and the coast (Vörösmarty et al., 1997; Ittekkot et al., 2000; Nixon, 2003). Reduced sediment loads may lead to erosion of banks and shoals that would otherwise be replenished with sand and silt; erosive effects may be observed on coastal beaches that depend on the sediments brought by freshwater for their maintenance and "nourishment." Inter-tidal wetlands, such as mangroves, which act as nursery areas for many fish species, may deteriorate without sufficient recharge by nutrient-rich and stabilizing sediments. This, in turn, could lead to reductions in populations of animals (including many commercial species) that depend on the shelter provided by these wetlands during sensitive and early stages of their lifecycle.

OTHER THREATS TO WATER QUALITY

As noted above, changes to the volumes and seasonal pulsing of inflows can themselves have major impacts on water quality. In addition, discharges of pollutants within the catchment, along the shores of the estuary or within the estuary itself can all impact water quality and ecosystem function. Historically, concerns over water pollution have focused initially on "point" sources. These are the readily identifiable discharges from a factory, mine or sewage treatment plant. In many instances, however, the diffuse "non-point" sources that accumulate from agricultural practices, urban runoff, and are carried by the atmosphere have proved to be equally or more important. These non-point sources of pollutants are far more difficult to regulate and control.

VI. A METHODOLOGY FOR INTEGRATING SCIENCE AND GOVERNANCE IN THE MANAGEMENT OF FRESHWATER INFLOWS TO ESTUARIES

Much has been written on how to integrate science and address governance in water resource management, and approaches for the incorporation of the water needs of natural ecosystems into decision-making processes (Davis and Hirji, 2003a, b; Dyson et al., 2003; Postel and Richter, 2003). This Methods Guide draws on these writings, particularly the successes and failures in applying IWRM and ICM practices in the United States and in countries in Latin America, Southeast Asia and East Africa.

The approach described in this Guide combines two dominant threads in the practice of managing any large ecosystem (Lee, 1993). The first is a governance process that works to understand and communicate the interests of the many upstream and downstream stakeholder groups in a linked watershed and estuary ecosystem. The governance process involves the negotiation of plans and policies and the subsequent decision making, monitoring, education and enforcement. The central goal is to create and sustain a *governance process* that is just, transparent and accountable to those affected by its actions. The emotions released by debate over values and different interpretations of the available information can produce conflicts that must be carefully managed to keep communications open and productive. In the governance process, the values, beliefs and views of individuals and groups are central and the differences can generate misunderstandings and conflicts.

Good governance must, in turn, be supported by the generation and incorporation of *reliable knowledge* that allows affected stakeholders and the project team to better understand, and forecast, the consequences of different courses of action. Such knowledge does not flow only from "the sciences;" it embraces traditional knowledge and the observations of people who know the systems of which they are a part. When a program's policies and actions are based upon clearly-stated hypotheses, and evaluated using suitable indicators, the resulting plans and actions can be viewed as experiments that can inform management improvements over time. This is the heart of adaptive management as used to improve governance.

Effective governance of an estuarine system can emerge and evolve in many different ways. The method offered here for assessing and managing freshwater inflows to estuaries begins with an analysis of problems and opportunities (Step 1; **Table 4**). It then proceeds to the formulation of a course of action (Step 2). Next is a stage when stakeholders, managers, and political leaders commit to new behaviors and allocate the resources by which the necessary actions will be implemented (Step 3). This involves formalization of a commitment to apply IWRM and the allocation of the necessary authority and funds to carry it forward. Implementation of the actions is Step 4. Evaluation of successes, failures, learning and a re-examination of how the issues themselves have changed rounds out a "generation" of the management cycle as Step 5. This conceptually simple cycle (**Figure 4** and **5**) is useful because it draws attention to the interdependencies between the steps within each generation and between successive generations of management. Progress and learning are greatest when there are many feedback loops within and between the steps (GESAMP, 1996; Olsen et al., 1997, 1999).

Table 4. Outline of the Essential Steps of the Approach Described in this Guide

Although the table presented below gives the appearance of a linear process, the reality is that the actions associated with each step often occur simultaneously or in a different order. Learning must be on-going between the project team and partners to help strengthen linkages among activities throughout the process.

STEP 1. IDENTIFY ISSUES AND BUILD CONSTITUENCIES	
a. Characterize historic and anticipated changes to freshwater inflows	• Conduct a hydrologic assessment of the river basin to assess trends in water use and changes in the volume and timing of freshwater inflows to the estuary. • Identify water uses within the basin that are having greatest influence on freshwater inflows to the estuary.
b. Identify stakeholders and their concerns	• Engage with key groups in the catchment and estuary and strive to build mutual respect and trust between them and the team. • Probe and understand the range of stakeholder perceptions of ecosystem change, past responses and trends in the condition and use of estuarine resources. • Select the VECs that may be threatened by altered freshwater flows. • Define the boundaries of the major issues and the interconnection among issues.
c. Evaluate potential future impacts to valued ecosystem components	• Construct conceptual models linking changes in freshwater inflow to key habitat conditions and species. • Evaluate the strength of quantitative flow-ecology relationships and their potential for predicting the ecological consequences of changes in water management.
d. Assess the existing management system	• Trace the impacts of past catchment and estuary uses and assess planning and decision making processes to evaluate the management capacity of the relevant institutions. • Assess the strengths and weaknesses within existing institutions as they relate to the practice of adaptive ecosystem management; specify the knowledge and skills required to successfully practice linked catchment-estuary management.
e. Determine the scope and focus of further analysis	• Review the significance of the issues identified. • Identify the most important uncertainties, knowledge gaps and set priorities for further consultation, monitoring and assessments. • Determine the geographical boundaries that limit the scope of further issue analysis and monitoring. • Assemble and distribute a Level One Profile as an initial statement on the initiative's issue-driven approach and purpose.
STEP 2. FORMULATE IWRM POLICIES AND STRATEGIES FOR THEIR IMPLEMENTATION	
a. Set goals with the stakeholders	• Work with the stakeholders to define the desired societal and environmental outcomes that constitute the goals of an integrated catchment–estuary management initiative.
b. Conduct targeted data collection and research	• Probe unknowns and uncertainties posed by potential changes in freshwater inflow to the estuary (as identified in Step 1).
c. Build scenarios	• Prepare scenarios to highlight the likely consequences of different courses of action and strengthen constituencies for a management initiative. • Use the scenarios as a means for discussing alternative courses of action with the institutions that will be involved in implementing a plan of action. • Socialize the results of the research and its implications. • Verify, correct, and refine freshwater management issues and their implications with stakeholders at the local and national level and identify additional issues if any. • Encourage dialogue between scientists/experts and local communities and stakeholders at all levels on the needs and benefits of an action plan.
d. Experiment and monitor	• Experiment with elements of a potential plan of action and new management regime, at a pilot scale. • Begin the implementation of a long term monitoring strategy that will document future change relevant to the stated goals. • Assemble and distribute the findings as a more complete Level Two Profile.
STEP 3. NEGOTIATE AND FORMALIZE THE GOALS, POLICIES AND INSTITUTIONAL STRUCTURES FOR FRESHWATER INFLOW PROTECTION	
a. Win formal endorsement of policies for freshwater inflow protection	• Gain support of authorities and select policies and rules for freshwater inflow protection. • Win the formal commitments necessary for the implementation of the plan of action. • Define and obtain the permitting, convocation and/or adjudication authorities that are needed to implement the plan of action. • Join with the appropriate governmental authorities to present and refine the proposed plan of action to stakeholders.
b. Select the institutional structure for IWRM policy implementation	• Select the governance instruments that will promote an advance towards the initiative's goals.
c. Secure the funding required for sustained implementation	• Estimate the funds will be needed to implement the plan of action. Distinguish between long term core funds and funds for specific shorter-term actions. • Secure the funding for an initial phase of implementation.

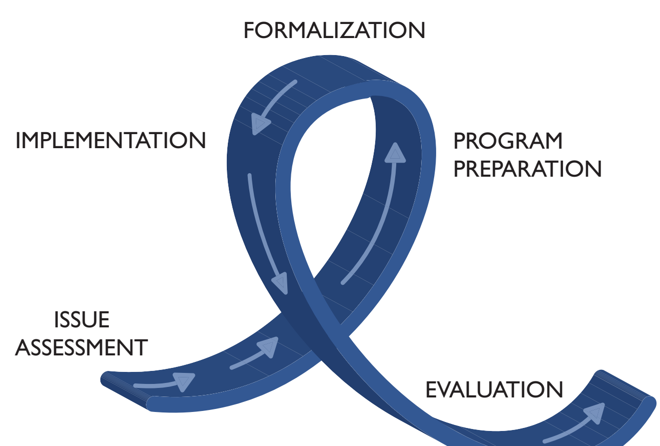
STEP 4. ADAPTIVELY IMPLEMENT THE IWRM PROGRAM	
a. Assess the degree to which the preconditions to implementation have been met	• Program goals. • Engaged constituencies for IWRM. • Commitment to action. • Capacity to implement the program.
b. Instigate changed behavior within institutions of government and NGOs	• Implementation of the plan of action through inter-institutional collaboration. • Enforcement of new rules and procedures in the field.
c. Instigate changed behavior of resource users	• Voluntary compliance with rules and procedures.
d. Instigate changes in financial investments	• Reconsideration of investments in infrastructure that increase the demand for freshwater. • Funds secured for long term implementation of the plan or program.
e. Monitor and practice adaptive management	• Monitor changes in freshwater inflows and valued ecosystem components (VECs). • Monitor freshwater inflows. • Monitor freshwater and estuary water quality. • Monitor changes in the VECs. • Monitor the behaviors that signal program implementation. • Adapt program policies and priorities accordingly.
STEP 5. EVALUATE THE PROGRAM AND LEARN FROM THE RESULTS	
a. Performance evaluation	• Assessments of the quality of execution.
b. Outcome evaluation	• Evaluations of environmental and social impacts. • Self assessments of learnings, changes in context, needs for adaptation.

These five steps (**Table 4**; Figure 5) may be completed in other sequences, as for example, when an initiative begins with enactment of a law (Step 3) that provides the mandate for analyzing issues and developing a detailed plan of action (Steps 1 and 2). Altering the sequence, however, often comes at the cost of efficiency, as when it becomes apparent that the authorities provided by the law prove to be inadequate for implementing the actions that are required.

An initiative to apply IWRM principles to conserve or restore freshwater inflows to an estuary may be triggered in a variety of ways. In some cases, a proposal to build a dam or to reallocate freshwater among users in a catchment may require an impact analysis and a planning process within the responsible governmental agencies. In other cases, the impulse comes from outside of government when members of the scientific community or those who believe that they may be affected by a redistribution of freshwater decide that they will press for an assessment or revisions to the existing water management system. A third possibility is that the degradation of the qualities of an estuary produces a demand for an analysis of the causes and a plan of action to correct existing problems. Whatever the trigger, the initiation of an IWRM effort that addresses the impacts of altering freshwater inflows to an estuary should prompt the formation of a team of people with the leadership and the energy to assess the issues and, if necessary, advocate for the implementation of IWRM policies and procedures that can respond effectively to identified problems.

The holistic nature of IWRM, and the need to understand the dynamics of water flows and water uses in the catchment, the uses and functioning of the estuary, the institutional dimensions of water management, as well as the politics of the issues at stake require a team with capabilities in these diverse fields. The inclusion of a coastal and marine system in the analysis and planning adds a layer of institutional and ecological complexity and requires a broader range of expertise than is typical in freshwater-focused IWRM. In this paper, we refer to this group as "*the project team.*" Ideally, the team will include individuals with expertise in estuarine ecology, hydrology, economics, and the traditions of governance in the locale. Depending upon the size of the ecosystem, the perceived significance of the issues

Figure 4
The ICM Policy Cycle



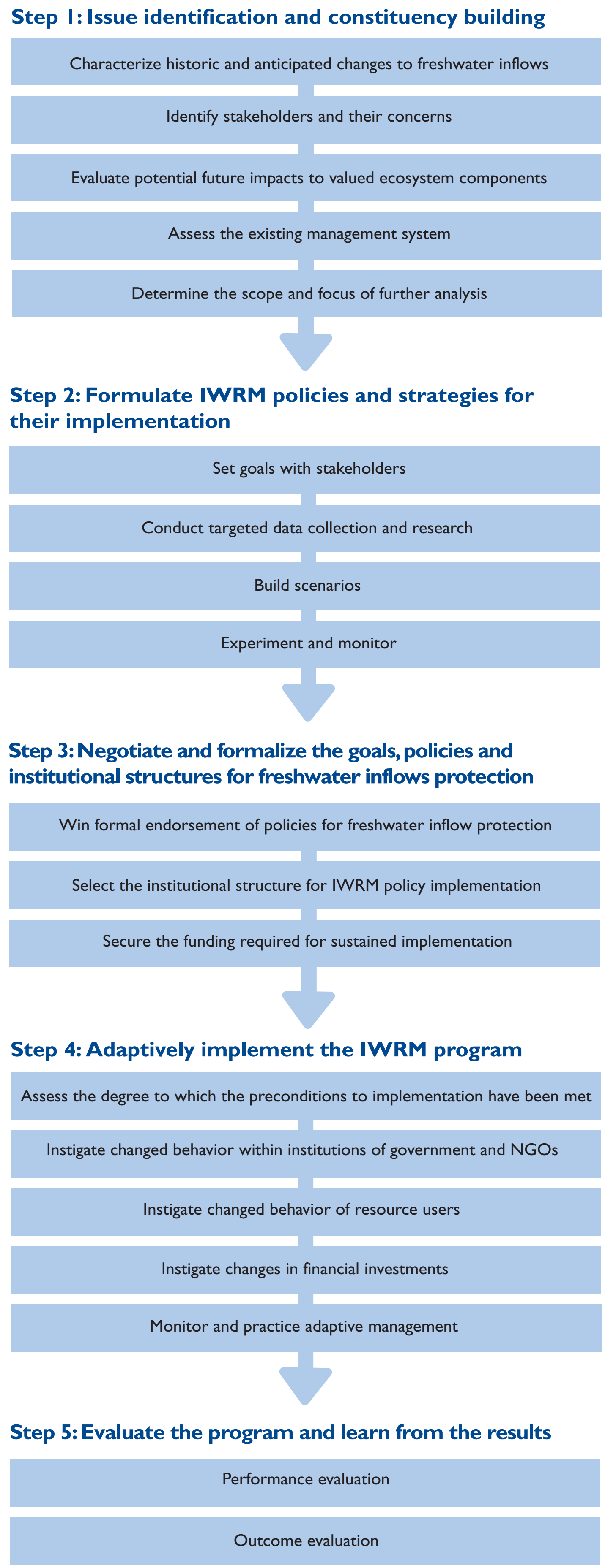
GESAMP (1996); OLSEN ET AL. (1997), (1999) posed by changes in freshwater inflows, and the capabilities of the individuals involved, "the team" may be no more than an informally constituted group of concerned citizens or a highly qualified, formally constituted expert team with dedicated funding. The methodology offered in this Guide for analyzing, planning and implementing a linked catchment-to-estuary IWRM program can be adapted to the full range of such situations.

When an IWRM initiative is being considered, an initial task for the project team is to identify which of the five steps most closely matches the current situation in their locale. The team's priorities should be different if the consequences of altering freshwater inflows to the estuary are known and the need is to influence the actions of an on-going program (Step 4), as compared to situations where the consequences of a change to inflows requires careful analysis (Step 1). Similarly, the actions most appropriate at a time of debate and decision-making within government on the policies and institutional framework that will guide future water management (Step 3) may suggest that rapid and highly strategic action on one or two key issues is most appropriate. The most tractable situation is when the governmental agencies responsible for the management of freshwater and the estuary are engaged in a planning and policy formulation process and have allocated the necessary resources. In this case, the project team will have a mandate and resources and all the steps outlined in this Guide can and should be followed sequentially.

A rule of all sound ecosystem-based planning and decision-making is that the issues, goals and strategies for a specific place must be viewed within the context of the next larger system. This larger context may be the province (or state) or, in the case of large estuaries with very large catchments, the nation or region within which the team is working. Events at these larger scales will have a major influence over the project team's prospects for applying new policies and procedures to water management within an individual estuary and its catchment. The prospects for an IWRM initiative that requires a high level of cooperation among several governmental agencies will be strongly influenced by the traditions and culture within the governmental agencies concerned and the presence or absence of inspired leadership in key positions.

Some freshwater or estuarine resource users may have a disproportionate degree of influence compared to others. Changes in governmental administrations from one party or political philosophy to another have the potential to cause major setbacks or advances to an IWRM effort. The progress that can be made, and the strategies adopted to achieve IWRM goals must therefore be tuned to the political climate and recognize that other issues are competing for attention in a given country at a given time. The project team must therefore keep itself well informed of events at these larger scales.

Figure 5
Flow Chart of the Approach Described in this Guide



BOX 5: EXAMPLES OF METHODOLOGIES TO ASSESS FRESHWATER REQUIREMENTS OF ESTUARIES

Estimating the effects of altered freshwater inflows to estuaries to effectively manage flows to sustain estuary health is a complex topic that has been approached from different perspectives. For example:

- In the United States, there have been at least two major compilations of research on the topic of freshwater inflow. A symposium convened in 1980 in San Antonio, Texas addressed "Freshwater Inflow to Estuaries" (Cross and Williams, 1981). The goal of the symposium was to identify potential solutions and recommendations to deal with the issues of altered inflow regimes. A second symposium was convened in 2001 in St. Petersburg Beach, Florida entitled "Freshwater Inflow: Science, Policy and Management" (Montagna et al., 2002). The second symposium is notable because in the intervening 21 years between the two conferences, many agencies began to implement freshwater inflow rules and regulations, performed research on the effects of the rules, and even attempted to restore estuaries where inflow was reduced. There are several detailed case studies in the 2002 volume for estuaries in Australia, South Africa and the United States (Montagna et al., 2002).

- The Water Resources Commission of South Africa published an integrated modeling approach to the problem (Slinger, 2000). Five models for the freshwater requirements of estuaries were identified and linked. The linked models were applied to two South African estuaries to simulate the downstream responses to a range of inflow scenarios.

- Pierson et al. (2002) prepared a detailed report that addresses the freshwater requirements of estuaries. The focus of this report is Australia, but the methods described may be adapted to estuaries in other nations. A methodology is developed to determine the level of threat to an estuary and the amount of flow necessary to maintain normal estuarine functions, identify gaps in the data, evaluate the effectiveness of flow criteria, and implement environmental flow requirements. This is a comprehensive report which focuses on the ecological effects of changing freshwater inflows to estuaries.

VII. PLANNING FOR THE MANAGEMENT OF INFLOWS TO AN ESTUARY: STEPS 1 THROUGH 3

STEP 1: IDENTIFY ISSUES AND BUILD CONSTITUENCIES

It is essential to recognize that any IWRM process that unites a catchment to its estuary will require governmental endorsement and must win support among the people of the place if it is to be implemented successfully. Therefore, a key feature of this approach is that future governance of the ecosystem must be rooted in developing with the people of the place and with responsible governmental agencies, a full appreciation for the past and current conditions and the social and bio-physical processes that have shaped them.

Integrating management of a catchment with the management of an estuary is particularly difficult because the major user groups or stakeholders most directly affected by changes in freshwater allocation may live and work in places at a great distance from one another. They may be unaware of the linkages between, for example, deforestation in the upper catchment or the construction of a dam on the future abundance of shrimp or the condition of the mangroves in a far-away estuary. Similarly, the governmental agencies responsible for managing conflicts and allocating freshwater in the catchment may have had no relationship with the agency responsible for the management of an estuary. Forging new relationships requires identifying common interests and building trust. This may be both difficult and time consuming. Identifying management issues of joint concern is a constructive first step to finding such common ground.

The project team should begin by assuming that considerable information exists on the catchment and estuary being addressed, including information held by inhabitants and users of the ecosystem. The first priority for a project team is to compile existing information on historical trends in the condition and activities of the catchment and its estuary, and on the management issues posed by changes to freshwater inflows. Low-cost data collection and research may be needed to augment pre-existing information. While the emphasis is on identifying the societal and environmental issues raised by changes to freshwater inflows, the initial profile must place these issues within their larger context of trends in the use and development of the entire ecosystem. This synthesis of existing information and knowledge on important management issues should be presented and distributed as a "Level One Profile." The key questions to be addressed in this Level One Profile document are presented in **Box 6**.

Depending upon the geographic scale and complexity of the project area and resources available, a project team will typically apply a mix of the following techniques to conduct the analysis:

- Unstructured conversations with groups and individuals.
- One-on-one interviews with pertinent authorities and stakeholder spokespeople (such as field interviews with knowledgeable fishers).
- One or more structured workshops with people selected for their knowledge and concern for the place.
- A review and synthesis of available secondary information, particularly environmental data.
- Commissioning of a more sophisticated analysis on the status and trends of selected variables.

The following sections describe some of the key elements of the assessment that should be integrated and summarized as a Level One Profile.

Characterize Historic and Anticipated Changes in Freshwater Inflows

As discussed in Sections II through V, the health of freshwater and estuarine ecosystems is intimately linked to the natural variability in water flows and volumes, and sustaining these ecosystems requires maintaining some semblance of those natural flows (Postel and Richter 2003; Longley, 1994). The objective of this initial task is to determine: (1) what the natural variability in the quantity and timing of freshwater inflows has been; (2) whether or not the quantity and timing of freshwater inflows have changed over time; and (3) whether they are likely to change in the future. Completing this first task is essential in building a foundation for everything that follows. If freshwater inflows have not changed and are unlikely to change in the future, there is no reason to continue with the approach described in this Guide.

This task begins by assembling and examining existing hydrologic data, reports, models, and other historical records. Data on water resource availability and use may be available at local or regional water agencies, agricultural institutions, or municipal entities. Depending upon the data available, and the time and resources available to conduct additional

BOX 6: IMPORTANT QUESTIONS TO BE ADDRESSED IN STEP 1

1. Characteristics of freshwater inflows

- Is there a strong natural fluctuation in water flow between seasons or years?
- What are the past and current impacts of human activities on the estuary, its catchment, and freshwater flows?
- How has freshwater been managed in the past and what outcomes resulted?
- How important are changes to freshwater (water use and allocation) compared to other social and environmental issues in this ecosystem?
- What institutions are responsible for managing freshwater in the catchment and what are their capacities to practice ecosystem-based management?
- What changes in the quantity, quality and timing of freshwater inflow have occurred, or are anticipated? What are the potential and future threats to valued ecosystem components (VECs) and estuary health, if any?
- What are the causes of such anticipated changes?
- What are the potential impacts of such change on the goods and services the estuary generates for the associated human population? What are the issues as they relate to the human society, the environment and the governance system?

2. Characteristics of the estuary

- What are the defining characteristics of the catchment and its estuary?
- Is this a negative, neutral or positive estuary in terms of water balance? Does this change seasonally?
- What is the ratio of the area of the estuary to the area of its catchment?
- Is the estuary shallow or deep?
- Are bottom sediments predominantly sand, mud or rock?
- Is circulation weak or strong?
- Is there evidence of eutrophic conditions?

3. Characteristics of the human community

- What are the interests of the various stakeholder groups in the catchment and the estuary? What do they see as the major issues, choices and the outcomes they desire?
- What are the VECs of most importance to the various stakeholders in the basin or coastal area?
- What is the distribution and intensity of human activities in the estuary? Where are the major fishing grounds, access points to the estuary, recreational areas and tourist attractions?
- What is the existing governance framework? How does planning and decision making affecting the watershed and the estuary occur? What is the capacity of this governance system to negotiate and then implement a plan of action that addresses both catchment and estuary issues and the inter-dependencies between the two?
- Overall, have societal conditions around the estuary and for those dependent on the estuary worsened or improved? Why?
- Given the broader context of societal and environmental issues, are anticipated changes to the estuary significant enough to command attention?
- How can the results of this assessment be translated into a strategy?

measurements of hydrologic conditions, different types of hydrologic analysis may be pursued, including assessment of changes in freshwater inflows based on historic records of river flow, construction of a water budget, or development of a catchment hydrology model. The use and need for these different approaches is further described in the following paragraphs.

The best way to gain an understanding of natural inflow characteristics, and human-induced changes in those characteristics, is to examine historical records of river flow. In the "best case" scenario, daily or monthly measurements of river flow will have been taken for a sufficiently long period of time to enable an assessment of changes over time. Ideally, these data will have been collected for a reasonably long period (*e.g.,* 20+ years) near the point(s) of major freshwater inflow into the estuary, and the measurement of flows will have begun prior to the onset of any substantial development of the water resources for human uses that might have significantly altered the inflows to the estuary (*e.g.,* large diversions, dam construction). When such data are available, it is fairly straightforward to characterize the natural inflow characteristics and the nature of any changes to those characteristics over the period of measured inflows. This hydrologic assessment might include statistical analysis of trends in freshwater inflows over time, or it may simply involve a visual examination of hydrographs, such as Figure 6. When examining historical data records, an investigator should look for indications of changes in aspects of the freshwater inflows likely to affect the health of the estuary (**Box 6**).

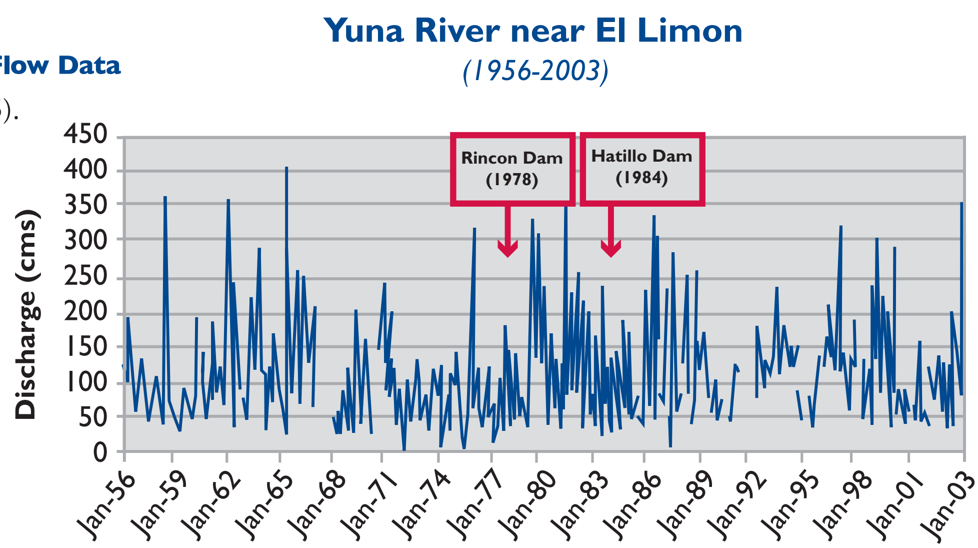
In many catchments draining to estuaries, data records of sufficient length for analyzing changes or trends may not be available, at least not at the major point(s) of inflow into the estuary. Additionally, data records may not have started early enough to provide indications of what the natural inflows might have been. Historical records also cannot tell us how much change might be expected in freshwater inflows in the future, as land and water uses in a catchment change. For these reasons, it will usually be necessary to develop a water budget or a hydrologic simulation model to gain an understanding of how much hydrologic change has occurred, or is likely to take place in the future.

A water budget can be developed to account for the sources and uses of water in a catchment, providing insight into the magnitude and nature of changes in freshwater inflows. Analogous to a bank account, a water budget accounts for all major deposits (inputs) and withdrawals (losses) of water in a catchment; if these inputs or withdrawals have changed substantially as a result of human activities, changes in the "balance" of the water budget will be reflected as changes in the freshwater inflows to the estuary. There are many sources of water inputs to estuaries, including rivers, ground water discharge, direct precipitation on the estuary, diffuse runoff from lands adjacent to the estuary, and perhaps imports of water from other catchments through inter-basin transfers. The primary natural loss of water from a river basin is evapotranspiration, representing the combined loss of water by direct evaporation and plant use. Human uses may include diversions of water for cities, farms, and industries. Some or much of the diverted water may be returned to the river after it is used (*e.g.,* for irrigation or hydropower), and these return flows must be accounted for in a water budget. Additionally, many water uses involve capturing and storing water in reservoirs, which can substantially modify the timing of water flows into downstream estuaries or increased loss of water to evaporation, and these effects also need to be factored into the water budget.

To gain insight into the impact of human water uses on freshwater inflows to the estuary, a water budget will need to be computed for both the "natural" (undeveloped) and "developed" condition. If the potential impacts of future changes in land or water use are of concern, a "future"

Figure 6
Typical River Flow Data

Warner, A. (2005).



scenario can also be evaluated using water budgets. A water budget accounting for all inputs and uses of water can be prepared for an entire catchment, or for only a part of the catchment. It may be desirable to assess a sub-catchment to determine the impact of water uses on an important tributary. Similarly, water budgets can be calculated for an average year, or for wet and dry years to draw comparisons, or they can be computed for shorter duration such as monthly or even daily time intervals.

The appropriate spatial and temporal resolution of a water budget will depend upon the level of accuracy and detail a project team feels is necessary to characterize human-induced changes in freshwater inflows to the estuary. This decision will largely be dictated by the need to understand potential or historical impacts of hydrologic changes on "valued ecosystem components" (VECs) in the estuary, as discussed later in this chapter. Some ecosystem components may be strongly affected by relatively short-term hydrologic events, such as the cessation of freshwater inflows for a short duration during a critical breeding season. In this case, water budgets may have to be computed on a weekly time frame, or even daily. On the other hand, many ecosystem components are dependent upon longer-duration hydrologic fluctuations, such as those that influence salinity gradients in an estuary. In these cases, monthly water budgets may suffice. Therefore, the necessary temporal resolution of hydrologic data or assessments will depend upon the nature of the causal linkages between freshwater inflows and ecosystem components to be evaluated in developing a management plan for the estuary.

The data required to develop a water budget will again depend upon the spatial and temporal resolution desired. However, a first-cut water budget can usually be developed using little to no field-measured data from the catchment of interest, especially if estimates of major variables such as precipitation or evapotranspiration can be estimated from regional climate maps, or from climate monitoring stations located in other catchments. If river flow measurements have been taken anywhere in the catchment, they can be very useful in calibrating or assessing the accuracy of water budget estimates. As a general rule, monthly water budgets should be developed if at all possible, because annual water budgets will not reveal important seasonal variations that can be of great consequence to freshwater inflows.

Hydrologic simulation models are very useful for understanding the temporal and spatial differences in the hydrologic cycle across a catchment. Most hydrologic simulation models are nothing more than computerized water budgets, which are being computed at time scales usually ranging from hours to days to months. Computing water budgets at daily or weekly time intervals can become very cumbersome or unwieldy to generate using spreadsheets or other tabular summaries, given the likely presence of numerous human activities in a catchment that affect water flows in different ways, at different times. Computer models can also simulate time lags in the movement of water through a catchment, such as ground water moving through the soil or a flood moving downstream in large river basins, which are not accounted for in water budgets. Computer models are also particularly useful in assessing the influence of dam operations, in which water is temporarily stored and then released to meet the needs of cities, farms, or industries, to control floods, or to generate hydroelectric power. Dam operations can exert considerable influence on the quantity and timing of freshwater inflows to an estuary.

Regardless of the hydrologic assessment method used by the project team, it will be critically important to also consider potential future uses of water that could induce change in freshwater inflows to the estuary. There will likely be water quality dimensions to these conclusions since the uses made of freshwater as revealed by this "big picture" analysis frequently imply additions of nutrients, greater or lesser inputs of pollutants (for example from mining or agriculture) and greater or lesser inputs of sediments. These future projections should be based upon known plans put forth by government entities, private proposals, or stakeholder values and demands. These future scenarios can be investigated to some degree in Step 1, but it will likely be necessary to loop back to this step after future scenarios are developed with input from stakeholders and decision-makers, (as discussed under Step 2) to further evaluate their likely influence of these scenarios on freshwater inflows.

Identify Stakeholders and Their Concerns

Stakeholders must be consulted so that the questions to be addressed in Step 1 and to be incorporated into the Level One Profile take into account perceptions of a diverse array of interested groups of people. This is essential if stakeholders are to understand, support and fully involve themselves in the effort.

A key objective of this task is to identify the attributes and issues in the estuary that people care about. After assessing the historic and potential changes to freshwater inflows, the project team can begin to identify which estuarine habitats and species are likely to be affected. Among the features thought to be in jeopardy, a subset will be perceived to be of concern or value to people living in the area or using the estuary. These subsets of biological features are called "valued ecosystem components" or VECs.

There are two broad categories of VECs—single species and estuarine habitats. Habitats, particularly the seagrass beds, shellfish beds, mangroves, other wetlands, and distinct bottom dwelling communities are fixed in place and can be readily identified and mapped. Freshwater or saltwater marshes, seagrass habitats, and oyster reefs are especially sensitive to changes in freshwater inflow. Measures of habitat productivity, extent (biomass or area), diversity, species composition, and persistence over time are all indicators of the health of these habitats, and by extension, the overall estuary. In areas without extensive vegetated or reef habitats, soft-bottom habitat characteristics will be important (Montagna & Kalke, 1992). Local people using an estuary usually understand and appreciate the functions of these habitats. Individual species such as shrimp, fish or shellfish important to the livelihoods of local people, or a particular species of bird or marine mammal, may also be good candidates as VECs. They may become icons with which the affected community and the public at large can identify.


THE NATURE CONSERVANCY

Because changes in the flow of water to an estuary will be evaluated in social, economic, and political terms, the selection of the species or habitats that will be the focus of goal-setting and management must consider their value to a cross section of stakeholders. The values may be economic—the source of livelihoods—or symbolic. While developing a Level One Profile, the project team should work with community leaders and government officials to identify which species or habitats are of interest to various groups. For example, in the Chesapeake Bay in the eastern United States, oysters and blue crabs once supported major fisheries and were centerpieces in the cultural identity of millions of people. These species were obvious choices for VECs. In the Wadden Sea off the coast of Holland, the public sees a healthy seal population as a symbol for a healthy sea.

There are five important considerations in the choice of a VEC:

- economic, cultural, environmental, and/or political importance
- scientific understanding of the connection of the VEC to changes in freshwater inflow
- ease of measurement
- sensitivity and rapidity of response to changes in freshwater inflows
- relative lack of influence on the condition of the VEC by factors other than freshwater inflow.

Some indicators of VEC condition are either difficult to measure or require sophisticated instruments or laboratory techniques. It is very difficult, for example, to obtain accurate estimates of the population size of highly mobile fish species. By carefully considering the five criteria listed above, the project team should be able to select sensible indicators for use in both determining freshwater inflow needs and monitoring the efficacy of the inflow management program. VECs that can be readily mapped and easily accessed in shallow waters are ideal. Saltmarshes, mangroves, oyster reefs and seagrass beds are examples of features that are influenced by freshwater inflows and can be mapped with relative ease.

Table 5 provides information on commonly-selected VECs. Because this Methods Guide places a premium on low-cost, low-technology approaches appropriate for use in low-income countries, we have given priority to indicators that may be relevant in those settings and can be readily measured.

Evaluate Potential Future Impacts to Valued Ecosystem Components

Once the VECs have been identified, the project team will need to undertake an evaluation of the potential impacts of freshwater inflow changes on them. Such an evaluation commonly begins by developing simple conceptual models depicting the known or presumed influence of freshwater inflows on each VEC. Oftentimes, the connection between freshwater inflows and VECs is indirect—for instance, freshwater inflows may affect salinity conditions in an estuary, which in turn have great influence on biological features. For example, in Samana Bay in the Dominican Republic, freshwater inflows determine the salinity of the inner estuary and the associated productivity of an important white shrimp fishery. The conceptual model presented in **Figure 7** was developed to illustrate known and hypothesized linkages between freshwater inflow quantity and timing, salinity conditions in the area of the bay inhabited by the shrimp, and their productivity.

Using the conceptual models as reference, the project team can then begin investigating key cause-and-effect linkages. For example, two years of measuring freshwater inflows and salinity levels in Laguna de Terminos in southeastern Mexico in projects associated with the development of this Guide revealed a fairly strong quantitative relationship between flow and salinity (**Figure 8**). Based on this relationship, investigators were able to offer predictions about the likely changes in salinity that would be associated with any future changes in freshwater inflow, as well as the implications for VECs dependent upon specific salinity conditions in that estuary (see Section XI for references to relevant reports).

Salinity is a critical determinant of the habitat characteristics of an estuary, as explained at the beginning of this Guide. To reiterate, shifting salinities caused by variations in freshwater inflow can affect the distribution of rooted vegetation and both sessile (relatively immobile) and mobile organisms, which in turn can cause adverse economic and ecological effects. Because salinity conditions in an estuary are so important to species distribution and diversity and life cycle needs, the flow-salinity relationship is used as the basis for setting inflow management targets and regulatory standards in a number of estuaries in the United States. This includes San Francisco Bay (Kimmerer, 2002), bays and estuaries in Texas (Powell et al., 2002), and the Loxahatchee River and estuary in southern Florida (Alber, 2002). Additional steps have been taken in each of these cases to further link salinity distributions and changes to a variety of biological indicators. Scientists and regulators have agreed that maintenance of freshwater inflows that sustain targeted salinity conditions is of central importance in estuary management.

Another important consideration in assessing impacts on VECs is the potential for changes in freshwater inflows to substantially change the flushing time of water in the estuary. The longer the flushing time, the more susceptible an estuary and its associated VECs will be to the effects of pollution. Further, increased residence times may have a negative impact on the organisms living in the estuary by changing

Figure 7
Conceptual Model of Relationships among Freshwater Inflows, Salinity Levels, and Shrimp Productivity in the Samana Bay, Dominican Republic

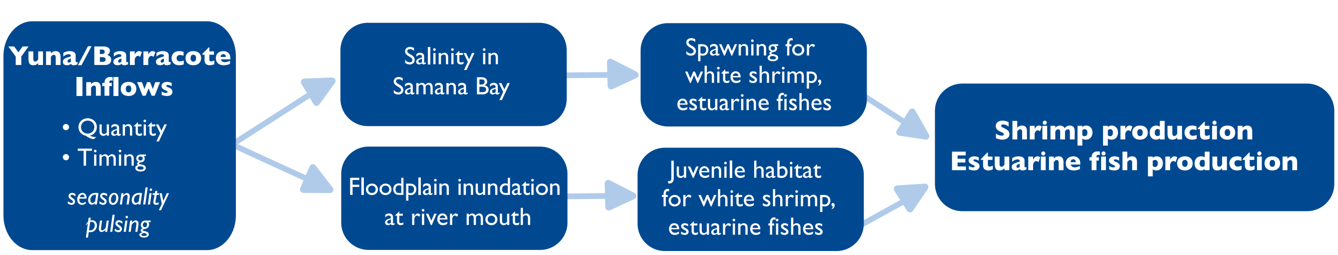


Table 5. Examples of Valued Ecosystem Components (VECs)

VEC	IMPORTANCE	INDICATOR TO BE MEASURED	IMPACT OF FRESHWATER ALTERATION AND REFERENCES OF INTEREST
Species			
Shrimp	Economically important fishery. High protein food source.	Population abundance, annual catch.	White shrimp populations have been observed to increase with higher rainfall and riverine discharge, possibly due to increased nutrients and productivity associated with higher river flow (Mueller and Matthews, 1987). Commercial catch data suggest that white shrimp are most abundant in low-salinity (less than 10 ppt) waters and that salinity is a limiting factor to distribution and abundance of shrimp in coastal waters (Longley, 1994; Gunter et al., 1964).
Clams	High protein food source. Economically important fishery. Ecologically significant because of their filtration activity which serves to improve water clarity.	Population abundance, annual catch, turbidity.	Higano (2004) attributes recent coastal changes (i.e., land reclamation, dam construction) to an increase in suspended fine sediments discharged into littoral zones and a subsequent decrease in annual catch of Japanese littleneck clams.
Scallops	High protein food source. Economically important fishery. Ecologically significant because of their filtration activity which serves to improve water clarity.	Population abundance, annual catch, turbidity.	Stone and Palmer (1973) suggested that long-term exposure to levels of turbidity greater than 500 parts per million (ppm) may interfere with normal growth and reproductive processes of Atlantic bay scallops.
Fish	High protein food source. Economically critical.	Population abundance, annual catch.	Increases in salinity of estuarine environments can lead to a decline in fish biodiversity and production (Craig, 2005). Peters (1982) suggests that high salinity estuarine conditions (the result of freshwater alterations) may be detrimental to the eggs of some fish species. Evidently, fish abundance is largely determined during this egg and larval stage (Drinkwater and Frank, 1994). Alterations in the timing of freshwater pulses can lead to increased salinity and allow predatory marine fishes to invade nursery areas (Craig, 2005).
Birds	Food source (meat, eggs), raw materials (feathers, guano). Tourist attraction.	Species diversity in wetlands is an ecological indicator of overall estuarine health.	Alteration of freshwater flows can lead to changes in land cover of wetland environments. As the land-cover of a wetland changes, habitat and the types of birds present also change (USEPA, 2005).
Bioengineered Habitats			
Seagrasses	Indirect (but nevertheless critical) economic value. Nursery habitat for shellfish, fish, and invertebrates, including many species of commercial importance. Food source for waterfowl. Stabilization of sediment.	Species abundance and health.	Because they provide important habitat, and exhibit marked sensitivity to changes in water, seagrasses can be useful to indicate overall health of an ecosystem. Zieman (1975) suggests an optimal salinity of 30ppt for T. testudinum, whose populations decline with increasing and decreasing salinities. Seagrasses need relatively high amounts of light to thrive (EPA, 2005). Alterations in freshwater flows can result in an increase in suspended sediments and diffuse and point-source nutrient loading. Seagrasses are particularly susceptible to sedimentation and experience decreases in abundance as a result of light reduction and direct smothering (Robertson and Lee-Long, 1991). Additionally, phytoplankton blooms, a result of nutrient loading can shade seagrass beds leading to dramatic losses in population (Cosser, 1997).
Oyster Reefs	High protein food source. Economically important fishery. Ecologically significant because of their filtration activity which serves to improve water clarity.	Population abundance, annual catch, turbidity.	Longley (1994) suggests a salinity of 15 ppt as optimal for survival and reproduction, but points out that salinity fluctuation in the range of 10 to 30 ppt promote more rapid oyster growth than relatively constant salinity. Changes in salinity patterns due to inflow reduction encourages the relocation of oyster reefs to upper estuarine environments where they are more susceptible to freshwater kills, pollution, and siltation (Mueller and Matthews, 1987). Butler (1954) argues that maintaining lowered salinity levels is the only effective method for controlling the spread of predatory oyster drills. Juvenile oyster survival is highly dependent upon water flow rates. Keck et al. (1973) noted that oysters in Delaware Bay were most abundant in regions of high water velocity.
Mangroves	Direct uses: Timbers, fuel wood, charcoal, bark tannins, edible plant products. Indirect uses: Fisheries habitat, nutrient filtration capacity, coastal stabilization, ecotourism.	Species abundance, diversity and health.	In one Australian study (Duke et al., 1998), regions of high freshwater inflows were observed to support more diverse communities of mangroves than those with limited runoff. Human alteration of the hydrologic system and subsequent changes in salinity at Cienega Grande de Santa Marta (Mexico) resulted in the demise of some 30,000 (of 51,000) hectares of mangrove forests (Elster et al., 1999). Kaly and Jones (1998) examine the impact of freshwater alterations on mangrove communities, particularly in tropical, developing nations. The authors additionally discuss mangrove restoration as a potential tool for the management of coastal ecosystems. A selection of useful web links pertaining to mangrove ecosystems can be obtained at: http://www.ncl.ac.uk/tcmweb/tcm/mglinks.htm.

Table 5. Continued

VEC	IMPORTANCE	INDICATOR TO BE MEASURED	IMPACT OF FRESHWATER ALTERATION AND REFERENCES OF INTEREST
Miscellaneous			
Phytoplankton	Foundation of aquatic food web. Indicators of global climate change, marine pollution, productivity.	Biomass, primary productivity	Increases in freshwater inflow volume have been indirectly correlated to phytoplankton productivity (Stockwell, 1989). Longley (1994) indicates that chlorophyll concentrations (a quantitative index of phytoplankton biomass) increase as freshwater inflow volumes rise from low to moderate, but slowly decrease as flow continues to rise. While freshwater inflows bring nutrients into estuarine environments, the point at which the effects of flushing overcome increased productivity is difficult to ascertain (Longley, 1994).
Water Quality	Critical to the health and survival of all biota (including humans) and the basis for regulations on seafood suitability for human consumption and water contact sports	Turbidity, oxygen concentrations, fecal bacteria counts, concentrations of toxics, loadings of nutrients	In 1999, NOAA released the first assessment on the effects of nutrient enrichment in the nation's estuaries - the National Estuarine Eutrophication Assessment (NEEA) report (http://ian.umces.edu/neea). This report has become the foundation document for the comparison of US estuarine eutrophication status, used at all levels of management and policy development, and could be useful to managers and practitioners in other regions, who are concerned with water quality issues. Questions discussed are: Overall, have conditions worsened or improved? Why? Where should management efforts be targeted to achieve the greatest benefit toward remediation and protection from degradation? To what extent do eutrophic conditions impair the use of estuarine resources, and what are the important impaired uses? Which data gaps and research and monitoring needs are most critical in terms of improving the ability to assess and respond to eutrophication symptoms? How can the results of this assessment be translated into a national strategy?

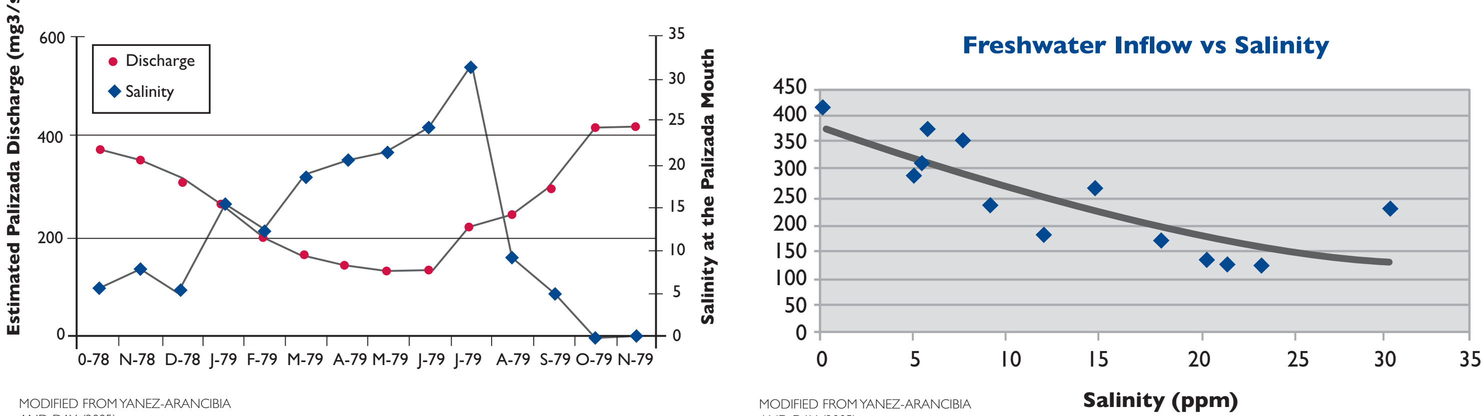
the circulation regime and supply of nutrients. Conversely, if the residence time is reduced (for example by dredging navigation channels and enlarging inlets into lagoons), fish and shellfish larvae and juveniles may be swept out to sea and lost to the system.

The work undertaken in Step 1 to define the relationships between freshwater inflows and VECs will serve to identify gaps in scientific understanding of the VECs and the need for additional data collection and research. This is critically important when selecting the targeted data collection and research to be conducted in Step 2.

Assess the Existing Management System

In addition to understanding long-term trends in freshwater flows and the biophysical condition of the estuary, it is critical to understand the evolution of the existing management systems for the catchment and estuary and how it has influenced the trajectory of change in the ecosystem. This feature of Step 1 may be termed a "governance baseline." Its purpose is to assess the existing capacity of formal and informal institutions to develop and apply the planning and decision-making processes that affect the management and allocation of freshwater and activity within the estuary. Rather than compiling a static "snapshot" of the existing

Figure 8
Relationship between Freshwater Inflow and Salinity in Laguna de Terminos Estuary in Mexico



MODIFIED FROM YANEZ-ARANCIBIA AND DAY (2005)

MODIFIED FROM YANEZ-ARANCIBIA AND DAY (2005) governance system, a governance baseline traces how the current system has evolved. To do this, the team should focus on the outcomes of past action—or inaction. This form of analysis will be a basis for making informed judgments on how best to influence the existing system. The purpose is not to pass judgment on whether past and current management is "good" or "bad," but rather to realistically assess the capacity of the current institutions to practice IWRM. A sound strategy should build on the strengths of the existing governance system and address its weaknesses.

In many developing nations, the rule of law is weak and at times has only a marginal influence on how decisions affecting the allocation and use of freshwater are made. In other situations, institutions—both formally constituted governmental institutions and the less formal business associations, unions or political parties—play important roles. A governance baseline works to understand these relationships and to analyze the distribution of power as this relates to the issues posed by changes to freshwater inflows.

The key questions to be addressed by a governance baseline are:

- What have been the successes and limitations of past catchment and estuary planning and management?
- What are the existing rights to use freshwater in the catchment?
- Does the existing legal framework provide for the protection of freshwater inflows required to sustain the VECs? If it does not, how could this need be filled?
- Are there governmental institutions with a sufficiently broad mandate to formulate and implement a plan of action to address perceived problems with freshwater inflows? Do they possess the necessary institutional capacity to implement such a plan successfully? If not, what human and financial resources will be required to implement the plan of action? How might they be obtained?

Determine the Focus of Further Analysis

Once the above preliminary analysis is completed, the team, in consultation with the stakeholders who have become involved in Step 1, will need to take stock of what they have learned. This is the time to decide how they will focus further efforts to understand the significance of a change to freshwater inflows and how they will work with stakeholders and organizations of government to formulate a course of action. The spatial scale of the cause and consequences of the issues identified will determine the geographic boundaries of the areas to be considered in a more detailed analysis. The review may suggest the need for consultation with additional stakeholders who may be at some distance from the estuary but whose actions are contributing to the problems of concern. In most instances, the time, resources and analytical tools available to the team will set limits to what can be done. In light of these limitations, decisions will need to be made on the most important gaps in the information base, how best to reduce uncertainty on important cause-effect relationships and what forms of public information and involvement in the issues are most likely to generate positive impacts. In some cases, however, decisions affecting freshwater inflows may be imminent and there may be no time for further analysis, and the team will need to focus its energies on drawing attention to the issues that have been identified and their potential implications.

STEP 2: Formulate IWRM Policies and Strategies for Their Implementation

Set Goals with Stakeholders

If the team has decided to embark on further analysis and developing a plan of action for governmental consideration, it will be essential to clearly articulate the goals that such management will work to achieve. Although such goals are likely to be refined and re-phrased throughout Step 3, it is essential that the fundamental purpose and specific desired outcomes of a linked catchment and estuary management scheme are made clear to all those participating in the initiative. It is strongly recommended that such goals define both the environmental and social conditions (outcomes) that, when achieved, would constitute success. Too often, goals are stated so vaguely and broadly that they are difficult for anyone to disagree with and of little use when assessing whether a given development proposal will or will not contribute to achievement of these goals. Defining the goals as "sustainable development," "balance among competing activities" or "ecosystem health" may indicate the desired direction of change—but little more. It is far more useful to set goals that define specifically how much by when. For example:

- Water quantity: By 2010, agricultural irrigation practices will be improved such that water consumption will be reduced by 10% while agricultural productivity is retained or increased, thereby increasing freshwater inflows to the estuary during the dry season when oyster mortality is high.
- Water quality: By 2010, each tributary will achieve a 20% reduction in nitrogen and phosphorus loadings compared to the year 2000 baseline.
- Catchment management: By 2010, the headwater areas of the catchment that are forested will have increased by 35% as measured against the year 2000 baseline.

- Fisheries: By 2010, procedures for seasonal closures of the shrimp fishery in Santa Catarina Bay will be in place—procedures based upon the volume of the previous year's freshwater inflow and recruitment into the shrimp stock.

- Habitat: By 2010, five kilometers of streamside mangrove wetlands in the two municipalities fronting on the upper estuary will be restored as a continuous belt and designated as a reserve. By that year, the total area of the mangrove reserve will be not less than 900 hectares.

Goals should "stir the blood" by addressing issues and outcomes about which the people of the place care deeply. Goals are critical when weighing among options and setting priorities. They are the basis for accountability. Specific goals are difficult to negotiate but they encourage the initiative to focus upon a few, carefully selected priorities and to think through what is feasible within a given time period. Goals associated with timeframes of a decade or more into the future make the fundamental purposes of the program tangible. Near-term goals mark the stepping stones to those ends. The capacity to manage an ecosystem must be assembled gradually over time and the goals should balance the complexity and scope of the issues to be addressed with the governance capacity that is present at a given time.

Conduct Targeted Data Collection and Research

The analyses conducted in Step 1 concerning the linkages among freshwater inflows, salinity conditions, and VECs should be the basis for setting priorities for additional data collection and targeted research. Such additional data gathering and analysis might be focused on collecting new data on river flows at targeted locations in the catchment, better defining the condition and distribution of VECs, or developing a more complete understanding of the salinity regime, nutrient levels and presence of pollutants in the estuary.

As in all assessments, the first priority is to answer the question "how vulnerable is this estuary to freshwater inflow change?" Signs of high vulnerability may include evidence that important habitats are already declining, reports of fish kills or an unusual abundance of rooted or floating algae or unusual planktonic blooms. Abrupt or sustained declines in specific species such as birds or cases of people living in the estuary getting sick from contaminated seafood are also signs of potential problems. Often, the most vulnerable estuaries are lagoons with a large catchment area relative to estuary volume (Horton and Eichbaum1992), or those with little exchange with the open sea and slight mixing. Estuaries where high rates of evaporation and relatively low inflows are vulnerable to reductions in flow that would further elevate salinities and lead to an inverse estuary. Such evidence of stress and vulnerability should greatly influence any investment in additional field work.

Refining the team's understanding of the estuary and how it may be affected by a change in freshwater inflows can easily become a complex and expensive research effort. The team should begin by seeking out an experienced estuarine ecologist, preferably with extensive field experience, who can either join the team or serve as its advisor. Such a person may be present in a nearby university or governmental laboratory. The first task is to work with such a person to review available information. If one does not already exist, the development of a spatial information database for the watershed and estuary should be a priority so that existing geographic information system (GIS) datalayers on landcover, elevation, bathymetry, water quality, and benthic habitats can be overlaid and evaluated for gaps. The team should then carefully prioritize what field work, if any, is most likely to reduce important uncertainties about the impacts on the estuary of the changes to freshwater inflows that are of concern to the team. The following can serve as an initial checklist when making such decisions.

- ***Distribution and condition of fixed habitats.*** It cannot be over-emphasized that the best indicator of change in an estuary can be seen as shifts in readily recognized habitats. Therefore, it is important to have maps of the extent of such features as seagrass beds, mangrove or saltmarsh wetlands, shellfish beds and oyster reefs, and any other readily recognizable habitat types in and adjoining the estuary. Experienced fishers usually have a wealth of knowledge on these topics and can play an important role in refining what is where and how such habitats have changed. Observations from the shore and from a boat in the company of locally knowledgeable residents can significantly refine such information. More sophisticated mapping of underwater habitats involving bottom sampling or remote sensing (*e.g.,* satellite image analysis or side-scan sonar) can become complex and expensive. The condition of some habitats can be evaluated by quantifying, for example, the density, height, presence of disease, or amount of mortality for seagrass beds, mangroves, or saltmarshes. In bare sediment areas, the amount and type of in-fauna (*e.g.,* worms, gastropods, mollusks, etc.) in shallow box cores can provide a useful measure of biotic conditions as well as clues for how nutrients are being cycled through the estuarine food web.

- ***Distribution and condition of mobile species.*** Quantifying distributions, particularly for highly mobile species, can be time consuming. It is important to recognize that many resident estuarine species occupy different portions of the estuary during different stages of their lives. Juveniles will often be found in the most protected, predator free areas whereas adults will tend to concentrate where food is most abundant. The sampling design of any new field-collection efforts should be developed with the assistance of an estuarine ecologist or geospatial statistician. One approach is to divide the estuary into representative areas based on habitats or known species distributions. Again, valuable information can be learned from experienced local fishers. Sampling of fishes or mobile invertebrates within each of these habitat types can be done using a variety of low-tech methods including visual assessment (where waters are clear enough), nets traps, or hook and line. The presence, absence or abundance of different species can provide a first order understanding of their distribution. Collected specimens can also be examined for a variety of useful condition measures including size, age, stomach contents, or any obvious abnormalities.

- ***Bottom topography.*** Most estuaries have been surveyed for navigational purposes and charts exist that show bottom depth contours. If such charts are badly out of date or if dredging, sedimentation or erosion have changed the shape of the estuary, better information on bottom topography may be valuable. Surveying the estuary by boat with a weighted measuring line is simple, but time consuming way to do this. An electronic "fish finder" or depth sounder is an inexpensive instrument that can be attached to almost any kind of boat and will profile depths with reasonable accuracy. Such bottom profiles must be associated with a global positioning system (GPS) and/or follow point-to-point transects that can be plotted on a chart. It is critical to know where you are measuring! In areas where tidal variation is large (*e.g.,* more than 20 cm), readings should be corrected for tidal variation.

The next level of sophistication in characterizing an estuary usually requires an investment in equipment. However, good quality equipment is becoming less expensive and easier to operate. One good option is to purchase a conductivity (salinity), temperature and depth (CTD) probe that can be connected to both a GPS and a lap-top computer. The link to a GPS can be extremely useful in determining sample locations. These instruments are being designed so that they can be connected to a lap-top computer that integrates and displays the data as it is generated. The following variables should be considered as potential targets for field work that can be analyzed to better understand the behavior and condition of the estuary.

- ***Salinity gradient.*** A change to the salinity structure of the estuary is the most likely consequence of a change to freshwater inflows. As discussed in sections II through V, it is very important to measure salinity at both the surface and the bottom and to monitor how salinity changes within the year (*e.g.,* measured monthly and at a similar stage of the tide). Understanding the impacts of floods and droughts on the salinity of the estuary is particularly important. A CTD is useful because it produces a continuous record of salinity, temperature and depth as it is lowered from a boat. This generates a profile that will reveal a great deal about the layering of higher and lower salinity water from the head of the estuary to its mouth. The temperature profile may reveal the boundary between seaward flowing surface water and the compensating layer of cooler, higher salinity bottom water that flows in the opposite direction. CTD profiles should be taken at pre-established locations or "stations" down the axis of the estuary or along two or more transects in the case of a lagoon. Good information on bottom topography is important so that profiles can be made in both deep and shallow areas and in isolated "holes." In a riverine estuary, the stations should be made along the main axis of the estuary where there should be less influence of streams or groundwater entering along the shoreline, as well as in more isolated coves where mixing may be less vigorous.

- ***Oxygen concentrations:*** Oxygen levels are a primary concern, especially where nutrient enrichment and eutrophication is an issue. Low oxygen conditions are most likely to develop at the bottom so it is best to take measurements concurrently with a CTD profile. Fortunately, an oxygen probe can often be purchased as an additional feature to a CTD. It is usually important to look for evidence of low oxygen in worst-case conditions—these are times when temperatures are high (the summer) and in the early morning after the oxygen-generating process of photosynthesis has been halted overnight. Areas of deep, isolated waters, the bottom of navigation channels, and isolated, poorly flushed coves and inlets are all potential sites for low oxygen conditions.

- ***Nutrient loadings and concentrations.*** These may be important to estimate, but their measurement is likely to greatly increase the complexity and the expense of the field work. Samples must be collected, filtered and then transported to a competent laboratory with the equipment and expertise necessary to measure the concentrations of dissolved inorganic nitrogen, phosphate and silica. High seasonal variability in nutrient concentrations is typical of many estuaries. It is important not to be misled by low concentrations of these nutrients in the water and assume that low readings mean that there is little risk of eutrophication. In some situations, the available nutrients are absorbed so quickly that the concentrations in the water remain low even when eutrophic conditions prevail. When comparative studies are being made, it is often most useful to measure total nitrogen and total phosphorus. This requires measuring and adding the dissolved organic and organic particulate forms of both nutrients to the dissolved inorganic reading. Another strategy is to estimate nutrient loadings (the volume of inflows) by measuring or estimating the amounts being placed in the estuary by rivers and streams, groundwater (very difficult to estimate) and important point sources such as the discharges from sewage treatment plants and some types of factories.

- ***Toxics.*** It is usually not worthwhile to invest in the measurement of such potential toxics as heavy metals, agro-chemicals or any of the host of other toxic substances unless the team knows of a potential source or there is evidence of disease or mortality that may be associated with these pollutants. Such measurements tend to be expensive and require careful sampling protocols and collaboration with competent laboratories. Where toxics are a concern, decisions will need to be made carefully on where in the estuary to sample and whether the analysis should focus on concentrations in the water, the sediments, and/or organisms.

New data and analyses should be integrated into a Level Two Profile that contains sufficient information to reasonably estimate the impacts of future changes to inflows. Such carefully targeted data collection and research may continue during implementation of the management plan (Step 4). A Level Two Profile is a document that contains a detailed analysis of existing information, knowledge and perceptions of future implications of environmental and social issues, especially those raised by changes to freshwater inflows. The Level Two Profile should also, where feasible, fill in the information gaps identified by the Level One Profile, and consider the implications of important uncertainties on how the ecosystem functions and is likely to change.

Build Scenarios

Plausible scenarios of contrasting future conditions can help in visualizing the likely implications of different courses of action. They can be helpful in prompting informed debate and in building constituencies for an emerging plan of action. Scenarios are developed by applying what has been learned from the Level One and Two Profiles and by engaging the people of the place and the institutions involved in grappling with the potential impacts of changes to freshwater flows. For example, the data that has been gathered to document historical trends in such important variables as land use, freshwater inflows to the estuary, growth in the human population, shrimp harvests and trends in estuarine water quality can be projected five, ten or twenty years into the future. What has been learned about the interconnection of such variables can be applied to "painting word pictures" that describe responsible and believable forecasts of future conditions in the estuary and future prospects for such important human activities as fishing and tourism. Such projections can then be the basis of thinking through the impacts of actions designed to avoid unattractive outcomes. Scenarios should crystallize the implications of alternative courses of action—or inaction. Well-prepared scenarios can play a central role in public education programs and in focusing the analysis and debate over what actions should be taken to address current or anticipated changes to the ecosystem and the human activities it supports. The economic dimensions of alternative scenarios may play a central role in mustering political support for a linked catchment-to-estuary IWRM initiative in Step 3.

Scenarios are only one means for helping institutions, stakeholders and the public at large to absorb, discuss and consider the issues raised by an analysis of changes to freshwater flows and the long-term implications of such changes. While public awareness of the issues is important, the priority is to build a well-informed constituency for the emerging IWRM initiative. The very nature of IWRM requires that this must be a constituency that draws together both groups concerned principally with the estuary and key groups concerned with the allocation and quality of freshwater in the catchment. The discussion of future scenarios that foster interactions among groups that otherwise do not know each other, and provide a forum where differing perspectives and needs can be aired and discussed, are particularly valuable.

Experiment and Monitor

The implementation of a management program designed to address current or impending issues will require changes in the behavior of key groups and institutions. The challenges of instigating and maintaining such changes in behavior lie at the heart of successful implementation (Step 4) and invariably raise unforeseen problems and benefits. Experience has repeatedly demonstrated, particularly in low-income settings and where top-down enforcement by governmental agencies has a record of yielding poor results, that experimenting with new policies and their associated behaviors at a pilot scale can be very useful. Seeing is believing. If a new practice—for example, a new approach to addressing habitat degradation or overfishing in the estuary or modifying how water is released from a dam—is implemented at a pilot scale during Step 2, the experience, if positive, can do much to build support and credibility for the ideas being put forward by the project team. Similarly, if what appeared at first to be a good idea—for example, increasing the penalty for mangrove cutting—proves in practice to be ineffective, it is best if the limitations are identified early before the process of formal adoption of a new law or regulation gets underway.

STEP 3: NEGOTIATE AND FORMALIZE THE GOALS, POLICIES AND INSTITUTIONAL STRUCTURES FOR SUSTAINING NECESSARY FRESHWATER INFLOWS

Gain Formal Endorsement of Policies for Sustaining Freshwater Inflows

Step 3 is the culmination of a process that has worked to integrate the two threads of adaptive management by combining the results of technical analysis with a process of mutual education and consensus-building with the various stakeholders. In many cases, implementation of the actions that will have emerged as most critical to sustaining the VECs will require formal endorsement from the governmental authority at the province (state) or national level. Where a catchment reaches into more than one province or nation, more complex negotiations with several governmental agencies may be required. Formal adoption of new IWRM policies and procedures may take many forms, but typically requires an executive decree, cabinet resolution or, at a minimum, a high level administrative decision. Generally, governments have a lead agency assigned to water resources management, although several other government agencies are generally also directly implicated in water sector issues (*e.g.,* Ministries of Agriculture and Irrigation, Urban Development, Environment, etc.). In managing freshwater inflows to estuaries, coastal, marine and/or fisheries-related government agencies will also need to be involved. Achieving an IWRM approach will, at a minimum, require a commitment for effective interagency coordination and collaboration on inflow issues. In some cases, a separate government coordination mechanism or management unit may be established to address inflow issues across agencies and jurisdictions. Important roles may also be given to nongovernmental organizations and private sector institutions in carrying out the program.

Formal adoption of a new IWRM set of policies and procedures usually affects the distribution of authority and influence among institutions, interest groups and politicians. This may trigger defensive behavior and bureaucratic maneuvering. Bargaining and accommodation will dominate the process by which a freshwater allocation policy finds its place in the existing structures and institutional territories of government.

Many initiatives fail in Step 3. They do not earn the necessary endorsements, or are so modified by interagency negotiations and the political influence applied by some interest group(s) that their potential to achieve significant progress on the issues they have been designed to address is reduced or lost. The meaningful and continued involvement of the pertinent private sector stakeholders and the pertinent institutions involved in Steps 1 and 2 is critical to success. If these institutions and decision makers have not been involved in the processes of analysis and in weighing the options suggested by the scenarios, it will be difficult to win their trust and support at this late stage.

By Step 3, the project team and its supporters should have clearly defined what changes to the current freshwater allocation and management process must be made or avoided to address the inflow problems they have identified. The institutional analysis conducted in Step 2 should have specified the adjustments needed to freshwater allocations if freshwater inflows to the estuary are to be protected. The solution being proposed must be politically as well as technically viable. Convincing arguments must be made that the ecosystem management approach—which is at the heart of IWRM—will, over the long term, generate greater benefits for both society and the ecosystem than will traditional sector-by-sector planning and decision-making. The fundamental points are that: (1) the values of sustained, or restored flows of benefits generated by a healthy ecosystem are large and benefit a diversity of groups and economically important activities in both the catchment and the estuary; and, (2) that a transparent and accountable system for allocating freshwater produces a secure environment for all concerned, including those who wish to make economic investments in the region. Simple graphics and cost-benefit tables can crystallize the basic points and focus debate on the substance of the issues.

At the core of any effort to apply ecosystem management principles to the issues of freshwater allocation is the concept of the "sustainability boundary" (Postel and Richter, 2003). As illustrated graphically in **Box 7**, this calls for defining the first building block of a freshwater allocation system as the water needed to sustain the goods and services that are generated by a healthy river and estuarine ecosystem. Rather than making an allocation for the ecosystem from whatever is left over after a diversity of human needs are met, the "sustainability boundary" approach calls for making this allocation the first and most essential step. Critical to this is the recognition that this allocation to assure the health of the ecosystem is defined so as to recognize both seasonal variations and the long-term cycles of relative abundance and relative scarcity that characterize freshwater flows in all catchments.

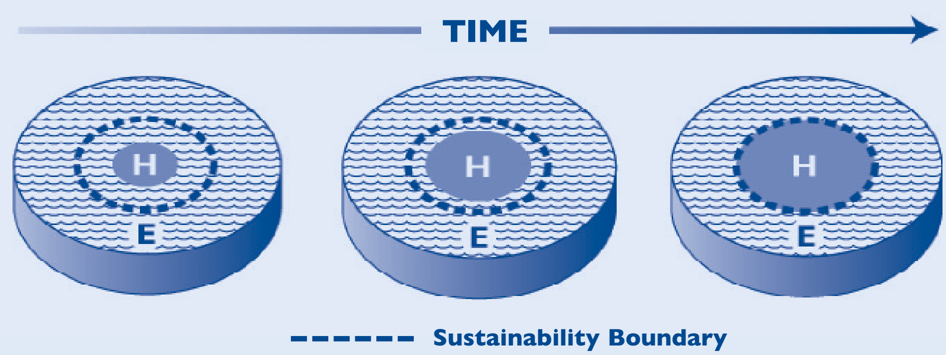
The best illustration of the "sustainability boundary" principle is South Africa's 1998 National Water Act. This landmark legislation builds upon the public trust doctrine that has its roots in Roman law. The public trust doctrine states that governments hold in trust for the people certain rights and entitlements including access to such resources as the air, the sea and freshwater. Governments are obligated to protect those rights for the common good. The South African legislation integrates public trust principles with the need to conserve the natural flows of rivers. The law establishes a water allocation known as the Reserve, which consists of two

BOX 7: THE SUSTAINABILITY BOUNDARY CONCEPT

Recognizing that human societies depend upon and receive valuable benefits from healthy ecosystems, Postel and Richter (2003) have suggested that the first priority in any freshwater allocation scheme should be to make an “ecosystem support allocation.” This allocation should be designed to ensure that ecosystems receive the quantity, quality, and timing of freshwater flows or inflows needed to safeguard the health and functioning of river systems and estuaries.

This approach places a limit on the degree to which society can alter natural river flows or inflows to estuaries. Postel and Richter have called this limit the "sustainability boundary." Rather than freshwater and estuarine ecosystems getting whatever water happens to be left over after human demands are met, they receive what they need to remain healthy. In the diagram, **human uses of water** (H) can increase over time but only up to the sustainability boundary.

At that point, new water demands must be met through conservation, improvements in water productivity, and reallocation of water among users. By limiting human impacts and allocating enough **water for ecosystem support** (E) society derives optimal benefits from healthy catchment and estuarine systems in a sustainable manner.



parts. The first is a non-negotiable allocation to meet the basic water needs of all South Africans for cooking, drinking, sanitation and other essential purposes. This basic human need has been defined as a minimum of 25 liters of water of adequate quality per person per day. The second part of the Reserve is an allocation of water to support ecosystem function. The National Water Act states that “the quantity, quality and reliability of water required to maintain the ecological functions on which humans depend shall be reserved so that the human use of water does not individually or cumulatively compromise the long-term sustainability of aquatic and associated ecosystems.” This second part of the Reserve is set so as to protect rivers, wetlands, estuaries and groundwater. All other water uses must be licensed and may be granted only after Reserve allocations have been met. The water allocated to the two elements of the Reserve has priority over all other uses and only this water is guaranteed as a right.

The South African legislation illustrates a number of important principles. The first is that the Reserve combines the meeting of basic human and ecosystem needs as the primary goal and the first priority. A second principle is that an ecosystem management approach requires that both surface water and groundwater be treated as elements of the same system. The third principle is that the allocation for the Reserve takes into account seasonal fluctuations in flows and the longer-term variations brought by periods of relative water scarcity and periods of relative abundance. A fourth is that all other uses are allocated through a permit (licensing) system. Finally, the South African law assures that the rights of people at the lower end of the system—including those living along the estuary—are not compromised by the activities of those living elsewhere in the catchment.

The State of Texas (U.S.) offers an example of a water allocation system that addresses freshwater flows in an arid region where competition for the available freshwater is intense and escalates to crisis conditions during periods of drought. The Texas coast is endowed with a number of lagoons and riverine estuaries that provide critical habitat to valuable brown, white, and pink shrimp populations that support an economically valuable fishery. The State of Texas has adopted a specific policy designed to protect the “beneficial flows” of freshwater to estuaries. Such flows are defined as “the freshwater necessary to maintain salinity, nutrient, and sediment loading regimes adequate to support an ecologically sound environment in the receiving bay and estuary system that is necessary for the maintenance of the productivity of economically important and ecologically characteristic sport or commercial fish and shellfish species and estuarine life upon which such fish and shellfish are dependent” (Science Advisory Committee to the Texas State Legislature, 2004).

BOX 8: THE TEXAS 3-ZONE WATER PASS-THROUGH SYSTEM

Arid regions with large coastal populations are among the first to face the issue of altered freshwater inflows. In the 1950s, a drought struck the state of Texas. It was so severe that many rivers dried up. A variety of dramatic changes occurred as freshwater was cut off from the estuaries along the Gulf of Mexico. This resulted in fish kills, loss of blue crabs, and drastic declines in white shrimp populations (Copeland, 1966; Hoese, 1967). Consequently, legislation was passed in 1957 that required water plans to consider the effect of upstream development on the bays, estuaries and inlets of the Gulf of Mexico. This inspired a series of assessments of all Texas estuaries, which were summarized by the Texas Department of Water Resources (1982). Those reports were later the basis for a methodology to determine the freshwater needs of Texas estuaries (Longley, 1994). The goal was to meet the freshwater needs of important commercial and recreational aquatic species (Powell et al., 2002).

The rules were formulated with provisions that vary inflow volumes under different climatic regimes and set different flow goals for dry and wet years. Minimum pass-through goals that govern reservoir operations are defined by dividing the reservoir behind each dam into three zones.

Zone 1 pass-through requirements are applied when the water level in the reservoir is greater than 80% of its storage capacity. When flow is within Zone 1, enough water is "passed through" (released) so that inflows are equal to the monthly medians (calculated by taking values of historically measured river flow, and correcting for transfers and estimated losses from the upstream watershed).

Zone 2 requirements are applied as dry conditions develop and the reservoir water level falls to between 50% and 80% of storage capacity. Under these conditions, pass-throughs are reduced to the 25th percentile of monthly inflow.

Zone 3 requirements are triggered when drought conditions develop and the reservoir water level falls below 50% storage capacity. Pass-throughs are then reduced to an amount equal to either: the amount of flow necessary to maintain pre-determined, established downstream water quality standards; or a continuous flow threshold determined by water agencies.

Regardless of the zone, the pass through flows are intended to protect downstream water rights and to meet the environmental needs of downstream bays and estuaries. The Texas Water Development Board monitors and collates river inflow and bay hydrographic data to estimate flows to the coast and the Texas Parks and Wildlife Department has an extensive monitoring program for fish in all Texas bays. These data are used in periodic assessments that are used to revise inflow targets.

The Texas legislation is an excellent example for rules that specify how scarce water will be allocated in periods of drought (**Box 8**).

Each state or nation must tailor IWRM principles to its particular needs, history and existing legal and institutional systems. Another approach has been taken by the state of California (U.S.), where competition over freshwater has been intense for many decades and a complex set of water laws govern the distribution of supplies among farmers and cities. The qualities of San Francisco Bay are protected by rules that stipulate the location of a specified salinity gradient. Freshwater inflows to the estuary are regulated to assure that the position of this gradient does not move inland from designated locations in the dry season. The required level of salinity (the 2 psu -practical salinity unit- isohaline) has been demonstrated to be necessary for the protection of phytoplankton, shrimp and desirable fish larvae.

In Australia, where competition for freshwater is also intense, a Water Reform Framework signed by the state premieres in 1994 recognizes the need to move toward sustainable use of water and greater protection of ecosystems. The goal to be achieved through the application of a set of twenty principles is "to sustain and where necessary restore ecological processes, habitats and biodiversity in water-dependent ecosystems" (Postel and Richter, 2003). Where environmental water allocations are not sufficient to prevent significant ecological harm, extractions of water from that river basin are capped. The Australian National Program for Estuary Protection calls for filling in a checklist of major ecological processes affected by freshwater flow to an estuary and then evaluating the anticipated impacts of change through a two-step phase of evaluation and detailed investigations.

Propose the Institutional Structure for IWRM Policy Implementation

As important as developing the legal basis for IWRM is the design of the institutional structure by which it will be implemented. The allocation of responsibilities for the management of freshwater, catchments and estuaries, and the capabilities of institutions involved vary so widely from region to region and nation to nation that there is no single model for the structure of an integrated catchment-estuary management program. There are, however, three important

BOX 9: THE PRECAUTIONARY PRINCIPLE

The "precautionary principle" is a concept that originated in the 1980s in Europe. Although controversial in some applications, the central idea is that a cautious approach must be taken in situations that pose serious or irreversible threats to human health, human societies, or the environment. The probable benefits of action must be cautiously weighed against the likely costs of inaction, so that a responsible course of action can be taken in the face of uncertainty. Important elements of this principle are: establishing the minimum level of proof needed to justify action to reduce risks, research and monitoring for early detection of hazards, promotion of environmentally sound practices, reducing risks before full proof of harm is available, and encouraging a cooperative approach between stakeholders to solve common problems. In terms of IWRM efforts, the precautionary principle calls for taking action to avoid potentially damaging impacts of altering freshwater flows, and not using lack of scientific certainty as a reason for postponing cost-effective measures to prevent destruction and degradation, especially where there are threats of serious or irreversible damage. The precautionary principle remains a subject of controversy and is not universally accepted.

principles that should guide this important element of IWRM design. The first is to match the scope and complexity of the agenda with the capacity of the institutions that will be responsible for implementation. Institutional capacity to successfully practice ecosystem-based management is in short supply everywhere—not least in developing nations. An IWRM process is most likely to succeed if it is applied incrementally and such capacity is "grown" within the responsible institutions and its supporting constituencies. The second principle is that institutional arrangements should be designed as a decentralized system in which authority and responsibility is delegated to the lower levels of an internally coherent "nested" system. A third principle that should guide IWRM efforts is the precautionary principle (**Box 9**).

Secure the Funding Required for Sustained Implementation

In developing nations, it can be relatively easy to find funding from international donors and other sources for a short term "project" that can help analyze a set of problems and plan a course of action. It is quite another matter to secure funds for the implementation of a set of rules and procedures that have been formally adopted by a government. This phase is considered to be a national responsibility and must typically be funded through national budgetary allocations to the institutions involved or by loans from international banks. In many countries, the funds to implement a program—which may include a permit program, field visits, monitoring and enforcement—are scarce or non-existent. Such budgetary constraints may be a central limitation to institutional capacity. Market-based management systems can contribute to the generation of revenues from water users that are licensed to withdraw specified volumes of water for specified uses that can be met without crossing the "sustainability boundary."

VIII. FROM PLANNING TO IMPLEMENTATION: STEPS 4 AND 5

Ecosystem-based management is complex and requires long-term commitment to processes in which multiple interests must be balanced and accommodated. Many initiatives fail to make the transition from planning to successful implementation—even when they have survived the rigors of Step 3 and won endorsement of IWRM principles and processes. It is useful to assess the degree to which the following four broad categories of preconditions to implementation have been met (Olsen, 2003):

1. ***Goals*** have been selected that define what the program is working to achieve. Ideally, such goals should be unambiguous, specific, time-bound and quantitative—describing how much and by when. Goals should appeal to the values of the society as well as reflect a solid understanding of the ecosystem and institutional processes that must be orchestrated to achieve them.

2. ***Constituencies*** who understand and actively support the program's goals must be present. Constituencies are essential at the local level within the groups that will be most affected by the program's implementation. If such support is absent, the task of imposing the implementation of new policies and decision-making procedures on an unwilling or uninformed society will prove difficult or unworkable. Constituencies are also essential at higher levels in the governance hierarchy—typically at the state (province) and/or national level.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3. ***Formal commitment*** from government provides a responsible institution or institutions with the necessary authority and the resources to implement an IWRM process over the long term.

4. ***Institutional capacity*** is essential if an adaptive, ecosystem-based approach to governance is to be implemented successfully over the long term. Too often, the scale and scope of internationally supported initiatives outstrips the capacity of the institutions charged with implementing and sustaining a program. This is wasteful and counterproductive and breeds frustration and cynicism.

STEP 4: ADAPTIVELY IMPLEMENT THE IWRM PROGRAM

The entire effort culminates in Step 4 with the sustained implementation of an integrated catchment-to-estuary management process that protects the VECs and the human activities they support. Because all living systems evolve and change over time, the implementation of an action plan cannot be a static or rote process. The implementation phase will have to adapt to new issues, new knowledge, and other changes in the context within which the system and its management operate.

The key to understanding the challenges of implementing a new policy and thereby working to influence the trajectory of societal and environmental change in an ecosystem is to recognize that this requires changes in the behavior of key groups and institutions. Success typically includes evidence of:

- new forms of collaborative action among governmental and nongovernmental organizations
- changes in the behavior of resource users; and
- changes in patterns of investment.

Instigate Changed Behavior within Institutions of Government and NGOs

The commitments won in Step 3 to apply new rules and procedures governing freshwater inflows and, in some cases, to implement a plan of action that addresses related freshwater allocation and use issues will usually require at least two forms of behavioral change in responsible governmental agencies and associated NGOs. The first is new forms of collaboration among institutions with responsibilities for the estuary with institutions that have responsibilities for freshwater management in the catchment. The second is to assemble the resources required to implement the new rules and procedures "in the field" that affect the users of freshwater and the estuary. The commitments to make the necessary changes negotiated and formalized in Step 3 are only commitments "on paper." In Step 4, they must become an operational reality. The agreements negotiated in Step 3 may have redistributed authority and resources in ways that will affect the inner workings of the organizations with roles in implementing the program—sometimes in ways that were not foreseen. These changes may be welcomed or they may be resisted.

The necessary forms of interagency collaboration may, for example, take the form of a joint interagency review of applications for permits to withdraw freshwater or discharge wastes. In Step 3, a high level interagency council or board may have been created, which is responsible for decision-making in droughts, the construction of new dams or the reallocation of water among user groups. The success of such innovations within institutions of government and their partners in civil society will depend on the leadership of key individuals and on the willingness and ability of staff members at many levels in the agency to adjust to new procedures and to invest in new relationships with their counterparts in other agencies. The adage "the devil is in the details" often captures the difficulties in how the business of an organization is adjusted in order to make collaborative action a sustained success.

In Step 4, the capacity of institutions responsible for managing freshwater inflows will ultimately be assessed by their ability to enforce the new procedures and regulations and carry out the actions that were negotiated in Step 3. In linked estuary-to-catchment management, the policies and procedures that address inflow issues typically will be expressed in rules governing:

- the withdrawals and allocation of surface and groundwater for human uses
- the discharge of wastewater and other substances that impact water quality
- reservoir operating procedures that influence base flows and seasonal pulsing
- watershed/catchment management and land use planning
- drought contingency plans.

All five of these variables may need to be managed in a coordinated manner since the interconnections between them will determine the impacts on the ecosystem. Enforcement of rules on such issues is far more than command and control. It requires educating the user groups whose behaviors will be regulated on the rules and the reasons for them, building a reputation for fairness, resistance to corruption and abilities in conflict resolution. In many developing nations, enforcement officers are poorly paid, poorly equipped and poorly trained. Such weaknesses must be overcome during Step 4. An organization that may have good capacity and experience in the analysis of issues and planning associated with Steps 1 through 3 may not have similar capabilities in implementing a program. In other instances, the members of an organization responsible for planning and policy development have little contact with those responsible for implementing a program. All of these issues make the transition to the implementation of a policy or plan of action a challenging time in any institution.

It is important to recognize that the formal rules that are written down and are the subject of a formalized process may in practice be less important than the informal rules that evolved over time and are followed by the common consent of those affected. Such informal rules may be the source of corrupt dealings and this may add additional layers of complexity when working to implement IWRM procedures founded upon transparency and consultation with all those affected, including the poor. On the other hand, informal rules such as those associated with common property management or other customary law or tradition surrounding resources rights can serve as a positive and reinforcing influence on sustainable and equitable water allocation for inflows to estuaries. These regimes must be identified and understood during Steps 1 through 3 and their successful incorporation into the manner in which the program is implemented may be central to success in Step 4.

Instigate Changed Behavior in Resource Users

The changes in behavior and attitudes within governmental agencies and NGOs may appear small when compared to the challenges of implementing new rules and procedures that are designed to alter the behavior of those who use freshwater—the farmers, the urban and domestic water users, those responsible for controlling releases from dams, industrial users and fishers who may need to change their practices in the estuary. Commitments to make such changes also exist only on paper until the implementation process takes hold.

The emphasis placed on consultation and active involvement of stakeholders throughout Steps 1 through 3 is grounded on the realization that the successful implementation of any set of rules and procedures that affect such a critical resource as freshwater will require the support of those who will be affected. The credibility and the ultimate impact of the program will hinge largely on the degree of voluntary compliance with the rules. If, for example, significant numbers of farmers in the watershed illegally withdraw water to irrigate their crops, if limitations on water consumption during droughts are ignored, if regulations on discharges of pollutants are ignored or subverted, then all the planning and the formal agreements made in Step 3 will be judged as meaningless. Research on compliance (Sutinen and Kuperan, 1994; Hanna, 1995) has demonstrated that coercion and threat of sanction is usually not the principal factor influencing compliance decisions by resource users. The users of freshwater will tend to comply when they view the regulations as a legitimate and equitable response to a recognized problem. The program must also earn a reputation for being effective if it is to sustain the respect of those who are affected by its policies and actions.

Instigate Changes in Financial Investments

Implementing a freshwater inflows management initiative may require two changes in existing patterns of financial investment. The first is that the established pattern of investments in infrastructure (*e.g.,* dams, water diversion projects, urban expansion)—patterns that increase the demand for water and affect how it is allocated—may need to be reconsidered if adequate flows to the estuary, as defined by the "sustainability boundary," are to be restored or sustained. The second change requires securing the flow of funds required by the institutions responsible for implementation if they are to effectively implement the program over the long term. Often the implementation phase will require sustained investments in institutional capacity building.

Market forces, increasingly markets that operate at the global scale, are frequently the dominant cause of changes in land use, in growing demands for freshwater and on resulting pressures on the qualities of estuaries. The successful implementation of a program or plan to sustain freshwater inflows to an estuary may therefore require modulating financial investments made in agriculture, power generation, and urban development. Such changes may be vigorously opposed by those anticipating economic gains from such investments.

Funding for program implementation is traditionally seen as the responsibility of government. There are four basic mechanisms by which governments raise the revenues to implement a program: taxes, user charges, borrowing (bonds and loans) and grants. Particularly in the poorer developing nations, national budgets are under enormous pressure. Needs for defense, health care, education or response to a natural disaster may alter national priorities and reallocate funds pledged for the implementation of the policies or action plan formally agreed to in Step 3. The economic climate both in the nation and internationally may change significantly over the many years that a linked estuary-to-catchment management program needs to be implemented if it is to succeed in achieving its long-term goals. Such changes can pose continuing challenges to those working to sustain an IWRM program.

Engage in Adaptive Management

Central to the practice of adaptive management is sustained and carefully targeted monitoring. Such monitoring falls into four broad categories. The first, as discussed in Step 2, is to monitor freshwater flows at selected sites in the catchment and points close to major discharges to the estuary. Continuous monitoring is best since important pulses may be of short duration and easily missed. Second, depending upon the issues identified in the analysis phase, monitoring of flows may be complemented by regular monitoring of water quality through a combination of measurement at important known discharge points (for example a mine or industrial facility) and periodic measurement of substances of concern in the river, groundwater or estuary. A third focus for monitoring should be directed at the abundance and distribution of the VECs that the inflow rules have been designed to conserve or restore. Finally, there should be some monitoring of selected measures of program performance in terms of the behaviors that most directly express the implementation of IWRM rules and procedures. These may include data on permit processing, enforcement actions and, very important, voluntary compliance with the program's policies.

Since ecosystems at the catchment and estuary scale are living systems that are in a constant process of change, monitoring activities should be linked to further research that can help interpret the data that are gathered and suggest the adjustments that should be considered to increase or sustain the efficiency and impact of the program. The implementation of new rules governing the allocation of water, and the monitoring of the accompanying changes in the system will invariably produce surprises and suggest new insights and ideas. In an adaptive management process these are welcomed and can form the basis of a culture that encourages learning. As in Step 2, new management techniques are often best tested initially at a pilot scale and applied to the whole system only when they have been shown to be workable and effective.

STEP 5: EVALUATE THE PROGRAM AND LEARN FROM THE RESULTS

There are dozens of approaches and methodologies for both self-assessment and external evaluation. These approaches vary greatly in their purposes, substantive rigor and the validity and persuasiveness of the conclusions they offer. These many methods can be assigned to two broad categories (Lowry et al., 1999b).

- ***Process or performance evaluations*** are designed to assess the quality of the execution of a program and the degree to which it meets the mandate and responsibilities awarded to it in Step 3 and/or the commitments made to a funding institution. Here, the focus is upon accountability and quality control to the program as designed. There may be no attempt to determine if the assumptions underlying the project design are well-founded and will likely to lead to desired outcomes.

- ***Outcome evaluation*** assesses the impacts of a program upon the environment—and in particular the VECs—and the societal conditions and human activities of concern to the program. An outcome evaluation examines the trends and indicators of direct relevance to the program and works to objectively estimate the relative contributions of IWRM policies and processes to observed social and environmental change. The relevant outcomes may include such expressions as a decrease in the destruction of important habitats such as mangrove wetlands or coral reefs, changes in the condition of VECs, and changes in target group behavior.

Most ecosystem-based management programs, particularly in developing country contexts, emphasize process evaluation. This is sensible since in the great majority of cases, ecosystem-based management, as expressed in ICM and IWRM programs, is a departure from traditional sector-by-sector planning and decision-making. Such young initiatives are, therefore, most concerned with identifying, and prioritizing the issues to be addressed, conducting the necessary studies, building capacity and winning political support for the actions and policy reforms required. Process evaluation typically addresses the outputs that such initiatives have generated—the number and quality of its reports, the number of people trained, the equipment and services that have been purchased, the degree to which stakeholders have been consulted. Since such programs have often benefited from financial investments by national and international institutions, evaluations are designed to assess the effectiveness and efficiency of the execution of a program and the degree to which they have met the commitments made to their funders. The results are frequently considered confidential and are not widely distributed (Lowry et al., 1999a,b8 and Lowry, 2000).

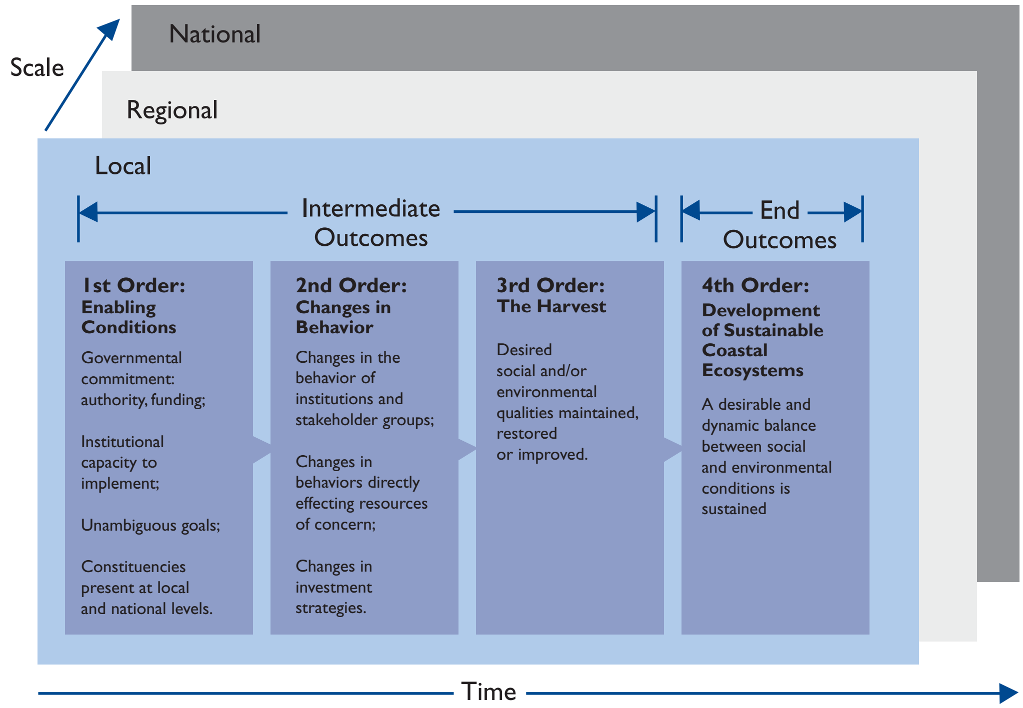
As the various expressions of ecosystem-based management mature, the need to complement methods of evaluating the processes of management described in this Guide with methods for assessing the outcomes of management becomes increasingly important. A unifying framework is needed that can disaggregate the ultimate goal of sustainable development into a sequence of more tangible thresholds of achievement. Such a framework was developed for assessing the outcomes of investments in water quality restoration (USEPA, 1994) and has been adapted to ecosystem management as a complement to the policy cycle (Olsen et al., 1997; Olsen, 2003). This framework (**Figure 9**) provides a means for tightening the linkages between planning, implementation and the achievement of social and environmental goals.

The framework identifies three Orders of Outcomes in this process. The First Order includes the results of a successful participatory, issue-driven planning process described here in Steps 1 through 3. These outcomes, as described at the beginning of Section VIII, create the preconditions for the full-scale implementation of an ecosystem management program. The Second Order addresses the outcomes of implementing a program as these are expressed by the changes in behavior described in Step 4. Only when such changes in behavior have been successfully implemented for several years can one expect to see the responses in the estuary and the associated benefits to the human uses dependent on those qualities. These are the Third Order outcomes that constitute the fulfillment of the program's goals as these were framed in Step 2. In an operational sense, the ultimate goal of sustainable forms of coastal development is a "north arrow" that points in the direction of desired change during the years of effort that are required to achieve Third Order goals at the scale of a large human-dominated ecosystem. It is important to recognize that some expressions of First, Second and Third Order outcomes will accumulate concurrently within a given time period. While there are causal relationships between the three Orders, they are not and should not be achieved in a strictly sequential order.

A companion paper prepared for the Global Program of Action for the Protection of the Marine Environment from Land-based Activities offers sets of indicators associated with the first two Orders that can used to assess progress in ecosystem-based management programs (Olsen et al., in press, UNEP/GPA, 2006).

In a program that is practicing adaptive management, the periodic external evaluations typically conducted by international organizations in developing country contexts should be complemented by frequent self-assessments. These are conducted by those involved in implementing the program—both the organizations with a formal role in the program and representatives of the user groups

Figure 9
The Four Orders of Outcomes in Ecosystem-Based Management



OLSEN (2003)

affected by the program's actions. Such self-assessments should draw on the four forms of monitoring described in the final section on Step 4. The purpose is to internalize the learning process within the program and to encourage the adjustments that will likely be necessary in terms of how the program is implemented as it responds to its own experience and to changes in the social, political and environmental context within which it is operating.

IX. CONCLUSION

Estuaries play a critical role in the functioning of the planet. They are already heavily stressed by the growing intensity of human activity in the world's coastal regions. These pressures are being further amplified by growing demands on the planet's limited supplies of freshwater—causing inflows to estuaries to be reduced, polluted, or eliminated. Yet, freshwater is the lifeblood of every estuary. It is the basis for their uniquely complex functioning and the extraordinary wealth of goods and services that they provide to humanity.

There is an urgent need to implement approaches to integrated water resources management that begin by recognizing the need to allocate sufficient freshwater to sustain rivers and estuaries as healthy ecosystems and then make allocations for additional human needs. This Guide describes a step-by-step process that links the catchment to its estuary and proceeds from issue definition and planning, to winning formal commitment to IWRM policies and procedures and on to implementation. Each step describes the priority actions that integrate the best available science with a participatory and transparent management process. To succeed and generate long-term societal and environmental benefits, the approach described in this Guide must be implemented over many decades. As expressions of adaptive ecosystem management, IWRM programs must adapt to changing conditions and to their own experience. They should be sources of new knowledge. In such long-term efforts, it is important to publicly celebrate successes—particularly when positive results come from local initiatives and local creativity in problem-solving.

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XI. ADDITIONAL SOURCES OF INFORMATION

The interested reader is referred to the following websites and publications that provide further information on some of the topics discussed in this Guide.

Environmental Flows

The following websites provide information on environmental flows:

The Nature Conservancy (TNC): www.nature.org/freshwaters

The World Conservation Union (IUCN): www.iucn.org/themes/wani

The following reports provide information on environmental flows:

Annear T, Chisholm I, Beecher H, Locke A and 12 other authors. 2002. *Instream Flows for Riverine Resource Stewardship.* Instream Flow Council, Cheyenne, Wyoming.

Dyson, M., Bergkamp, G. Scanlon, J. (eds). Flow. The Essentials of Environmental Flows. IUCN, Gland, Switzerland and Cambridge. Available from the IUCN Publications Services Unit. http://www.iucn.org, and the IUCN Water and Nature Initiative, http://www.iucn.org/themes/wani/publications.html

Richter, B.D., J.V. Baumgartner, J. Powell, and D.P. Braun. 1996. A method for assessing hydrologic alteration within ecosystems. *Conservation Biology* 10:1163-1174.

The following is a report of a course on environmental flows (not necessarily just coastal), in Tanzania, highlighting issues they consider important:

Tanzania Ministry of Water and Livestock Development. (2003). Building capacity to implement an environmental flow programme in Tanzania. World Bank Netherlands Water Partnership Program—Environmental Flow Allocation Window, IUCN-The World Conservation Union—Water and Nature Initiative http://www.iucn.org/themes/wani/pub/EFTanzania.pdf

These reports provide detail on water management in Texas:

National Wildlife Federation, Environmental Defense & Lone Star Chapter of the Sierra Club. (2005). Q & A for freshwater inflows. Retrieved December 21, 2005 from http://www.texaswatermatters.org/pdfs/q_and_a.pdf

National Wildlife Federation, Environmental Defense & Lone Star Chapter of the Sierra Club. (2005). Principles for an environmentally sound regional water plan. Retrieved December 21, 2005 from http://www.texaswatermatters.org/pdfs/articles/nwf-sb1principles.pdf

Texas Parks and Wildlife Department. (2005). Freshwater inflows and estuaries. Retrieved December 21, 2005 from http://www.tpwd.state.tx.us/landwater/water/conservation/coastal/freshwater/

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Water Budgets

Dunne, T. and L.B. Leopold. 1978. Water in Environmental Planning, San Francisco, CA: W.H. Freeman and Co.

The Precautionary Principle

Harremoes, P., Gee, D., MacGarvin, M., Stirling, A., Keys, J., & Wynne, B. et al. (2001). Late lessons from early warnings: The precautionary principle 1896-2000 (Environmental issue report No. 22). Copenhagen: European Environmental Agency. http://reports.eea.eu/environmental_issue_report_2001_22/en

Eutrophication

Below is the website for the National Estuarine Eutrophication Assessment (NEEA), which contains a database of 141 U.S. estuaries with satellite imagery, maps (including salinity zone information), location, physical characteristics, land use and population, hydrology, climate, oceanic details, sediment and nutrient loads, an image library, and discussion forum. NEAA is concerned with the effects of nutrient enrichment in U.S. estuaries, and contains the foundation document for the comparison of US estuarine eutrophication status, used at all levels of management and policy development:
http://ian.umces.edu/neea

Chesapeake Bay Foundation (2003) Fact Sheet: Water Pollution in The Chesapeake Bay. Outlines sources of nutrients and water pollutants, and discusses implications of nutrient loading on dissolved oxygen levels. http://www.cbf.org/site/PageServer?pagename=resources_facts_water_pollution

Global Water Data and Trends

UNESCO provides a free, downloadable, pdf version of the UN World Water Assessment Program's (WWAP) Water Development Report: Water for People, Water for Life (2003). The report is targeted to policy-makers and resource managers, and aims to provide a comprehensive review of the state of the world's freshwater resources. The document opens with a chapter describing the global water situation.
http://www.unesco.org/water/wwap/wwdr/index.shtml

UNEP offers an online version of their publication entitled Vital Water Graphics (2003) at http://www.unep.org/vitalwater/. The goal of this publication is to present an overview set of graphics, maps and other illustrations, describing the state of the world's fresh and marine waters.

Estuaries and the Importance of Freshwater Inflows

Nixon, S. W., S. B. Olsen, E. Buckley, R. Fulweiler. Lost to the Tide–The importance of freshwater flow to Estuaries. (2004) Available at http://www.crc.uri.edu

The EPA's National Estuary Program outlines a number of challenges facing estuarine ecosystems, including toxic pollutants, habitat degradation, nutrient loading (eutrophication) and alterations to freshwater inflows. This site also introduces several key management approaches relevant to these challenges.
http://www.epa.gov/OWOW/estuaries/about3.htm

Estuarine Classification and Morphology

NOAA's National Ocean Service provides a useful and straightforward overview of estuarine classification and morphology at http://oceanservice.noaa.gov/education/kits/estuaries/welcome.html. Also included in this online tutorial is an overview of estuarine habitats, the threats facing them, and efforts to monitor and protect estuaries nationwide, all described in easy to read, non-technical language.

XII. PROJECT DOCUMENTS AVAILABLE ON THE WEB

The publications listed below were produced by the CRC-TNC project team. They are available on the CRC Project Website or can be ordered by contacting the Coastal Resources Center, Graduate School of Oceanography, University of Rhode Island Bay Campus, 220 South Ferry Road, Narragansett, RI 02882.
Ph: 401-874-6224
Fax: 401-874-6920
Website: http://www.crc.uri.edu/

Background Information

Montagna, P.A. (2004). *A Freshwater inflow methods guide.* Port Aransas, TX: Marine Science Institute, University of Texas at Austin.

Nixon, S. W., S. B. Olsen, E. Buckley, R. Fulweiler. (2004). Lost to the Tide The importance of freshwater flow to Estuaries. Narragansett, RI: University of Rhode Island, Graduate School of Oceanography.

Volk, R. (2005). *Incorporating an IWRM approach into ICM.* Washington, DC: United States Agency for International Development.

Dominican Republic

Herrera-Moreno, A. (2005). *Historical synthesis of biophysical information of Samana region, Dominican Republic.* Santo Domingo, DR: Center for the Conservation and Eco-development of Samana Bay and its surroundings (CEBSE, Inc.).

XII. PROJECT DOCUMENTS AVAILABLE ON THE WEB, continued

Herrera-Moreno, A. (2005). *Síntesis de información biofisica histórica de la región de Samana (Borrador/documento en elaboración).* Santo Domingo, DR: Centro para la Conservación y Ecodesarrollo de la Bahía de Samana y su Entorno (CEBSE, Inc.).

Kramer, P. (2005). *Samana Bay rapid ecological assessment.* Presented at: The USAID Watersheds Planning Meeting (May 19-20), Washington, DC.

Lamelas, P. (2004). *Workshop summary.* Proceedings from: The Influence of the Yuna Watershed on the Estuary of Samana Bay CEBSE Workshop with Local Stakeholders (October 2), Santo Barbara de Samana, DR.

Lamelas, P. (2005). *Perfil socio económico de las comunidades de Sánchez, Sabana de la Mar y Agua Santa del Yuna.* Santo Domingo, DR: CEBSE, Inc.

Núñez, F. (2006). *Resumen del taller.* Socialización de Resultados de la Evaluación del Impacto de la Cuenca del Yuna en la Bahía de Samana (17-18 Febrero), Hoyo del Pino, Bonao.

Núñez, F. (2006). *Workshop summary.* Proceedings from: Sharing the Results of the Evaluation of the Impact in the Yuna River's Watershed (February 17-18), Hoyo del Pino, Bonao.

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Medina, J., Ortiz, A., &, Núñez F. (2005). Project Yuna River Basin: Phase II. Santo Domingo, DR: The Nature Conservancy.

Tobey, J. (2004). *Human dimensions of the Yuna Watershed and Samana Bay estuary.* Presented at: The Influence of the Yuna Watershed on the Estuary of Samana Bay (September 21), Santo Domingo, DR.

Tobey, J. (2004). *Dimensiones sociales de la cuenca del Yuna y el estuario la Bahia de Samana.* Presented at: The Influence of the Yuna Watershed on the Estuary of Samana Bay (September 21), Santo Domingo, DR.

Tobey, J. (2004). *Impacts of altered freshwater flows to estuaries: Yuna river watershed and Samana Bay, Dominican Republic: Draft Profile.* Includes: Ortiz, A. Appendix 1: Water budget of the Yuna river watershed.Narragansett, RI: Coastal Resources Center, University of Rhode Island and The Nature Conservancy.

Tobey, J. (2004). *Workshop summary.* Proceedings from: The Influence of the Yuna Watershed on the Estuary of Samana Bay (September 21), Santo Domingo, DR.

Tobey, J., & Mateo, J. (2004). *Dimensiones sociales de la cuenca del Yuna y el estuario de la Bahía de Samana.* La Influencia de los Flujos de Agua Dulce Desde la Cuenca del Rió Yuna en el Estuario de la Bahía de Samana (21 de Septiembre), Santo Domingo, DR.

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Wang, J., & Schill, S. (2005). *Using field and satellite data to create a water balance for the Yuna River Watershed, Dominican Republic.* Santo Domingo, DR: The Nature Conservancy.

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Mexico

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