Principles for Protecting Freshwater Resources and Biodiversity during a Low-Carbon Energy Transition

Carey W. King, Ph.D.

Assistant Director

energy institute
THE UNIVERSITY OF TEXAS AT AUSTIN

Introduction

Energy production systems require water inputs to produce and transform energy resources. Growing populations need fresh water for drinking and agriculture. Climate change will express itself via changes to the hydrological cycle. These linkages have been much explored in technology, research, and policy. Freshwater biodiversity, however, also depends upon naturally flowing and clean water in which to thrive, and these freshwater ecosystems are impacted by human decisions in response to future water, energy, and climate change constraints. Through our past experiences and research , we do understand much about these multidimensional interactions, but unfortunately, there is still more to learn regarding the impacts that our energy, water, and climate-related choices will have on the ecosystems around us.

The purpose of this report is to begin the conversation on the risks to conservation of regional freshwater biodiversity that are driven by national and global strategic objectives related to solving water, energy, and climate challenges.

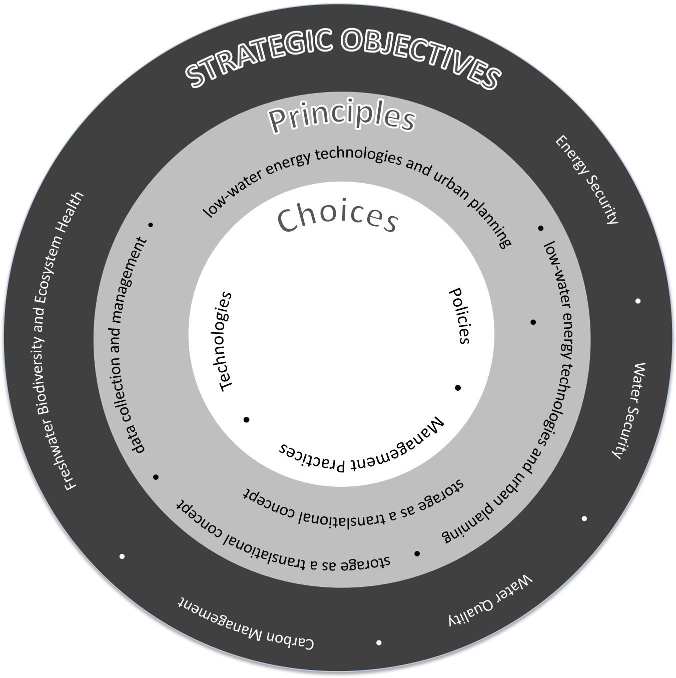


Figure 1. Five governing principles provide guidance for discussion on how to achieve multiple objectives related to energy, water, climate change, and biodiversity.

There are many tradeoffs to consider in achieving future energy and environmental objectives while protecting freshwater biodiversity, and this report suggests five overarching principles that help guide decision making:

- Advance Integrated Water Resource Management
- Protect and restore environmental flows
- Invest in energy technologies and urban planning to minimize water consumption, withdrawal, and stream alteration
- Use storage as a translational concept
- Effective governance needs good data collection and management

These principles are not specific answers because when considering multiple objectives there is no single optimal answer. These principles, however, provide context to understand potentially disparate objectives: energy security, water security, water quality, carbon management, and freshwater biodiversity and ecosystem health. To achieve any one of these strategic objectives, one can choose one or more of many policy choices (regulation, taxes, subsidies, etc.), and each policy can promote one or more technologies and management practices.

This structure of this report considers projections of United States future energy supplies to infer how the energy sector might impact the freshwater biodiversity objective. It is important, however, to remember that we do not need to imagine future energy scenarios to plan for protection of freshwater biodiversity – the energy sector represents only one aggregate water user and water constraints driven by all water users already impair freshwater biodiversity today. *The question presented here is: How do we manage current and future low-carbon energy supplies to protect freshwater biodiversity?*

In order to explore the most important technologies, management practices, and policies for reducing the impact of future energy production on freshwater biodiversity, The Nature Conservancy hosted a stakeholder workshop during the summer of 2012. The recommendations of this paper are informed by the participants of The Nature Conservancy workshop, The Nature Conservancy policy and research staff, existing literature, and previous research of the author and his colleagues. This paper discusses many of the options available to us today, introduces a decision matrix for evaluating options in the energy-water-carbon-biodiversity nexus, and summarizes recommended principles to guide future actions.

Water implications for future energy supply, climate trends, and biodiversity

The energy supply chain is changing, and this can impact freshwater biodiversity

Over the last decade the United States has seen the production and installation of more types of energy resources and technologies than in the previous century: wind turbines, photovoltaic panels, biofuels, and oil and gas from shale formations, etc. These actions, together with more efficient energy consumption, are a response to the depletion of many high-quality energy stock reserves (e.g. onshore conventional oil fields) and concentrated renewable flows (e.g. rivers with high flow rates and elevation changes for hydropower). But unlike at the beginning of the 19th Century, at the beginning of the 21th Century we know that human consumption and production of natural resources, largely the combustion of fossil fuels, has emitted greenhouse gases (GHG) at such a rate that we have overcome the absorptive capacity of the planet systems that absorb CO_2 (e.g. forests, ocean). Subsequently, the warmer average conditions caused by the accumulation of heat-trapping gases in the atmosphere are predicted to cause temperature regimes that humans have not yet experienced.

While many of the interactions of the energy-water-carbon nexus are known on the individual facility and technology level, there is much less coordination at larger scales. This lack of coordination in energy-water policy leaves many uncertainties as to how federal energy and climate policies can impact local and regional actors (GAO, 2012). Most of our future energy options have tradeoffs for water security, energy security, greenhouse gas (GHG) emissions, and biodiversity. Creating solutions with benefits in all areas will necessitate government agencies to work alongside both for-profit and non-profit non-governmental organizations as well as academic institutions.

It is important to point out that "coordinated" policy might not achieve one or more strategic objectives important to one stakeholder group. For example, the exemption of hydraulic fracturing from the Safe Drinking Water Act (SDWA) as part of the Energy Policy Act of 2005 was coordinated energy-water policy for the purpose of facilitating oil and natural gas production from shale (Tiemann and Vann, 2012). While there are state and federal regulations aimed to protect groundwater, and hydraulic fracturing water use and disposal are still regulated at the state level, the SDWA federal exemption has led to fear that the government and industry are not taking all necessary steps to protect water quality and freshwater biodiversity.

This example of water and energy policy is an important aspect of future North American energy supply. Since 2005, the subsequent production of natural gas from shale has played a significant role in facilitating lower U.S. CO_2 emissions from fossil fuel energy with respect to the peak emissions rate in 2007 (6,023 million metric tonnes CO_2 in 2007 and 5,494 million metric tonnes CO_2 in 2011; see Table 12.1 (EIA, 2012)) because of the recent shift from coal- to gas-fired electricity. However, high oil prices and a sluggish economy since 2008 are also major reasons for less energy consumption and energy-related CO_2 emissions. Long-term CO_2 emissions reductions as outlined by past proposed U.S. climate policies (e.g. Clean Energy Standard Act of 2012, American Clean Energy Security Act of 2009) necessitate nearly fully mitigated and/or reduced oil, coal, and natural gas consumption. The extremely high correlation between economic growth and low-cost energy (Cleveland et al., 1984, Cleveland et al., 2000, Hall and Klitgaard, 2012, King, 2010) is a primary reason for the reluctance of some stakeholders to wholeheartedly embrace full GHG mitigation that internalizes the costs of emissions into fossil energy prices.

In contrast to studies investigating energy-water impacts related to infrastructure and GHG emissions, there is little information describing how energy sector changes in freshwater withdrawal and consumption impact freshwater biodiversity. *This report begins to add the context of biodiversity to the existing information on the energy-water-carbon nexus.*

Depending upon one's perspective, the energy sector is a very large or very small water 'user', and for that reason it is important to use more specific terminology when discussing the *quantity* of water associated with energy production and consumption. The terms water *withdrawal* and *consumption* are more descriptive water flows within energy life cycles and will be used in this report[1].

---

[1] *Water withdrawal*: the water that is extracted from the environment and returned in liquid form to the same water basin (possibly with some alteration such as with higher temperature or higher dissolved constituents). *Water consumption*: water that is extracted from the environment but not returned in liquid form to the same water basin, primarily because of evaporation.

Climate trends for water resources

Because a warmer climate enables the atmosphere to hold more water vapor, changes in the water cycle are one of the major ways in which climate change is expressed. Global climate modeling generally predicts dry regions to become drier with wet regions becoming wetter, but with low confidence in attributing anthropogenic forcing to any changes in individual regional drought trends. Analyses of precipitation trends over the last half-Century show that there have likely been more global regions experiencing increased heavy precipitation events than not (IPCC, 2012).

Scientists have measured increased variability in precipitation more so than a change in average precipitation. For North America, historical observations indicate that it is likely that there has been an increase in heavy precipitation events, but the average trend is inconclusive (IPCC, 2012). Further, there is evidence of anthropogenic influence on land precipitation patterns of the 20th Century. Models and observed trends agree on a trend toward higher precipitation at high northern latitudes (50^o – 80^o N, northern Canada), lower precipitation in low northern latitudes (0^o-30^o N, Mexico to equator), but with no conclusive trend for mid-latitudes encompassing the majority of the United States and southern Canada (Zhang et al., 2007). Thus, the United States resides in between regions projected to have increasing (northern North America) and decreasing (Central America) precipitation. Additionally, under high greenhouse gas emissions scenarios, most climate models tend to show increased values for drought indicators (more consecutive dry days and/or more soil moisture anomalies) in southwestern United States and Central North America but no consistent anticipated trend in drought tendency for more northern states (see Figure 3-10 and Table 3-3 (IPCC, 2012)).

Changes in freshwater use from future low-carbon energy supplies

In order to limit the severity of impacts from climate change, including changes to the hydrological cycle, the world must emit much fewer GHGs from energy production life cycles. Proposed reductions in global annual GHG emissions targeted for 2030-2050 range between 50% and 80% relative to emissions during the last decade (IPCC, 2007). These global emissions reductions cannot occur without equivalent reductions in the United States. There is a variety of energy technologies that can be combined to reach these emissions targets for new and existing infrastructure, but there is a need to improve the beneficial coordination between water and climate policies (Pittock, 2011).

The United States Geological Survey estimates total U.S. freshwater withdrawals at 350 billion gallons per day (Bgal/d) in 2005 and consumption at 100 Bgal/d in 1995 (Kenny et al., 2009, Solley et al., 1998). The annual water consumption for thermoelectric power generation ranges near 3-4% of the U.S. total consumption, and annual thermoelectric withdrawals are 45-49% of U.S. total withdrawals. The last several years saw rise to a significant body of research characterizing implications and changes in water consumption and withdrawal for future energy supply scenarios – both low and high-carbon (Averyt et al., 2011, Chiu and Wu, 2012, DOE, 2006, King et al., 2008, King and Webber, 2008, Macknick et al., 2011). Thus, we have information to assess regional changes in water use associated with future energy scenarios, but because of various factors ranging from energy resource constraints to economic conditions to climate mitigation policies, no one can accurately predict the series and distribution of future energy investments in the U.S.

> In general, it seems that many of our future low and high-carbon energy options are more water intensive (e.g. higher water input per energy output) than past energy supplies. U.S. energy-related water withdrawal and consumption are expected to increase in business as usual scenarios, but likely more so for low-carbon and biofuel-intensive scenarios.

There are different anticipated water impacts for transportation fuels and electricity life cycles as currently there is very little coupling between electricity generation and transportation fuels. Considering energy for transportation, under both a business as usual (BAU) and diversified portfolio for energy interdependence by 2030, an estimated 4-5 Bgal/day, or 4-5% of U.S. total, could be consumed for production of fuels only for light duty transportation – primarily for irrigating feedstocks for low-carbon biofuels but also with some large regional consumption for unconventional fossil fuels (King et al., 2010). Considering BAU and low-carbon electricity generation scenarios to 2030, U.S. thermoelectric water withdrawal is expected to slightly decrease by 2%-14%, and water consumption is expected to increase 24%-42% with significant regional differences driven by the mix of generation portfolios (Chandel et al., 2011).

A recent study by The Nature Conservancy forecasted future changes in total energy-sector water use based on various energy scenarios to examine implications for freshwater ecosystems (McDonald et al., 2012). Annual water withdrawn was predicted to increase by 18-24%. Water consumption was predicted to more rapidly increase by 26% largely due to increased biofuel production. Regional differences indicated increased water withdrawal in the Southwest and Southeast may increase, with anticipated decreases in water use in some areas of the Midwest and Northeast. This author published a similar analysis with Environmental Protection Agency staff using their 9-Region MARKAL model to simulate a 40% reduction in energy CO_2 emissions by 2055 (Dodder et al., 2011). In that work, we estimated that total U.S. water consumption for electricity and transportation fuels could be 14-16 Bgal/day by 2030 when encouraging high conversions to electric vehicle travel, but closer to 13 Bgal/day with less electric vehicle travel. These 2030 estimates compare to 8 Bgal/d in 2005.

All the while we consider the water impacts of energy production, we must recognize the context that the vast majority of U.S. water consumption (> 75%) is for irrigating crops. In addition the overall water balances for water basins are largely driven by the evapotranspiration of the vegetation. The more we tie vegetation to energy via biofuels, the more we integrate our land and water resources to our energy supply.

Adding biodiversity to the energy-water-carbon nexus

Not only will climate change impact biodiversity through changes in the water cycle, but our choices for future energy supplies will also impact biodiversity. There exists a large body of literature that has established impacts of changing water flow, sediment, water quality, and thermal regimes on freshwater biological diversity (Annear et al., 2004, Bunn and Arthington, 2002, Poff et al., 1997, Poff and Zimmerman, 2010). Water withdrawal and consumption by the energy sector may increase in some areas and alter water quality and quantity in freshwater ecosystems, thus further threatening an already imperiled fauna. McDonald et al. (2012) statistically related historical water use by the energy sector to patterns of fish species endangerment, where water resource regions with a greater fraction of available surface water withdrawn by hydropower or consumed by the overall energy sector[2] correlated with higher probabilities of imperilment. Since future increases in energy-sector surface water use are

---

[2] McDondald et al. (2012) allocates 100% of water evaporation from hydropower reservoirs to hydropower.

anticipated to occur in areas of high fish endemism (e.g., Southeast), the study argued that additional management and policy actions will be needed to minimize further species imperilment.

Energy systems can impact water resources, and thus biodiversity

When crafting policies and best management practices that affect energy and water resources, there are a few broad, and potentially conflicting, strategic objectives for managing these resources. Some energy technologies and systems benefit one objective more than another. Thus, any individual technology, management practice, or policy can be simultaneously viewed in the context of each of these broad strategic objectives. A previous work by the author and colleagues has investigated the coherence between energy and water objectives (King et al., 2013). This previous work and its structure are used with the additional objective of *biodiversity and ecosystem health*. In this way, we can view the tradeoffs among energy, water, GHG emissions, and biodiversity for specific technologies and policies. See Appendix for descriptions of energy and water technologies and management practices that are listed in Table 1.

Strategic Objectives: Energy, Water, Carbon, and Biodiversity

To understand the tradeoffs among the multiple strategic objectives, consider the following definitions (King et al., 2013):

Water security[3] is the consistent and reliable availability of freshwater or the services it provides. Efforts that increase freshwater supply, reduce freshwater consumption for the same level of service (efficiency), or conserve freshwater consumption in aggregate (conservation) enhance water security.

Energy security[4] is the consistent and reliable availability of energy resources or the services they provide. Efforts that increase energy supply, reduce energy consumption for the same level of service (efficiency), or conserve energy consumption in aggregate (conservation) enhance energy security. Because this report does not explicitly discuss economic costs, any energy technology that produces energy or fuels is assumed to increase energy security, even if costs might be prohibitive.

Water quality is the chemical composition of water in lakes, rivers, and wetlands. Efforts that prevent impacts from human activity that alter the ambient natural aquatic environment

---

[3] In terms of water security, the default assumption for Table 1 is that water efficiency or conservation benefits freshwater biodiversity with the assumption that any 'saved' water remains in the environment (e.g. as instream flow). In reality, there are more complex feedbacks in that water 'saved' is often used for some other pure economic purpose that does not return the 'saved' water to the environment.

[4] Just as Stanley Jevons considered more efficient use of coal would exhaust coal resources quicker, not slower, historical data shows that human economies have continuously employed more energy-efficient technologies only to enable higher overall energy consumption (Polimeni, et al., 2008). This report does not address any differences between overall energy (or water) ***conservation*** versus energy (or water) ***efficiency***. Any goals for energy and water conservation should not be confused with efficiency. Policies that employ technology-specific tactics must consider if results are measureable at larger system scales (e.g. Independent System Operator regions, water basins, global).

due to, but not limited to, release of total dissolved solids, unnaturally warm or cold water, dissolved gases, and dissolved nutrients protect water quality.

Carbon management relates to efforts that reduce or avoid anthropogenic greenhouse gas (GHG) emissions in aggregate or sequester carbon from the atmosphere. For simplicity, the default assumption is that higher energy consumption equates to higher GHG emissions (because the vast majority of current U.S. primary energy consumption is of fossil fuels).

In addition to these four objectives that focus upon the energy-water-carbon nexus, the additional objective of this document is to consider freshwater biodiversity (for some discussion of energy impacts on terrestrial habitat, see (McDonald et al., 2009)):

Freshwater biodiversity and ecosystem health is the diversity of aquatic life in freshwater habitats and the natural processes that occur in a normal functional ecosystem. Efforts to minimize negative impacts on freshwater biodiversity and ecosystem health are numerous, but might include limiting the amount of water withdrawn and/or consumed, limiting alteration in the physical or chemical properties of the water, and limiting any barrier to the connectivity of a river system.

Summary of energy-water-carbon-biodiversity tradeoffs

Table 1 presents a list of energy and water technologies, legal instruments, and management practices that are relevant to the energy-water-carbon-biodiversity nexus (some items added to the table of (King et al., 2013)). The Appendix at the end of this report provides more description of each item in Table 1.

For each listed technology or management practice (left column), a relationship to the objectives is given as follows: an up arrow (↑) indicates that the technology helps to achieve the strategic objective, a down arrow (↓) indicates that the technology hinders achievement of the objective, a level arrow (↔) indicates that the technology has choices and tradeoffs that make its effect upon the objective site-specific or unclear, and dashes (--) indicate that the technology has no appreciable impact on the strategic objective. In situations where a technology can be used for widely varying purposes (e.g. hydraulic fracturing, which can be used for accessing natural gas and geothermal resources), multiple arrows indicate the outcome can be different depending upon the application.

The (●) symbol indicates policy choices that can be effective in affecting increased or decreased use of a technology or practice, and the (○) symbol indicates policy choices that are only moderately effective. The effectiveness of a particular policy in promoting a technological solution is independent of whether that solution produces good or bad outcomes for the objectives. In other words, it is possible to craft a policy that is effective at creating a negative outcome for any one strategic objective.

To briefly summarize takeaways from Table 1, several technologies show a “multiple win” scenario in terms of positively addressing more than three of the strategic objectives: low-flow fixtures, energy-efficient appliances and buildings, rainwater collection for non-potable uses, solar hot water heating, geothermal heat pumps, electricity peak shaving as a demand response method, solar PV power, wind power, combined heat and power (CHP), hydropower, and converting municipal waste to energy. Other technologies have various tradeoffs: biofuels development, groundwater pumping, electricity peak shifting for demand management, carbon capture and storage (CCS), greywater reuse for potable purposes, and inter-basin water transfer.

The costs and benefits of many water management practices and legal instruments are dictated significantly by the individual context within the water basin or region. For example, water funds and integrated water resource management are largely meant to increase water security and quality, thus benefiting biodiversity, but the degree of achieving any objective varies tremendously across each case study. The subsequent descriptions of recommended principles to protect freshwater biodiversity illustrate some ideas on how to incorporate the technologies, management practices, and legal instruments of Table 1 in managing water resources impacted by energy and climate policies.

Table 1. Various technologies and practices impact water, energy, and environmental objectives in different ways.

	Technologies and Management Practices …	… can be used to meet …	… Strategic Objectives …					…. with help from …	… Policy Choices							
			Water Security	Energy Security	Water Quality	Carbon Mgmt.	Freshwater Biodiversity and Ecosystem Health		Product Labeling &/or Certification	PR Campaign	Data Gathering	Mandate/ Regulation	Right Pricing	Subsidy	Financing	Public Works
Energy Management	Energy-conserving appliances and buildings		↑	↑	--	↑	↑[a]		○	○		●	○	●		
	Electricity peak shifting		↔	↔	↔	↔	↔			○	●		●	○		
	Electricity peak shaving		↑	↑	↑	↑	↑			○	●		●	○		
Electricity Generation	Solar photovoltaics		↑	↑	--	↑	↑					●	●	●	●	○*
	Wind power		↑	↑	--	↑	↑					●	●	●	●	○*
	Concentrating Solar power (steam cycle)		↓	↑	--	↑	↓					●	●	●	●	○*
	Freshwater wet-cooled power plants (steam cycle)		↓	↑	↔	--	↓					○				○*
	Sea water wet-cooled power plants (steam cycle)		↑	↑	↔	--	↑[b]					○				○*
	Dry-cooled power plants (steam cycle)		↑	↓	--	↔	↑					○	●		●	○*
	Gas combustion turbines		↑	↑	↑	↔	↑									
	Carbon Dioxide Capture		↓	↔	↔	↑	↓ to ↔				●	●	●	●	●	○
	Combined Heat and Power		↑	↑	↑	↑	↑					●	○	●	○	○*
	Hydropower		↑	↑	↓	↑	↓					●	○		●	●
Energy Resource Extraction and Waste Injection	Conventional oil and gas extraction		↓	↑	↔	↓	↔					●	○			
	Hydraulic fracturing		↓	↑	↔	↔	↔					●	○			
	Mining (coal, uranium)		↓ to ↔	↑	↓ to ↔	↓	↓ to ↔					●	○			
	Carbon Dioxide Sequestration		-- to ↔	↔	-- to ↔	↑	-- to ↔				●	●	●	●	●	○
	US Corn Ethanol (Midwest)		↔	↔	↓	↔	↓ to ↔				●	●	●	●		
	Brazilian (State of Sao Paulo) sugar cane ethanol		↔	↑	↔	↑	↓ to ↔				●	●	●	●		
	Solar hot water heating		↑	↑	↑	↑	↑		○	○		●	●	●	○	
	Geothermal heat pumps		↑	↑	↔ to ↑	↑	↑		○	○		●	●	●	○	
	Municipal waste to energy		↑	↑	--	↑	↑					●	●			●
Water Supply and Management	Low-flow water fixtures		↑	↑	--	↑	↑[a]		○	○		●	○	●		
	Distributed rainwater collection (non-potable)		↑	↑	↑	↑	↔			○		●	○	●		
	Distributed rainwater collection (potable)		↑	↓	↑	↓	↔					●	●	●	○	
	Groundwater pumping		↔	↓	--	↓	↔			○	●	●	●	●	○	
	Desalination		↑	↓	↓	↓	↔ to ↑					●	●		●	●
	Greywater and reclaimed water use		↑	↔	--	--	↑[a]					●	●	○	○	●
	Aquifer storage and recovery		↑	↓	↔	↓	↔				●		●			●
Legal Instruments	Conservation Easements		↔ to ↑	↓ to ↔	↔ to ↑	↔ to ↑	↔ to ↑		●		●				○	●
	Water rights and permits		↔	↔	↔	↔	↔					●				
	Inter-basin water transfer		↔	↓	--	↓	↓				●		●			●
System Management Practices	Intergrated water resource management		↑	↔ to ↑	↔ to ↑	--	↔ to ↑		○	●	●					
	Water funds		↑	--	↑	--	↑		○		●		●		●	
	Non-potable water use for energy		↑	↓ to ↔	↑	↔	↑		○	○	●	●	●	●	○	●

○* Because many cities and regions have electric grids operated by government-owned utilities, electric generation infrastructure projects are public works projects.

a: Assuming in combination with ecologically based limits on further water withdrawals to ensure instream flows

b: There can be impacts to marine biodiversity

	not likely effective
○	somewhat effective
●	effective

***Recommended Principles* to protect freshwater biodiversity in a future with climate change and low-carbon energy**

As societies experience new challenges, they require added complexity to solve these challenges (Tainter, 1988, Tainter and Patzek, 2012). The means for handling this increased complexity comes from either increased energy consumption, increased information processing, or both. More than increasingly efficient energy technologies and systems, what we need in the future are increasingly resilient organizations and social constructs that recognize the differences between our historical trajectory and future visions (Dearing et al., 2010, Rockstrom et al., 2009, Westley et al., 2011). We can try to label our future visions as *transformative* or *sustainable pathways* and *resilient economies and societies*. However, a driving future characteristic is the need to have multiple stakeholders learn to work together in new ways rather than employ past solutions that were often in isolation. The world has effectively passed the time when optimal isolated solutions have minimal isolated impacts – environmentally, economically, and socially. Our contemporary and future energy and environmental problems cannot be solved by focusing on a single issue or variable. Because of the complex interactions between multiple energy and environmental objectives, we now live in a time and place where a single “optimal” solution cannot be defined, much less derived. Beneficial solutions can now be defined as those that keep us from exceeding a “space” defined by critical boundaries and thresholds rather than finding the optimal location within the space (Rockstrom et al., 2009).

Acting on the following recommended principles inevitably requires tradeoffs for the inclusion of several of the energy technologies, management practices, and legal instruments described in this document and elsewhere. These principles are organizational concepts that allow stakeholders to view how individual technologies and policies can be included in holistic solutions that practically have physical benefits and impacts in one location yet can also benefit people and ecosystems somewhere else. These principles are important for creating the necessary dialogue among energy and water industries, environmental stakeholders, the public, and regulators.

Integrated Water Resource Management (IWRM) – ensure energy and biodiversity are included

IWRM is a collaborative engagement process with the goal to consider ecosystem health and biodiversity in tandem with other goals for freshwater use such that management of water resources is as fair and equitable as possible to all water users. Technically, no water use or impact is excluded within IWRM; practically, all uses and impacts will not be addressed to full satisfaction by all.

While often neglected historically in water planning, energy production systems should be an integral consideration. One of the most recent impacts has been that drought and high water temperatures are influencing the ability of thermoelectric power plants to fully operate and/or meet regulatory limits across the United States from Texas to the Midwest to Connecticut (Flessner, 2010, Reuters, 2011, Wald, 2012, Wald and Schwartz, 2012). Of course, these factors also impact freshwater ecosystems and biodiversity. The designs for nuclear and other thermoelectric generating stations did not account for the magnitude of some of the low precipitation and high temperature events of the last few years. Because dry cooling technologies operate less efficiently than wet cooling systems, a move to dry cooling to benefit freshwater biodiversity and increase water basin resilience will increase energy costs to some degree. Further, retrofitting wet cooling systems from once-through to cooling towers, as potentially required under future rulings and local decisions driven by the Clean Water Act Section 316(b), has increased cost implications for electricity consumers (EPRI, 2007, Stillwell et al., 2011).

Ultimately, the electric power industry's product is of such high value that added economic value from consuming water is usually above the direct cost of water. This enables the electricity industry to afford higher water costs than most competing users (Smart and Aspinall, 2009). Thus, the need for water security for cooling thermoelectric power plants provides the driver for water conservation efforts in that industry. On the other hand, economic sectors that rely on ecosystem services can have more incentive to keep sufficient freshwater flows than industry or agriculture. For example, it can very well be the case that fisherpersons are willing to pay a price for some additional stream flow that exceeds the price that farmers are willing to sell some of their water (as was estimated in 51 of 67 river basins that have a significant level of irrigation (Hansen, 1991)).

Many low-carbon thermoelectric supplies (e.g. nuclear and coal/natural gas steam power plants with carbon capture) have increased cooling needs per unit of electricity put on the grid, but wind, solar photovoltaics, and natural gas combustion turbines can help increase water-resiliency. Stakeholders can consider these energy-water tradeoffs during IWRM, including in state water planning processes. However, the different boundaries of electricity markets, water basins, and governmental boundaries (e.g. counties, states) create difficulty for holistic solutions.

The thermoelectric cooling anecdote exemplifies the future climate challenge. Air and water temperatures will increase. Drought frequency is predicted to increase in much of North America. All other energy systems that require water will run into increasingly competitive water situations with all other water stakeholders. Metrics for product life cycles, such as the water embodied in driving a vehicle (e.g. gallons of water per mile driven), can be useful for characterizing technology options, but these metrics must be correctly aggregated to total broader scales such as overall water consumption in a water basin (Bingaman, 2011, King and Webber, 2008, King et al., 2010). While we need to consider that our future energy supplies might need an increasing share of available water resources, it might not be best to put a water use limit on one product versus another (e.g. crops for food versus crops for biofuels). The IWRM process and the use of computational models can avoid such water allocation confusion, but the process is more effective if stakeholders understand and are part of model development.

This is why certification standards for products, such as the Alliance for Water Stewardship and Forest Stewardship Council, add value in terms of assessing products and business practices at proper ecosystem scales. Successful IWRM plans often include many of the following concepts to create arrangements that are as fair and equitable as possible to all water users:

- Use of the best available science, including recognition of the physical linkages between groundwater and surface water,
- reliable data and consistent definitions for water uses (withdrawal, consumption, diversion) upon which to make decisions,
- seasonal or flow and storage-related triggers that cause water users to adjust with the local and temporal conditions (e.g. governance of the water withdrawals from the Athabasca River for oil sands production in Alberta). In this way, all stakeholders are prepared when drought (or flood) conditions do occur.
- estimation of costs and benefits of potential solutions including the importance of determining the costs to implement and maintain a process/program while recognizing that some stakeholders cannot express their water-related values in terms of money,
- because the value of water is one of a larger set of local values (geographically) - local money, taxes, and incentives should fund local water solutions,
- metrics and/or models that assess basin-scale water flows that are consistent from top-down (basin scale) and bottom-up (product level) analyses, and

- preparation for rare events – planning for periods for society and nature to survive instead of thrive.

The Nature Conservancy's *Development by Design* (DbD) concept is a means to employ landscape and water basin-level context to the "mitigation hierarchy" (avoid, minimize, restore, or offset - in decreasing preferential order) when considering land and water resources development within IWRM (CEQ, 2000, Kiesecker et al., 2009). In the cases where environmental offsets are necessary to mitigate ecosystem impacts, DbD can benefit biodiversity by considering offset investments in a higher priority ecosystem than the one being disturbed by the immediate development project. In other words, in attempting to be as fair and equitable as possible to all parties, IWRM processes can consider avoiding development in the most ecologically sensitive areas and investing in ecosystem services in an area different than where a new energy (or other) project will occur. In practicing DbD, it can be beneficial to have non-governmental third parties to act as 'neutral' arbiters that help guide solutions for private developers to comply with government regulations. These third parties can enable private companies to consider basin-scale ecoregional planning and coordination that avoids regulatory and legal barriers (See BOX 1). In addition, stakeholders can engage in solutions that benefit the environment on a large enough scale and in strategic locations such that the entire benefit might be greater than the sum of the individual parts.

BOX 1:
How can stakeholder engagement processes minimize environmental footprints?

Concepts such as Integrated Water Resources Management and Development by Design can assist in creating plans that minimize the environmental footprint of energy activities of multiple companies in the same location.

One example of how IWRM and DbD can help biodiversity and energy production is by enabling cooperative use of a water pipelines and infrastructure for treating and distributing fresh and produced water within an oil and gas basin. This cooperative practice is not widespread as existing regulations can prevent collusion and coordination among competing oil and gas companies even when they operate in the same geographic region, ecosystem, and freshwater basin. Yet the environmental footprint in the basin is minimized by sharing infrastructure. Thus, each company might have to build and operate its own infrastructure, use truck transport to take flowback water to treatment facilities, or treat water on-site (Chernova, 2011). There are, however, some companies combining funding in research consortia, and some sharing of water treatment sites in oil and gas basins (Ryan, 2012).

Another example is the strategic removal of hydropower dams coordinated with hydropower upgrades and stream flow management to enhance migratory fish habitat. By bringing stakeholders together, concepts such as IWRM and DbD can plan the formation of an organizational entity that either owns the infrastructure or transitions it to an open-access model as is common for electrical transmission and natural gas pipelines.

Protect and restore environmental flows using legal instruments

Environmental flows are the seasonal and annual streamflow patterns needed to maintain healthy aquatic and riparian ecosystems. They include high flows as well as low flows, as both serve equally important ecological functions. Changes in natural streamflow patterns can severely impact the plants and animals that depend on the life-cycle cues they provide and the habitat they create and maintain. Dam operations, water withdrawals and return flows, and certain land-use practices alter streamflow patterns.

Environmental flows define limits on flow and water-level alteration, and are unique to each type of aquatic ecosystem. The legal designation and protection of instream flow is essential to ensure the physical flows needed to protect freshwater biodiversity. For example, native species that thrive in intermittent streams in the southwestern U.S. are adapted to very different streamflow patterns than those that thrive in northeastern mainstem rivers. Environmental flow determination should precede the siting and design of hydropower dams, and the timing and amount of water released from dams should, to the extent possible, create downstream environmental flows that mimic natural conditions. Likewise, water withdrawals for energy development, combined with all other upstream withdrawals, should always leave enough water in rivers to provide environmental flows.

Even energy supplies that have low water intensities (e.g. energy production per water consumed or withdrawn) can have significant local impacts in areas of water scarcity such as small streams and arid regions. For example, hydraulic fracturing for natural gas withdrawing and injecting millions of gallons of water for production of billions of cubic feet of gas has low water consumption intensity compared to many energy alternatives. However, if the needed water is extracted from local surface water or groundwater supplies near small streams (e.g. in Marcellus Shale (Weltman-Fahs and Taylor, 2013)), the timing of withdrawals can help avoid seasons of low or critical streamflow. While we can always learn more science about local and regional ecosystems, in many cases enough science is known to specify thresholds beyond which additional stream withdrawals can cause disproportionate harm to biodiversity. Working with local water trusts and Fish and Game Departments can help determine the timing and rates for instream flows to ensure that water flows in the river are high enough at specific times and places to meet energy project and biodiversity needs.

Some US states and interstate basin authorities legally enforce streamflow standards that protect environmental flows. In the eastern U.S., riparian water law allows state agencies to limit and periodically revise water withdrawal permits to ensure those standards are maintained.

In the western U.S., most surface water – especially during the irrigation season – has been appropriated for *beneficial use* on a first-in-time, first-in-right priority basis. The first water rights that were claimed on a river are called senior rights and have priority over subsequently claimed junior rights. Thus, during dry years, senior water right holders may use their entire allocations, while junior users may get “cut off” partway into the irrigation season. While the prior appropriation (e.g. “first in time, first in right”) doctrine of most of the western U.S. water rights outlines priorities, most of the water rights under prior appropriation were put in place in a time period of much lower human population, no consideration of climate change, less knowledge of past precipitation patterns, and little to no focus on biodiversity. Thus, the historical prior appropriation doctrine might not be the best framework for future water allocations in increasingly constrained basins. In fact, recent drought events forced regulatory agencies to subvert strict date-based priority allocation for reasons of public health and safety – power generation included (TCEQ, 2011, TCEQ, 2012).

Because the modern economy is driven by flows of energy, or power more specifically, the direct economic drivers to maintain those power flows usually outweigh the immediate direct and indirect benefits of healthy freshwater ecosystems and biodiversity. In some western states, instream flows have recently been accorded the legal status of a *beneficial use*. However, new instream flow rights, like any new water right, have junior priority and therefore cannot be invoked during droughts, when freshwater ecosystems are most vulnerable to excessive withdrawals. Only by changing the designated beneficial use of a senior water right to instream flow can an instream flow right be meaningful. Such legal changes can be expensive and time consuming, but they are needed since the simple act of conserving water only makes that water available for another offstream use. On the other hand, a water-consuming energy development can positively impact freshwater biodiversity by obtaining an existing senior water right or permit, converting a portion of that permitted water withdrawal from its previous use to industrial use, and legally dedicating the remaining water to instream flow.

As drought conditions often drive IWRM planning processes, it is paramount to fund assessments that quantify the environmental flows for a given river and basin that preserve biodiversity during drought. Government efforts, such as the United States Department of Interior's WaterSMART initiative (www.usbr.gov.WaterSMART), can provide expertise, coordination, and leadership. Different specific solutions will be needed for relatively water abundant regions (e.g. northeastern U.S.) versus water scarce (e.g. western and southwestern U.S.), but the tools, modeling approaches, and metrics for analysis can be consistent.

Also, planning processes should outline the prioritization of environmental flows relative to water uses in other sectors. Interesting but difficult questions arise: if an energy industry facility reduces water consumption and/or withdrawals for environmental benefits, is the owner of that facility to be compensated? For example, regulated and deregulated energy industries that are responsible for maximizing shareholder or bondholder value may be opposed to trading profit for environmental protection.

Invest in energy technologies as well as project and urban planning to minimize water consumption, withdrawal, and stream alteration

Freshwater biodiversity is enhanced by installing energy technologies that have less direct impact on freshwater resources. Thus, a recommended principle is to increase investment in the research, design, development, and demonstration of freshwater-conserving technologies related to low-carbon energy production. As can be seen within the list of energy-water technologies in this document, there are many opportunities, primarily within the electricity sector. In response to oil supply constraints and fuel/GHG regulations (e.g. Corporate Average Fuel Economy standards) the transportation sector will come increasingly tied to electricity and subsequent water impacts.

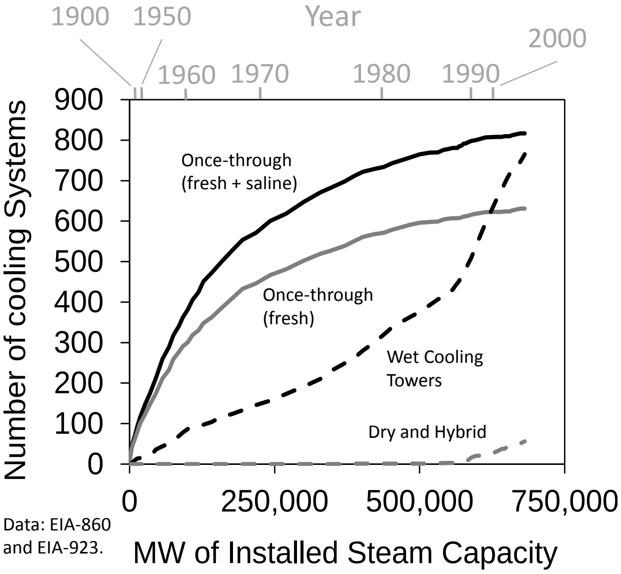
There are 100 GW of installed U.S. hydropower capacity at approximately 200 locations generating 250-290 TWh/yr (or 6-7 % of U.S. electricity). Because much of the hydropower infrastructure is old, there is an opportunity to increase hydropower capacity while decreasing impacts to freshwater biodiversity. Today, existing fish-friendly hydropower turbines need investment to get past the development and demonstration phases. When the Low Impact Hydropower Institute considers hydro projects for certification, it evaluates impacts with respect to eight general criteria[5]. Many existing projects have passed these criteria and been certified as "low impact" in the U.S., and many more could qualify with the deployment of advanced technologies. After years of research, design, and demonstration of efficiency and decreased fish impacts (94%-100% fish passage), hydropower turbine retrofit projects at

---

[5] The Low Impact Hydropower Institute is a non-profit 501(c)(3) organization dedicated to reducing the impacts of hydropower generation through the certification of hydropower projects that have avoided or reduced their environmental impacts pursuant to the Low Impact Hydropower Institute's criteria. The eight criteria are: (1) river flows, (2) water quality, (3) fish passage and protection, (4) watershed protection, (5) threatened and endangered species protection, (6) cultural resources protection, (7) recreational use and access, and (8) recommendations for dam removal.

large scale are underway, for example at Wanapum Dam (~ 1,000 MW) that resides 415 miles upstream of the mouth of the Columbia River (Hogan et al., 2012). This Wanapum project is significant because the successful experimental retrofit of 1 of the 10 turbines indicated increased power efficiency without affecting the survival of salmon smolts passing through the unit – giving confidence to move forward in replacing all of the original 10 turbines.

Additionally, many freshwater-free energy technologies can be employed. Dry cooling technologies for thermoelectric power plants clearly reduce water consumption and withdrawal, but the local situation determines the circumstances in which they are appropriate. While very few new once-through cooling designs have been installed since the early 1980s (see Figure 2), from the standpoint of the power plant owner, the benefits of retrofitting once-through systems to cooling towers, possibly for new Phase II regulations of Clean Water Act Section 316(b)[6], must weigh against the costs. Oil and gas extraction, particularly from unconventional resources such as shales, can increasingly use saline water for mining needs such as hydraulic fracturing. Low-water and low-carbon renewable energy technologies such as solar photovoltaics and wind power have had past support at both federal and state levels.



Data: EIA-860 and EIA-923.

Figure 2. The type of cooling systems installed as a function of time and capacity of the U.S. thermoelectric generation fleet.

Because many future solutions involve collective agreements and management, *public-private partnerships can be a valuable funding option*. Public benefits from freshwater conservation can help fund common energy industry infrastructure for water recycling and reuse. Funding models can also work in the other direction with energy projects funding cheaper per unit water conservation projects in agriculture in order to make water available for energy or other sectors (Cook et al., 2013, Hansen, 1991). As both federal and state budgets continue to be tight after the 2007-2009 U.S. (and global) recession, cooperative funding of projects by private and non-governmental agencies might become more prevalent. Trusted third parties that help coordinate ecoregional planning can also solicit or be a part of new corporate entities. Smart grid demonstration initiatives provide examples of public-private funding forming non-profit corporations to foster cooperation and innovation among universities, private companies, city governments, and environmental organizations[7].

In addition to individual large-scale technologies, the collective benefits of many small-scale energy and water investments creates freshwater resiliency. Improved building codes following green building and Leadership in Energy and Environmental Design standards can help conserve both water and energy to lower GHG emissions associated with operating buildings. The promotion of native landscapes, passive

---

[6] http://water.epa.gov/lawsregs/lawsguidance/cwa/316b/upload/Notice-of-Data-Availability-Factsheet.pdf: accessed October 12, 2012.

[7] Pecan Street Research Institute: http://www.pecanstreet.org/

solar design, and the removal of split ownership incentives[8] are notable efficiency/conservation tactics. Urban designs can integrate local rainwater capture for use within buildings, storing runoff during intense precipitation periods (expected to increase in frequency with climate change) and recharging local aquifers that can be part of aquifer storage and recovery systems. This level of systems thinking can create the situation to increase dialogue between water and electricity utilities.

Storage as a translational concept

“Storage” and “demand management” are concepts considered in both water and energy sectors that can help ‘translate’ motives and solutions between the sectors to enable cooperation. The energy and water sectors should work and learn together how to use new energy and water storage concepts to manage future shifts in climate patterns and to low-carbon energy generation.

Both energy and water demand follow regular diurnal to annual cycles. U.S. electricity demand increases in the summer due to residential and commercial air-conditioning loads. U.S. water demand also increases in the summer due to irrigation in both agriculture and residential sectors. Natural gas demand, driven largely by heating demand in the northern and northeastern U.S., is higher in winter than summer. As natural gas has recently (2011 and 2012) become more prominent as a fuel for electricity generation (due to economic competitiveness and/or more strict regulations on coal power), North American demand could level or become higher in summer.

Both the energy and water industries have used storage to handle these demand changes: summer accumulation natural gas in salt domes and depleted reservoirs, spring collection of snowmelt in reservoirs for summer irrigation and hydropower. Climate change and lower GHG emission energy technologies will likely push both industries toward more reliance on storage systems and technologies. Dam operators will continually learn and adjust to earlier and faster snowmelt. As future precipitation patterns become less predictable, it can be advantageous to use storage as part of adaptive management strategies. For example, aquifer storage and recovery systems can help manage for extreme drought alongside of other planning by storing water underground in times of high rainfall for extraction during drought.

The least water-intensive electricity technologies are driven by wind and solar power flows. In turn, wind turbines, photovoltaic panels, and concentrating solar power systems are not disptachable as stand-alone technologies. Pumped hydropower storage is the most prominent concept for using water to shift electricity demand and smooth variable generation input to the grid. Ecological impacts are minimized if pumped storage is used in combination with re-regulation reservoirs to release environmental flows, and wind and solar power the pumping. While natural gas combustion turbines consume practically no water and have sufficient ramp rates to follow wind and solar electricity output patterns, relying solely on natural gas power plants to integrate low-carbon renewable electricity might not achieve sufficient long-term GHG reductions in the electric sector (and water-use during extraction

---

[8] Split incentives are common barriers between commercial building owners and tenants that inhibit improvements to environmental performance. In a gross lease, for example, most commonly used for office spaces, the landlord pays for all services, including utilities, so the tenant has no motivation to limit energy consumption. Another example of a split incentive is found in a triple net lease, common in the retail and industrial sectors. In these arrangements, the building owner is rarely motivated to pay for energy efficiency upgrades because the savings accrue to the tenant. Tenants have little incentive to install efficiency upgrades if the payback period is longer than the lease term (http://www.greentenanttoolkit.com/glssenergy.html).

in some specific areas). In truth, the similar difficulties hold for integrating other industrial scale energy storage technologies such as compressed air energy storage, electrochemical batteries, thermal salts, and others. While modeling informs that we can have a 100% renewable electricity production sector (Hand et al., 2012), we need more understanding of the required economic, social, and environmental investments that preclude that infrastructure ever getting in place.

Effective governance needs good data collection and management

Data collection is a valuable policy approach to solve the informational challenges that exist during IWRM and other planning processes. Gathering information is possible through the creation of well-structured and maintained databases and reporting functions for energy and water data. Many energy databases were created after the 1970s oil embargo, and those data-gathering efforts serve as a model for water data. Governments have a solid foundation for integrated policymaking by designing policies based on these data and the latest scientific and engineering understanding.

Governments, however are not the only entities that can collect or house data. Effective coordination of data collection and reporting can also be facilitated by other parties perceived as neutral, such as some non-profit organizations. It is still effective to require water consumption and withdrawal data to be included in federal and state forms as filled out for energy production facilities. Having senior facility personnel record and be accountable for these water data can ensure data consistency from local to federal levels. The data can be reported on environmental and/or energy reporting forms. The collected data would preferably state the water body and basin from which the water is withdrawn and discharged, the quantity of water in units of volume per time, and the associated energy production (e.g. megawatt-hours, volume of liquid fuel, etc.). Government, industry, and environmental organizations must coordinate data collection to avoid reporting conflicting data. This coordination requires clarification of the words used to describe water usage and their definitions, the physical location within a water system at which the data are taken, and clear designation of the party responsible for collecting and verifying data.

Regulatory agencies need accurate data and tools to incorporate energy projections, along with agricultural water demand, into their management practices. Water availability-based governance exists at some western river authorities when considering agricultural demand, and similar data-based rules can ensure inclusion of quantified needs for environmental instream flows to protect freshwater biodiversity[9].

Because of the need for data on energy-water trends, the federal government has shown keen interest in energy-water interdependencies (GAO, 2009a, GAO, 2009b), leading agencies to work together on data collection and management. For example, the U.S. Energy Information Administration has made recent changes to its electric generator reporting forms (e.g. forms 860 and 923). These changes include providing useful diagrams to obtain more meaningful and accurate water use information about power plants. Data collection mechanisms can better inform policy and technology solutions for energy-water

---

[9] In 2012, and subsequent to the worst one-year drought in Texas history from late 2010 to 2011, the Lower Colorado River Authority decided not to provide irrigation water flows to downstream rice farmers because their Highland Lake storage levels were less than the required 850,000 acre-feet on March 1, 2012. Downstream farmers diverted 368,000 acre-feet of water from the Highland Lakes in 2011 (http://www.lcra.org/water/supply/wmp.html - accessed October 13, 2012; http://www.mysanantonio.com/business/article/No-LCRA-water-for-rice-growers-3378115.php - accessed October 12, 2012).

challenges by using engineering-like diagrams to indicate where water is being consumed and withdrawn within the energy system.

Conclusion

There are a host of choices in deciding how to manage future energy supplies that have lower greenhouse gas emissions and lower overall regional water consumption and withdrawal. Various technologies, management practices, and legal instruments can interact in myriad combinations. The increased complexity of these multi-metric (energy-water-carbon-biodiversity nexus) solutions derives from the different magnitudes and scales of the concerns. Freshwater resource and biodiversity impacts are local and regional. The oil and natural gas supply chain is global, electricity is traded across continents using transmission lines, but primary energy resource extraction is again local and regional. Further, greenhouse gases emitted from anywhere can affect climate everywhere.

The recommended principles presented here focus on how to plan for resilient energy and biodiversity solutions that are driven by global needs for energy and greenhouse gas mitigation:

- Advance Integrated Water Resource Management
- Protect and restore environmental flows
- Invest in energy technologies and urban planning to minimize water consumption, withdrawal, and stream alteration
- Use storage as a translational concept
- Effective governance needs good data collection and management

Specific changes within the hydrological cycle driven by anthropogenic forcings from climate change are out of our direct control. We do, however, directly control freshwater withdrawals and consumption for a variety of anthropogenic purposes – including the extraction and conversion of energy resources. The human appropriation of freshwater affects the timing, quality, and flow rates of freshwater within ecosystems that in turn affect the level of freshwater biodiversity. Further, *many of our future low-carbon energy solutions are more water-consumptive than at present*. But even business-as-usual scenarios that project reduced water withdrawals within the energy sector translate to increased water consumption. Thus, freshwater ecosystems are already at risk due to overexploitation of water resources, and opportunities exist to produce energy using technologies that need low quantities of freshwater such that future energy supplies do not exacerbate biodiversity decline. The principles highlighted in this report point to strategies to create both resilient natural and industrial ecosystems, and by working together, energy-water-carbon-biodiversity stakeholders have a much better chance of achieving this goal.

Acknowledgements

This report was wholly funded by The Nature Conservancy, but the writing and views are solely those of the author. The author would like to thank The Nature Conservancy for feedback and comments as well as some of his colleagues at The University of Texas at Austin (Dr. Michael E. Webber, Ashlynn S. Stillwell, Kelly Twomey Sanders, and Dr. Ian J. Duncan) upon which he owes much of his insight from his previous collaborations and research. Sincere thanks also goes to the various stakeholders of The Nature Conservancy July 2012 workshop that took part in discussions and to the following individuals who provided specific feedback on this report: Dr. Susan Hovorka of The University of Texas at Austin, David Marshall of Tarrant Regional Water District, Liese Dart of The Wilderness Society, Dr. Jordan Macknick of the National Renewable Energy Laboratory, and Ross Tomson of the Shale Water Research Center.

References

Annear, T., et al. (2004) *Instream Flows for Riverine Resource Stewardship, revised edition,* Cheyenne, WY.

Averyt, K., Fisher, J., Huber-Lee, A., Lewis, A., Macknick, J., Madden, N., Rogers, J. & Tellinghuisen, S. (2011) Freshwater use by U.S. power plants: Electricity's thirst for a precious resource. A report of the Energy and Water in a Warming World initiative. Cambridge, MA, Union of Concerned Scientists.

Bingaman, J. (2011) S. 1343: Energy and Water Integration Act of 2011, Accessed on October 10, 2012 at http://www.govtrack.us/congress/bills/112/s1343.

Bunn, S. E. & Arthington, A. H. (2002) Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management,* 30**,** 492-507.

CEQ (2000) Protection of the environment (under the National Environment Policy Act), Report No 40 CFR 1500-1517. Washington, DC, Council on Environmental Quality.

Chandel, M. K., Pratson, L. F. & Jackson, R. B. (2011) The potential impacts of climate-change policy on freshwater use in thermoelectric power generation. *Energy Policy,* 39**,** 6234-6242.

Chernova, Y. (2011) In Fracking's Wake: Some companies love that dirty water, because it means more money for cleaning it up *Wall Street Journal (accessed January 19, 2013 at: http://online.wsj.com/article/SB10001424053111903918104576502562678793674.html).* Dow Jones & Company, Inc.

Chiu, Y. W. & Wu, M. (2012) Assessing County-Level Water Footprints of Different Cellulosic-Biofuel Feedstock Pathways. *Environmental Science & Technology,* 46**,** 9155-9162.

Cleveland, C. J., Costanza, R., Hall, C. A. S. & Kaufmann, R. K. (1984) Energy and the U.S. Economy: A Biophysical Perspective. *Science,* 225**,** 8.

Cleveland, C. J., Kaufmann, R. K. & Stern, D. I. (2000) Aggregation and the role of energy in the economy. *Ecological Economics,* 32**,** 301-317.

Cook, M., Stillwell, A., King, C. & Webber, M. (2013) Alternative Sources of Water for Hydraulic Fracturing in Texas, May 20-22, 2013. *World Environmental & Water Resources Congress* Cincinnati, OH, American Society of Civil Engineers.

Dearing, J. A., Braimoh, A. K., Reenberg, A., Turner, B. L. & van der Leeuw, S. (2010) Complex Land Systems: the Need for Long Time Perspectives to Assess their Future. *Ecology and Society,* 15**,** 19.

Diaz, R. J. & Rosenberg, R. (2008) Spreading dead zones and consequences for marine ecosystems. *Science,* 321**,** 926-929.

Dodder, R., Felgenhauer, T., Yelverton, W. & King, C. (2011) Water and greenhouse gas tradeoffs associated with a transition to a low carbon transportation system, IMECE-63991. *Proceedings of the ASME 2011 International Mechanical Engineering Congress and Exposition.* Denver, CO, November 11-17, 2011.

DOE (2006) Energy Demands on Water Resources: Report to Congress on the Interdependency of Energy and Water. Washington D.C. , United States Department of Energy.

Donner, S. D. & Kucharik, C. J. (2008) Corn-based ethanol production compromises goal of reducing nitrogen export by the Mississippi River. *Proceedings of the National Academy of Sciences,* 105**,** 4513-4518.

EIA (2012) Monthly Energy Review, Accessed on January 20, 2013, 2013 at http://www.eia.gov/totalenergy/data/monthly/.

EPA Chapter 316(b) of the Clean Water Act: Cooling Water Intake Structures. United States Environmental Protection Agency.

EPRI (2007) Issues Analysis of Retrofitting Once-Through Cooled Plants with Closed-Cycle Cooling: California Coastal Plants. TR-052907. Palo Alto, CA.

Flessner, D. (2010) Hot river forces costly cutback for TVA [accessed August 23, 2010 at: http://www.timesfreepress.com/news/2010/aug/23/hot-river-forces-costly-cutback-tva/]. *Times Free Press.*

GAO (2009a) Energy-Water Nexus: Improvements to Federal Water Use Data Would Increase Understanding of Trends in Power Plant Water Use (GAO-10-23). Gorvernment Accountability Office.

GAO (2009b) Energy-Water Nexus: Many Uncertainties Remain about National and Regional Effects of Increased Biofuel Production on Water Resources. IN UNITED STATES GOVERNMENT ACCOUNTABILITY OFFICE (Ed.

GAO (2012) Energy-Water Nexus: Coordinated Federal Approach Needed to Better Manage Energy and Water Tradeoffs. IN UNITED STATES GOVERNMENT ACCOUNTABILITY OFFICE (Ed.

Gerbens-Leenes, W., Hoekstra, A. Y. & van der Meer, T. H. (2009) The water footprint of bioenergy. *Proceedings of the National Academy of Sciences,* 106**,** 10219-10223.

Hall, C. A. S. & Klitgaard, K. A. (2012) *Energy and the Wealth of Nations: Understanding the Biophysical Economy*, Springer.

Hand, M. M., Baldwin, S., DeMeo, E., Reilly, J. M., Mai, T., Arent, D., Porro, G., Meshek, M. & Sandor, D. (Eds.) (2012) *Renewable Electricity Futures Study. 4 vols. NREL/TP-6A20-52409,* Golden, CO, National Renewable Energy Laboratory.

Hansen, L. T. (1991) National Estimates of The Recreational Value of Streamflow. *Water Resources Research,* 27**,** 167-175.

Hogan, T., Dixon, D. & Sale, M. J. (2012) Environmentally Enhanced Turbines Allow for Safer Fish Passage. *Hydro Review,* June**,** 48-56.

IPCC (2007) Climate change 2007: Mitigation. Contribution of Working group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IN METZ, B., DAVIDSON, O. R., BOSCH, P. R., DAVE, R. & MEYER, L. A. (Eds.). Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

IPCC (2012) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation,* Cambridge, UK, and New York, NY, USA, Cambridge University Press.

Kenny, J. F., Barber, N. L., Hutson, S. S., Linsey, K. S., Lovelace, J. K. & Maupin, M. A. (2009) Estimated use of water in the United States in 2005. U.S. Geological Survey.

Kiesecker, J. M., Copeland, H., Pocewicz, A. & McKenney, B. (2009) Development by design: blending landscape-level planning with the mitigation hierarchy. *Frontiers in Ecology and the Environment,* 8**,** 261-266.

King, C. W. (2010) Energy intensity ratios as net energy measures of United States energy production and expenditures. *Environmental Research Letters,* 5: 044006

King, C. W., Holman, A. & Webber, M. E. (2008) Thirst for Energy. *Nature Geoscience,* 1**,** 283-286.

King, C. W., Stillwell, A. S., Sanders, K. T. & Webber, M. E. (2013) Coherence Between Water and Energy Policies. *Natural Resources Journal (in press),* 53**,** TBD.

King, C. W. & Webber, M. E. (2008) Water Intensity of Transportation. *Environmental Science & Technology,* 42**,** 7866-7872.

King, C. W., Webber, M. E. & Duncan, I. J. (2010) The Water Needs for LDV Transportation in the United States. *Energy Policy,* 38**,** 1157-1167.

Macknick, J., Newmark, R., Heath, G. & Hallett, K. (2011) A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies [NREL/TP-6A20-50900].

McDonald, R. I., Fargione, J., Kiesecker, J., Miller, W. M. & Powell, J. (2009) Energy Sprawl or Energy Efficiency: Climate Policy Impacts on Natural Habitat for the United States of America. *PLoS ONE,* 4**,** e6802.

McDonald, R. I., Olden, J. D., Opperman, J. J., Miller, W. M., Fargione, J., Revenga, C., Higgins, J. V. & Powell, J. (2012) Energy, Water and Fish: Biodiversity Impacts of Energy-Sector Water Demand in the United States Depend on Efficiency and Policy Measures. *PLoS ONE,* 7**,** e50219.

Pittock, J. (2011) National Climate Change Policies and Sustainable Water Management: Conflicts and Synergies. *Ecology and Society,* 16.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., Sparks, R. E. & Stromberg, J. C. (1997) The natural flow regime: a paradigm for river conservation and restoration. *BioScience,* 47**,** 769-784.

Poff, N. L. & Zimmerman, J. K. H. (2010) Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology,* 55**,** 194-205.

Polimeni, J. M., Mayumi, K., Giampietro, M. & Alcott, B. (2008) *The Jevons Paradox and the Myth of Resource Efficiency Improvements,* London, Earthscan.

Rabalais, N. N., Turner, R. E., Sen Gupta, B. K., Boesch, D. F., Chapman, P. & Murrell, M. C. (2007) Hypoxia inthe Northern Gulf of Mexico: Does the Science Support the Plan to Reduce, Mitigate, and Control Hypoxia? *Estuaries and Coasts,* 30**,** 753-772.

Reuters (2011) Drought adds to 2012 Texas power supply worry [accessed October 18, 2011 at: http://af.reuters.com/article/commoditiesNews/idAFN1E79H1L620111018?sp=true.

Rockstrom, J., et al. (2009) Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society,* 14**,** 33.

Romanak, K. D., Smyth, R. C., Yang, C., Hovorka, S. D., Rearick, M. & Lu, J. (2012) Sensitivity of groundwater systems to CO2: Application of a site-specific analysis of carbonate monitoring parameters at the SACROC CO2-enhanced oil field. *International Journal of Greenhouse Gas Control,* 6**,** 142-152.

Ryan, M. (2012) Shale Water Research Center takes new approach to industry issue. *Houston Business Journal* (accessed January 18, 2013 at: http://www.bizjournals.com/houston/print-edition/2012/08/03/shale-water-research-center-takes-new.html?page=all).

Smart, A. & Aspinall, A. (2009) Water and the electricity generation industry: Implications of use, Waterlines Report Series No. 18. Canberra, National Water Commission of Australia.

Solley, W. B., Pierce, R. R. & Perlman, H. A. (1998) Estimated Use of Water in the United States in 1995. US Geological Survey.

Stillwell, A. S., Clayton, M. E. & Webber, M. E. (2011) Technical analysis of a river basin-based model of advanced power plant cooling technologies for mitigating water management challenges. *Environmental Research Letters,* 6**,** 034015.

Tainter, J. (1988) *The Collapse of Complex Societies*, Cambridge University Press.

Tainter, J. A. & Patzek, T. W. (2012) *Drilling Down: The Gulf Oil Debacle and Our Energy Dilemma*, Springer.

TCEQ (2011) TCEQ restricts junior water rights [accessed August 9, 2011 at: http://www.tceq.texas.gov/news/releases/080811drought11brazos4].

TCEQ (2012) TCEQ restricts junior water rights [accessed January 9, 2012 at: http://www.tceq.texas.gov/news/releases/010912DroughtLittleSandy].

Tiemann, M. & Vann, A. (2012) Hydraulic Fracturing and Safe Drinking Water Act Issues [7-5700, R41760]. Congressional Research Service.

UNEP-DHI (2009) Integrated Water Resources Management in Action. *World Water Assessment Program, DHI Water Policy.* UNEP-DHI Centre for Water and Environment.

UNEP FONAG: Quito´s water fund, A municipal commitment to protect the watersheds [accessed on October 13, 2012 at: http://www.unep.org/gc/gcss-viii/USA-IWRM-2.pdf].

Wald, M. L. (2012) Heat Shuts Down a Coastal Reactor. *New York Times Green blog.* New York Times.

Wald, M. L. & Schwartz, J. (2012) More Weather Extremes Leave Parts of U.S. Grid Buckling [accessed July 25, 2012 at: http://www.nytimes.com/2012/07/26/us/rise-in-weather-extremes-threatens-infrastructure.html?_r=0]. *New York times.* New York, New York Times.

Warner, N. R., Jackson, R. B., Darrah, T. H., Osborn, S. G., Down, A., Zhao, K., White, A. & Vengosh, A. (2012) Geochemical evidence for possible natural migration of Marcellus Formation brine to shallow aquifers in Pennsylvania. *Proceedings of the National Academy of Sciences*.

Weltman-Fahs, M. & Taylor, J. M. (2013) Hydraulic Fracturing and Brook Trout Habitat in the Marcellus Shale Region: Potential Impacts and Research Needs. *Fisheries,* 38**,** 4-15.

Westley, F., et al. (2011) Tipping Toward Sustainability: Emerging Pathways of Transformation. *Ambio,* 40**,** 762-780.

Yang, C., Mickler, P., Reedy, R., Scanlon, B. R., Romanak, K. D., Nicot, J. P., Hovorka, S. D., Trevino, R. & Larson, T. (in review) Single-Well Push-Pull Test for Assessing Potential Impacts of CO2 Leakage on Groundwater Quality in a Shallow Gulf Coast Aquifer in Cranfield, Mississippi. *International Journal of Greenhouse Gas Control*.

Yang, C., Romanak, K., Horvoka, S., Holt, R. M., Lindner, J. & Trevino, R. (in press) Large Volume of CO2 Injection at the Cranfield, Early Field Test of the SECARB Phase III: Near-Surface Monitoring. *SPE Journal*.

Zhang, X., Zwiers, F. W., Hegerl, G. C., Lambert, F. H., Gillett, N. P., Solomon, S., Stott, P. A. & Nozawa, T. (2007) Detection of human influence on twentieth-century precipitation trends. *Nature,* 448**,** 461-465.

Appendix: Technologies, Management Practices, and Policy Choices that are guided by Principles to achieve Strategic Objectives

Energy-Water-Carbon-Biodiversity Policy Choices

Product labeling includes the dissemination of information regarding water, energy, and biodiversity life cycle impacts on consumer products.

Certification for products and best management practices describes products and practices that comply with a predefined set of principles, characteristics, and/or technologies. Certification programs are often operated by 3rd party organizations specifically set up for the purpose (e.g. Forest Stewardship Council governing forest harvesting and management, Alliance for Water Stewardship governing freshwater resources, and Low Impact Hydropower Institute for hydropower)

Public relations (PR) campaigns (information dissemination) encompass targeted educational and outreach activities, by governments, non-governmental organizations, or private for-profit and non-profit companies that inform consumers or persons who can take direct action upon learning about a topic of interest.

Data gathering involves data collected on wider scales of cities and countries that can be used to create statistics for policy decisions and track whether policy decisions produce intended outcomes.

Mandates and regulations encompass government laws and rules that consumers and businesses must follow to avoid civil and/or criminal penalties (e.g. building codes, efficiency standards, water rights).

Right-pricing and full-cost recovery describe policies ensuring that energy and water tariffs (or charges) are sufficient to cover the full supply costs of energy and water. Included in this definition are concepts such as ecological zoning and carbon pricing as means to incorporate externalities.

Government subsidies (and taxes) encompass targeted monetary incentives given by the government to specific projects, categories of projects, or industrial sectors.

Financing as a policy includes options that enable private businesses and consumers to spread the capital costs of technology over time rather than paying 100% up-front.

Public works (and private partnership) projects encompass public capital projects funded partly or entirely by the government via bonds or other public financing instruments.

Technologies and Management Practices

This section adds the context of biodiversity to existing discussion of energy-water-carbon tradeoffs. The reader is referred to the existing work (King et al., 2013) for a full discussion of these tradeoffs as they relate to each technology, policy, and management practice. Here, each item has a short description that focuses solely on the positive, negative, neutral, or site-specific impacts on freshwater biodiversity. Table 1 summarizes the ability of each technology and management practice to achieve or hinder each of the strategic objectives.

Energy Management

Energy-conserving appliances and building designs (e.g. domestic and commercial) benefit freshwater biodiversity because end-use energy conservation in turn conserves the water resources needed to produce, refine, and distribute energy. It is extremely important, however, to consider energy (and water) conservation in the context of scales ranging from that of individual technology to the overall economy.

Electricity peak shifting moves electricity consumption from peak demand hours (e.g. summer afternoons with high air-conditioning load) to low demand hours (e.g. early mornings), but by this definition does not lower total consumption. Energy storage technologies are one method to shift peak electricity loads in which total electricity consumption increases because of efficiency losses in the round-trip charge and discharge cycle. Because total energy consumption is not reduced, but the timing of water withdrawal and consumption for electricity generation is affected, there are no general impacts or benefits to biodiversity as they are specific to the regional electricity generating stations and seasonal situation. Peak shifting might increase or decrease total CO_2 emissions depending upon the mix of generating units (e.g. shifting from peak natural gas generation to off-peak coal increases total CO_2 emissions for the same total generation, but shifting from fossil-fuled on-peak generation to off-peak wind power that occurs in much of the central U.S. could lower total CO_2 emissions for the same total generation).

Electricity peak shaving (e.g. paying consumers to turn off when loads are too high) as a demand response mechanism decreases peak electricity consumption without shifting that consumption to other times of the day. Thus total electricity consumption reduces along with the associated embodied water within the energy production life-cycle. Generally, biodiversity slightly benefits.

Electricity Generation

Solar photovoltaics, wind power, and Stirling engine-based concentrated solar power electricity technologies benefit freshwater biodiversity by avoiding the embodied water consumption and withdrawal from the normal primary energy fuel extraction supply chain. Because these energy service technologies provide electricity without using steam cycles, they do not need cooling systems that usually consume and withdraw water for operation.

Thermoelectric generating power plants that use steam cycles require cooling systems to condense the steam after it passes through the turbine. Thermoelectric power plants are fueled by fossil fuels, nuclear fuels, biomass, solar radiation (concentrating solar power troughs and towers), and geothermal heat. There are a handful of the most common designs that have different impacts for freshwater biodiversity that can be of varied intensity for each specific circumstance. See McDonald et al. (2012) and Chandel et al. (2011) for information on how low-carbon policies affect freshwater withdrawal and consumption for electricity generation.

Freshwater wet-cooled thermoelectric power plants include those using *once-through* and *cooling tower* designs. *Once-through* designs withdraw ambient water and return the vast majority of that water to the water source after it absorbs heat. The general once-through design is implemented on rivers, shared-purpose reservoirs, and single-purpose cooling ponds – each with its individual implications for biodiversity. For all *once-through* systems water intakes can impinge and entrain aquatic wildlife and warm water discharge can cause water temperatures to go above safe limits if unregulated (practically all *once-through* cooling systems require a permit that regulates safe discharge temperatures) (EPA). For *once-through* systems on rivers, warm water sections of rivers can also block fish migration. *Cooling tower* designs withdraw ambient water and evaporate the majority of that water, and thus require one to two orders of magnitude lower water flow rates extracted from the local ecosystem with the tradeoff of approximately twice as much water consumption compared to once-through designs. Because these systems extract water from the ecosystem and/or discharge heated water to the ecosystem, freshwater biodiversity is negatively impacted.

Sea water wet-cooled thermoelectric power plants generally include those using *once-through* designs to avoid scaling effects associated with leaving dissolved solids on cooling infrastructure after evaporating saline water. As power plants using sea water for cooling reside on coastal areas, there are not direct impacts to freshwater biodiversity. However, there are impacts to marine biodiversity in coastal estuaries, wetlands, and coasts that are similar to the impacts if the power plant would withdraw freshwater, but that topic is beyond the scope of this document.

Dry-cooled thermoelectric power plants include those using cooling tower designs and air-cooled condensers that cool a power plant without withdrawing water for cooling from the ecosystem. Generally, this avoidance of water extraction for cooling has no impact on freshwater biodiversity. Energy security is viewed as site-specific depending upon if dry-cooling is used where water is available (thus decreasing energy security relative to usinga wet-cooled power plant) or where water is unavailable in an arid or desert environment (thus increasing energy security by enabling thermoelectric power that would otherwise not be possible).

Natural gas combustion turbines, unlike most other "thermoelectric" generating power plants, do not utilize a steam (e.g. Rankine) cycle to generate power. Instead natural gas combustion turbines utilize the Brayton cycle, and their design is inherently a type of air-cooling. Thus, there is practically no water withdrawal or consumption for operation and impacts to freshwater biodiversity are negligible.

CO_2 capture equipment installed on a fossil or biomass thermoelectric generation facility necessitates the use of significant internal power consumption such that the power plant consumes more water per unit of electricity output. Thus, a wet-cooled power plant delivering the same quantity of electricity to the grid has a higher water consumption impact, and potentially on freshwater biodiversity. Of course, the new service is the extraction of (likely up to 90%) of the CO_2 from the flue gas. Because a power plant with CO_2 capture equipment has the same cooling design options as a power plant without CO_2 capture, freshwater biodiversity impacts are similar to overall thermoelectric plants.

Combined heat and power (CHP) systems make fuller use of the input fuel than electricity-only power plants, and thus enhance energy efficiency and consume less water per energy service output. The freshwater biodiversity impacts of CHP generally follow those of energy efficiency or conservation practices (water security and freshwater biodiversity can benefit as long as water consumption and withdrawal from the overall ecosystem does not increase). The indirect impacts of needing less water for cooling should also lead to benefits for water quality in addition to water security.

Conventional hydropower stores large quantities of water to create high hydraulic heads to drive turbines by gravity-driven water. These systems require dams that can negatively impact biodiversity by altering flow regimes, blocking migratory fish passage, trapping sediment and changing water quality (e.g., temperature and dissolved oxygen). Note that many reservoirs provide multiple purposes, such as water supply and flood management, so that the negative impacts from a multipurpose dam cannot be attributed only to hydropower. Both upstream (fish ladders) and downstream (fish-friendly turbines, bypass flows) mitigation measures can help to minimize impacts to migratory fish.

Run-of-river hydropower projects either store lower quantities of water compared to conventional hydropower or use bypass water with no dam, and thus have much lower impacts on flow regime and water quality; although, the use of small dams can still trap sediment and impact fish migration. Overall, run-of-river designs have lower impacts on freshwater ecosystems but the tradeoff is that they do not allow for as dispatchable operation as conventional hydropower.

Energy Resource Extraction and Waste Injection

Conventional oil and gas extraction typically does not involve withdrawal and consumption of significant quantities of freshwater. Handling any produced waters, with high salt content, can negatively impact water and freshwater biodiversity if not treated or disposed of properly. Considerable sedimentation issues due to land cover fragmentation around well sites can also impact water quality. Thus, to minimize impacts to freshwater biodiversity it is imperative that best management practices include locating well pads and access roads to minimize erosion and runoff into streams. Because oil and gas are fossil fuels, their unmitigated combustion negatively impacts the strategic objective of carbon management.

Hydraulic fracturing for extraction of oil and gas from shale formations or extraction of geothermal heat from deep rocks injects millions of gallons of water, plus sand and a small ratio of chemicals, per well. All water and biodiversity impacts from conventional oil and gas extraction also apply to wells that undergo hydraulic fracturing, and the impacts specific to hydraulic fracturing activities are still very much under study. The fracturing water is usually extracted from local surface and groundwater supplies, and thus can reduce water availability for ecosystems. Fresh fracturing water is often removed from the natural water cycle in that it is either not recovered during drilling or is injected into deep disposal wells. However, the water withdrawals are temporary (individual well completions occur in a matter of weeks) such that quantity-related impacts to local ecosystems are unlikely unless thousands of wells are drilled in a relatively water-scarce region over an extended period of time. Properly designed and operated well drilling operations and water disposal and treatment systems can minimize water quality impacts that can harm local freshwater ecosystems. Local geologic conditions vary widely such that hydraulic fracturing operations in some regions might have higher possibility of enhancing natural upward migration of non-fresh fluids and constituents into shallow fresh groundwater (e.g. more so in the Marcellus Shale of Pennsylvania), but there is much more to learn (Warner et al., 2012). While mobile water treatment systems can be located anywhere, hydraulic fracturing backflow disposal options (e.g. hazardous disposal wells) vary across regions making fluid disposal a site-specific challenge.

Mining (coal, uranium, other minerals) can negatively impact freshwater biodiversity depending upon the site-specific factors, but it is difficult to consider that coal mining can improve biodiversity. Mine tailings and mountaintop removal can deposit silt and contaminants (e.g. those naturally occurring in rocks) into local streams and rivers, directly harming local ecosystems. Solution mining of uranium deposits must be done with careful design to protect fresh groundwater. Impacts to freshwater biodiversity are negative to site-specific (e.g. surface mining far from freshwater ecosystems). Because mining, and coal mining in particular, typically uses fossil-fueled machinery, mining operations and the unmitigated combustion of coal negatively impact the strategic objective of carbon management.

CO_2 geologic sequestration involves the injection of CO_2 into deep geologic repositories such as saline water reservoirs. Potential impacts to freshwater biodiversity could occur due to some migration of subsurface fluids (saline water more so than CO_2) into shallow freshwater aquifers that connect to surface waters. While to date CO_2 sequestration is not a widespread practice, historical injection of CO_2 into mature oil fields for enhanced oil recovery has occurred in regions such as the Permian Basin of west Texas and U.S. Gulf Coastal regions without negative impact to groundwater (Romanak et al., 2012, Yang et al., in review, Yang et al., in press). Proper site selection and management of injection and well performance is needed to protect freshwater (and biodiversity) from degradation by upward displacement of saline formation water from deep storage zones.

Biofuels impact watersheds primarily by removing water from ecosystems for growing feedstocks (via transpiration of rainfall and irrigation water from local surface or groundwater that might otherwise recharge aquifers of flow in freshwater ecosystems) and impairing water quality from agricultural practices. Biorefineries that convert feedstocks into fuels can withdraw and consume significant local quantities of water for operation, but the biofuel water life cycle is dominated by the feedstock growth stage (Gerbens-Leenes et al., 2009, King and Webber, 2008). Biofuel feedstocks can be grown in rain-fed regions to avoid surface and groundwater extraction for irrigation (e.g. sugar cane grown in Sao Paulo, Brazil), but holistic basin-wide thinking is required to assess total impacts to ecosystems from irrigation and all other water extracted from freshwater ecosystems. There is a multitude of known negative impacts to freshwater quality from non-point source pollution from agriculture (e.g. soil and nutrient runoff), and growing biofuel feedstocks are no exception. Because the vast majority of U.S. biofuel production is corn-based ethanol, the negative freshwater biodiversity impacts associated with corn agriculture translate to U.S. biofuel production. Dissolved inorganic nitrogen in water runoff within the Mississippi-Atchafalaya River Basin transcends freshwater impacts by driving a hypoxic “dead zone” in the Gulf of Mexico that poses risks to benthic organisms and fisheries (Diaz and Rosenberg, 2008, Donner and Kucharik, 2008, Rabalais et al., 2007). Depending on where and when biofuel feedstocks are grown, mitigation practices such as buffer zones, tilling and fertilizing practices, and crop rotations can work to reduce the water quantity and quality degradation from biofuel life cycles that impairs freshwater (and marine) biodiversity.

Solar hot water heating and *geothermal heat pumps* benefit freshwater biodiversity by providing heating energy services while avoiding the embodied water consumption and withdrawal from the normal primary energy fuel extraction and electricity conversion supply chain.

Municipal waste (solids, landfill gas) *and wastewater* (biomass, anaerobic digesters) *for energy* technologies can be viewed as energy efficiency technologies that can prevent the extraction of fossil fuels and new biomass (at constant overall energy consumption). Thus, the freshwater biodiversity impacts can be viewed as those of a generic energy efficiency or conservation measure: positive if reducing total energy consumption.

Water Supply and Management

Low water flow appliances, fixtures, and building designs (e.g. domestic use) benefit freshwater biodiversity inasmuch as they reduce total water extracted from the watershed while avoiding feedback such that end-use efficiency leads to system wide increase in water demand.

Distributed rainwater collection considers collection of rain from roofs of residential and commercial buildings for *non-potable* or *potable* uses. While collecting rainwater in municipal areas reduces the flow to the watershed during times of precipitation, there are also benefits. Rainwater collection can both reduce the withdrawal of water from watersheds and aquifers during times of low precipitation and absorb/store runoff from impervious surfaces during high rainfall events (thus preventing stormwater and sewage systems from overflowing into freshwater ecosystems). Thus, the impacts the biodiversity depend upon many factors related to the integration of distributed rainwater collection systems in a watershed.

Fresh groundwater extraction, because of the physical interconnection of surface and groundwater, extracting groundwater that eventually evaporates or transpires into the atmosphere effectively decreases water available in the watershed and can reduce streamflow. *Aquifer depletion* describes activities that pump groundwater faster than the recharge rate. This issue is pronounced for fossil aquifers that are relatively geologically isolated from rivers and other aquifers (e.g. Ogallala Aquifer of the Southern High Plains) such that there are little to no direct impacts on freshwater biodiversity. In other aquifers that have fast flow and high connectivity to surface waters, freshwater biodiversity can suffer from overpumping and aquifer depletion. The Edwards Aquifer of central Texas is an example of preventing aquifer depletion to protect biodiversity and create a resilient municipal water supply (for San Antonio, Texas), initially driven by court order to protect the Texas Blind Salamander, an endangered specie. Each aquifer has specific connectivities to surface water and recharge rates such that assessing impacts to biodiversity is site-specific.

Aquifer storage and recovery involves injecting water into aquifers during times of high surface flows (removed from surface or groundwater), and removing that water for use during times of low surface water flows. The water injection can be via engineered infrastructure or natural recharge zones. This practice can enhance cold water biodiversity as the injected water slowly discharges from cool aquifers into lakes and streams, especially during warm seasons. However, high surface flows are ecologically important, so ecological limits of withdrawal need to be determined and protected from aquifer storage schemes.

Desalination of *brackish groundwater* or *sea water* can reduce the extraction of surface and shallow fresh groundwater, although it is rarely pursued as a replacement of existing freshwater extraction. Because brackish groundwater is deep, it generally does not interact with surface water flows. Likewise, the extraction of sea water does not directly affect freshwater availability. Thus, use and desalination of brackish groundwater and sea water can be seen as reducing the need for freshwater availability. However, it is often the method of disposal of waste brines (the concentrated salts extracted from saline waters) that dictate whether or not water quality, and thus potentially biodiversity, are impacted at a significant level. But because disposal of concentrated brines cannot be envisioned to help water quality, it is assumed to only harm water quality (to some degree). Desalination is viewed as having a neutral (site-specific) to positive impact on freshwater biodiversity.

Greywater and reclaimed water use center on recycling water already extracted from the ecosystem into human-engineered water systems. Thus, generally biodiversity benefits from these water recycling and reuse concepts if using reclaimed water precludes new withdrawals from natural systems for other uses.

Biodiversity Management Practices and Legal Instruments

This section lists and describes management practices and legal instruments that can affect (positively or negatively) one or more energy-water-carbon-biodiversity strategic objectives. Some of these are discussed more fully in previous work (King et al., 2013). Generally, these practices and legal instruments are a set of non-technological tools that complement the specific technologies and designs of the previous section. Further, governments and/or private entities can employ any of these practices.

Legal Instruments

Conservation easements are voluntary, permanent, legal agreements entered into by a landowner and a land trust, for the purpose of specifying development and land use restrictions that will protect the property's open space values. Easements often preserve ecosystem services ranging from aquifer recharge, surface water supply and filtration, and increased biodiversity. The preservation of the Catskill watershed that feeds New York City is an example of a successful easement for water supply.

Water rights and permits can govern and define which users can withdraw and/or consume an allocated quantity of water. Permits also describe the water quality conditions that discharged water must meet. Historically, water rights have not been allocated for instream flows as a *'beneficial use'*. Thus, water rights and permitting can enhance biodiversity by including environmental flows into existing frameworks.

Interbasin water transfer involves pumping water from one water basin with excess water to another basin with a water deficit. Often interbasin water transfer necessitates a legal agreement that may change the legal priority of the transferred water. By its definition this practice decreases natural flows in the basin with removal, and – equally damaging to freshwater ecosystems – increases flows in the target basin, and can be seen to generally decrease biodiversity.

System Management Practices

Integrated Water Resource Management is defined by the United Nations as "…a process which promotes the coordinated 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" (UNEP-DHI, 2009).

Landscape/watershed scale planning projects development at the ecosystem scale and employs the mitigation hierarchy to avoid, minimize, and offset impacts based on conservation priorities across the system. This approach can be done in conjunction with or in absence of IWRM and can be applied to land impacts such as fragmentation from oil and gas development and associated infrastructure, as well as water impacts such as hydropower facilities and associated flow management across a watershed.

Water funds support the sustainable provision of clean water from a healthy watershed to a downstream water user, typically a municipality. Funds can be endowed from many sources such as user and voluntary fees, donations, grants, and intergovernmental agency allocations. The water fund for the water catchments surrounding Quito, Ecuador is an example of a successful water fund to protect water resources and biodiversity (UNEP).

Non-potable water use for energy involves using reclaimed, recycled, or high total-dissolved solids (e.g. brackish or sea water) water for energy needs such as power plant cooling and oil and gas drilling. Because many energy-related operations do not need fresh or potable water supplies, the quality of the water quality can match the requisite quality needed. Thus, one avoids the energy embodied in potable water, but possibly increases embodied energy when recycling water – still below potable standards. As long as overall energy consumption is not increased, this practice enhances biodiversity.