Water Management for Smart Cities: Implications of Advances in Real-Time Sensing, Information Processing, and Algorithmic Controls

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New sensing and monitoring technologies, and new methods for analyzing and routinizing responses to ecological information, have opened new possibilities for effectively coordinating diverse human endeavors with dynamic environmental conditions. The possibilities for innovation, in gathering and transmitting information, and in designing regulatory requirements and compliance procedures, are especially conspicuous in the multiple and fragmented legal regimes governing water, wastewater, and stormwater management in urbanized areas.

Modern ecological goals in waterways incorporate dynamic concepts of quality, quantity, timing, and distribution of water that vary seasonally with the weather and over longer periods as the climate changes. Such goals of environmental management call for adaptation and adjustment of human uses and protection of complex processes in aquatic habitats, coordinating human demands with the needs of nonhuman organisms in a responsive manner.

Recent decades have brought important advances in understanding natural dynamics and the interactions between human and nonhuman systems. But formulating effective regulatory, compliance, and enforcement strategies to achieve wise and synergistic outcomes at multiple scales in aquatic ecosystems has been notoriously difficult.[1] Multiple jurisdictions and property boundaries stand in the way of highly coordinated activities. Complexities in tracing causal connections and difficulties in dealing with contingencies lead regulators to set fixed limitations on pollution discharges, water withdrawals, and flood control measures, or resort to ad hoc decisions that may poorly respond to ecological dynamics.[2]

Recent advances in localized and remote sensing and information communication and analysis enable the collection and understanding of ecological data, as well as integration with socioeconomic data related to the demands and behavior of human populations. So-called "smart" technologies can facilitate or even automate responses that have previously required costly, site-specific evaluation and compliance interventions. This Perspective Piece considers the implications of advances in technologies for sensing, and making sense of, information about aquatic ecosystems, not merely for ensuring compliance with mandates and metrics in existing permits and regulations, but also for incorporating "systems" thinking[3] into regulatory and management regimes. It gives particular attention to the problems of cities—or more broadly, urbanized areas with dense human populations—where the socioeconomic system typically depends on various kinds of infrastructure and multiple administrative bodies to channel interactions between human and natural systems.

Part I discusses some well-known obstacles that stand in the way of wisely coordinating urban activities with the dynamics of aquatic ecosystems, with a focus on the institu-

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This Perspective Piece incorporates views presented by the Author at The George Washington University Law School 2015 J.B. and Maurice C. Shapiro Environmental Law Symposium on The Role of Advanced Monitoring, Remote Sensing, and New Forms of Information Gathering, Analysis, and Disclosure in Environmental Compliance and Enforcement.

1. *See, e.g.*, Robert W. Adler, *The Two Lost Books in the Water Quality Trilogy: The Elusive Objectives of Physical and Biological Integrity*, 33 Envtl. L. 29, 75–76 (2003) (highlighting disparities between legislative aspirations and ecological realities); Holly Doremus & A. Dan Tarlock, *Can the Clean Water Act Succeed as an Ecosystem Protection Law?*, 4 Geo. Wash. J. Energy & Envtl. L., No. 2, Summer 2013, at 46, 46–47 (noting statutory deficiencies, political barriers, and failures to use available legal tools to coordinate different aspects of water management).
2. *See* Robert W. Adler, *Resilience, Restoration, and Sustainability: Revisiting the Fundamental Principles of the Clean Water Act*, 32 Wash. U. J. L. & Pol'y 139, 147 (2010) (noting that dynamic goals of ecological resilience cannot be met simply by setting numeric parameters or identifying a fixed ecological state).
3. *See generally* Robin Kundis Craig, *Learning to Think About Complex Environmental Systems in Environmental and Natural Resource Law and Legal Scholarship: A Twenty-Year Retrospective*, 24 Fordham Envtl. L. Rev. 87 (2013) (providing an overview of relevant scholarship).

tional barriers that prevent decisionmakers from adequately perceiving and taking action based on important ecological information. Part II highlights aspects of recent technological advances that facilitate new efforts to overcome such obstacles. Enhanced sensing and monitoring capabilities, paired with advances in data analysis and visualization, sharpen ecological understanding and streamline adaptive responses. Finally, Part III discusses the promise and the perils of close dependence on smart technologies that include algorithms for automatically sensing, comprehending, and adjusting human activities, and it considers the implications of technological advances for structuring legal requirements.

I. Problems of Fragmentation, Inflexibility, and Short-Sightedness

Can a "smart" city wisely coordinate the human activities of a dense urban population with the survival of organisms in aquatic ecosystems? Law and social science commentators have long noted that existing institutional frameworks—expressed through disparate federal, state, and local regulatory programs and through private property arrangements—often fail to adequately recognize and coordinate protection for aquatic resources.[4]

Legal arrangements in practice may serve human needs in short-term ways while failing to take account of the healthy functioning of aquatic ecosystems, even when ecological goals are voiced in governing legislation and agency policies.[5] Urbanized areas, relying on multiple levels and forms of administrative expertise and complex allocations of property rights, face particularly difficult challenges in seeking to coordinate human activities with maintenance of healthy aquatic ecosystems, despite many layers and forms of regulatory oversight.[6]

At the federal level, the Clean Water Act[7] famously declares Congress' goal "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters,"[8] a goal sometimes termed "ecological integrity" for short. To that end, the statute sets subsidiary goals,[9] including an interim water quality goal "which provides for the protection and propagation of fish, shellfish, and wildlife and provides for recreation in and on the water."[10] As the legislative history suggests, Congress envisioned a coordinated effort by federal and state governments to strive for ecological integrity in water bodies by maintaining and reintroducing natural structures, functions and processes in aquatic ecosystems.[11] These national goals establish important ecological guideposts for water infrastructure projects that otherwise have the primary purposes of meeting immediate human needs (e.g., drinking water supply, wastewater disposal, drainage, and flood protection).

Through the U.S. Environmental Protection Agency ("EPA") regulations implementing the National Pollutant Discharge Elimination System ("NPDES"), and through delegated state-level programs designed to meet federal approval, the Clean Water Act has brought about significant measures to eliminate point source pollution of waterways.[12] Yet the broader aspirational goals of ecological integrity are widely unmet.[13] The federal regulatory programs of the Clean Water Act, as implemented by federal and state environmental agencies, remain narrower in scope than the overarching aims of the opening statutory provisions.[14]

The gaps between statutory aspirations and on-the-ground implementation inevitably raise questions about compliance with permit requirements, regulations, and the efficacy of enforcement efforts by government agencies in carrying out statutory programs. But the disparities between the aspirations of the Clean Water Act and the achievements of its regulatory programs also present fundamental questions about whether existing organizational arrangements (federal, state, local, and private, viewed collectively) are sufficient to achieve the legislative goals.[15]

Commentators have highlighted various institutional reasons for the disparities between the broad aspirations of the Clean Water Act and the achievements of water management and water pollution control programs pursued in its wake.[16] Three classic, related obstacles merit particular mention here: jurisdictional fragmentation, inflexibility, and institutional myopia.

A. *Jurisdictional Fragmentation*

Aquatic ecosystems are subject to multiple competing and overlapping allocations of decisionmaking authority. Numerous regulatory controls at the federal, state, and local levels govern development projects affecting wetlands, tidelands, floodplains, or waterways. Property rights holders, lenders, and insurers also bring multiple forms of control, scrutiny,

4. *See* Robert W. Adler, *Addressing Barriers to Watershed Protection*, 25 Envtl. L. 973, 991–95 (1995).
5. *See, e.g.*, Adler, *supra* note 1, at 69–71 (noting failures of federal agencies to pursue legislative goals using available authority); Doremus & Tarlock, *supra* note 1, at 46 (noting barriers to water quality control posed by entrenched property rights).
6. *See* Craig Anthony "Tony" Arnold, *Introduction: Integrating Water Controls and Land Use Controls: New Ideas and Old Obstacles*, *in* Wet Growth: Should Water Law Control Land Use? 1, 37–46 (Craig Anthony "Tony" Arnold ed., 2005) (discussing problems of fragmentation in coordinating land use, water use, and water pollution controls).
7. Clean Water Act of 1977, Pub. L. No. 95-217, 91 Stat. 1566 (codified as amended at 33 U.S.C. §§ 1251–1387 (2012)).
8. 33 U.S.C. § 1251(a) (2012).
9. *Id.* § 1251(a)(1)–(7).
10. *Id.* § 1251(a)(2).
11. Ecologists have come to understand ecological integrity as necessarily including dynamic concepts that involve persistence of ongoing functions, capacity to withstand stress, and continuing development in the face of changing conditions, rather than a stable condition. *See generally* Adler, *supra* note 2 (providing an extended discussion).
12. 33 U.S.C. §§ 1311(a), 1342.
13. U.S. Envtl. Prot. Agency, EPA 841-R-08-001, National Water Quality Inventory: Report to Congress: 2004 Reporting Cycle 7–8 (2009), http://water.epa.gov/lawsregs/guidance/cwa/305b/upload/2009_01_22_305b_2004report_2004_305Breport.pdf.
14. *See* Adler, *supra* note 1, at 29; Doremus & Tarlock, *supra* note 1, at 51–52.
15. Robert W. Adler, *The Decline and (Possible) Renewal of Aspiration in the Clean Water Act*, 88 Wash. L. Rev. 759, 775–800 (2013).
16. *E.g.*, Dave Owen, *Urbanization, Water Quality, and the Regulated Landscape*, 82 U. Colo. L. Rev. 431 (2011) (exploring in depth the origins of urban water degradation and the underlying institutional obstacles that have allowed pervasive pollution problems to persist).

and oversight to bear. Federal Clean Water Act programs are only one piece of a complex legal landscape.

As commentators have long noted, the boundary lines delineating powers and defining missions of federal, state, and local entities—as well as the property boundaries separating the decisionmaking powers of public, private, and nonprofit landowners and water rights holders—create fragmented management regimes in which the decisions of semi-autonomous entities and organizations are difficult to coordinate.[17] Nowhere are the difficulties posed by jurisdictional fragmentation more prominent than in the management of human activities in urbanized areas situated in or near aquatic ecosystems.[18]

The Clean Water Act itself recognizes jurisdictional boundaries between agencies and between levels of government. Point source and nonpoint source pollution, water pollution control and water withdrawal permits, filling of wetlands and discharges of other sorts of pollutants all fall in different categories. States retain important autonomy in fashioning land use controls and allocating water rights, while EPA administrative authority, including the federally-sponsored permit system, is limited to defined locations and activities.[19]

Federal, state, and local legal provisions establish an array of decisionmaking bodies or forums to implement distinct management regimes under a range of laws.[20] At the federal level, the entities exercising authority over a development project affecting an aquatic ecosystem may readily include the EPA and the Army Corps of Engineers under the Clean Water Act and the Department of the Interior or Department of Commerce pursuant to the Endangered Species Act.[21] State environmental departments, fish and wildlife departments, water resources agencies, and municipal bodies implementing local wetlands requirements, zoning controls, and public works requirements also exercise regulatory authority. Each of these governmental entities asserts public interests in aquatic resources and exercises partial control over property development. Meanwhile, ownership may also be divided among multiple private, nonprofit, and governmental entities.

In metropolitan areas that depend on extensive infrastructure for drinking water, sewage disposal, stormwater management, and protection from flooding, quasi-governmental agencies and private utilities exercising both ownership and regulatory authority oversee the delivery of specific resources and services. The "gray" infrastructure facilities these entities operate—from pipes to pumping facilities and reservoirs to treatment plants—confine and channel water to meet distinct purposes of urban populations.

As Eric Freyfogle has observed, such situations can result in a "tragedy of fragmentation" reinforced by jurisdictional boundaries.[22] Narrow agency missions and the profit-making transactions of property rights holders in practice result in failures to take ecosystem-wide repercussions of economic development activities into account.[23] By protecting the autonomy of decisionmakers, both public and private, to operate within their defined boundaries, applicable legal systems create conflicting decisionmaking powers that get reconciled, if at all, through lengthy administrative processes or site-specific negotiations. Although environmental impact review procedures under the National Environmental Policy Act[24] or comparable state laws provide forums that encourage stakeholder participation and negotiated compromises,[25] jurisdictional limits embedded in political and property lines remain significant impediments to fostering ecological integrity in aquatic ecosystems.

B. *Inflexibility and the Failure to Inquire, Learn, and Adapt*

A closely related critique focuses on the difficulties that resource management agencies and property owners have in adjusting to changing environmental conditions and coping with uncertain ecological information through experimentation, learning, and adaptation over time.[26]

Conservation biologists refer to the need for understanding the "natural flow regime" of waterways in order to restore and maintain ecological integrity.[27] Dynamic cycles in the quality, quantity, timing, and distribution of water underlie the capacity of water bodies to support healthy and diverse communities of life. Seasonal variations may be critical to essential feeding, mating, and sheltering activities of aquatic organisms.[28] Physical changes in water bodies over time may affect connectivity among waterway segments and the capacity of organisms to migrate.[29] Aquatic ecosystems may be able to sustain dynamic equilibria for long periods of time but they may also be highly sensitive to perturbations that trigger nonlinear feedback loops, leading abruptly to rapid

17. *See* Lee P. Breckenridge, *Special Challenges of Transboundary Coordination in Restoring Freshwater Ecosystems*, 19 Pac. McGeorge Global Bus. & Dev. L.J. 13 (2006) (discussing institutional barriers to transboundary coordination); *see also* Adler, *supra* note 4, at 991–95 (noting problems of political fragmentation, issue fragmentation, and program gaps).
18. *See generally* Arnold, *supra* note 6, at 37–40.
19. 33 U.S.C. §§ 1311(a), 1342, 1344, 1362 (2012); Adler, *supra* note 4, at 992.
20. *See* Craig Anthony "Tony" Arnold, *Fourth-Generation Environmental Law: Integrationist and Multimodal*, 35 Wm. & Mary Envtl. L. & Pol'y Rev. 771, 792–94 (2011) (describing how multiple modes of environmental protection are pursued by different decisionmaking bodies).
21. Endangered Species Act of 1973, Pub. L. No. 93-205, 87 Stat. 884 (codified as amended at 16 U.S.C. §§ 1531–1544 (2012)).
22. Eric T. Freyfogle, *The Tragedy of Fragmentation*, 36 Val. U. L. Rev. 307, 322–31 (2002).
23. *Id.* at 324–26 (discussing transaction costs, problems with free riders and holdouts, and incentives to ignore spillover effects of activities).
24. National Environmental Policy Act of 1969, Pub. L. No. 91-190, 83 Stat. 852 (1970) (codified as amended at 42 U.S.C. §§ 4321–4347 (2012)).
25. *See generally* Bradley C. Karkkainen, *Toward a Smarter NEPA: Monitoring and Managing Government's Environmental Performance*, 102 Colum. L. Rev. 903, 904–06 (2002) (summarizing views of NEPA proponents and critics).
26. J.B. Ruhl, *Thinking of Environmental Law as a Complex Adaptive System: How to Clean Up the Environment by Making a Mess of Environmental Law*, 34 Hous. L. Rev. 933, 935–36 (1997).
27. N. LeRoy Poff et al., *The Natural Flow Regime: A Paradigm for River Conservation and Restoration*, 47 BioScience 769, 774–77 (1997).
28. *See, e.g.*, Adler, *supra* note 4, at 1090–94 (discussing need to tailor water quality controls to natural variations).
29. *See, e.g.*, Adler, *supra* note 1, at 50–52 (discussing problems of physical and biological integrity in aquatic ecosystems).

changes.[30] Ecosystems can shift suddenly into other dynamic equilibrium conditions that do not support diverse populations of aquatic organisms and are less desirable from a human perspective.[31]

Aquatic ecosystems provide important ecosystem services to people, for example, by offering spawning grounds for fish, purifying drinking water supplies, and retaining and filtering stormwater.[32] Human socioeconomic systems depend profoundly, in the long run, on the iterative regeneration of the ecosystems in which they function.[33] But encouraging desired ecosystem regeneration on a continuing basis is no easy task when human populations are also exploiting or diverting water to serve immediate human demands.[34]

An important difficulty in coordinating human socioeconomic demands with the dynamics of aquatic ecological systems lies in assessing the uncertainty of ecological information. The dynamics of ecosystems, the impacts of future human activities, and the likely interactions between interdependent human and natural systems cannot be definitively projected in a snapshot proceeding. Decisionmaking entities, whether public or private, must cope with fundamental questions of risk and uncertainty.[35]

In light of such difficulties, many commentators in recent decades have recommended retooling decisionmaking frameworks to allow flexible, contingent decisions that forego finality in favor of iterative, adaptive adjustments, using a pragmatic experimental approach that learns from outcomes and constantly revisits human plans and designs for resource management.[36]

A truly adaptive management approach, however, flies in the face of fundamental legal and policy constraints that provide autonomy and security to individuals and organizations. Policies against disrupting human expectations are thoroughly embedded in administrative frameworks governing water resource management and in basic concepts of private property.

Permits, once issued, may be difficult to change, even if they are ostensibly subject to periodic review and renewal. By explicit legislative provision or by regulatory policy, decisionmakers often give significant weight to human dependencies on static quantities or conditions.[37] As urban areas expand, for example, developers and the subsequent residents or companies to whom they sell become dependent, and form expectations about the availability of water supplies, sewage disposal, and flood protection. Across the array of licensing regimes an entrenched bias toward securing the economic benefits of resource exploitation undermines the protection of ecological processes. In the United States, constitutional principles protecting private property rights from regulatory takings of property without just compensation also reinforce the caution of government agencies in disrupting settled expectations premised on secure rights to exploitation.[38]

The once-and-for-all aspect of project-specific approval processes compound the difficulties of pursuing administrative proceedings that accommodate continuing inquiry and change. Environmental impact reviews and substantive statutory provisions that call for "considering" or "balancing" lists of relevant ecological and economic factors encourage interdisciplinary investigations of risk and uncertainty across an array of topics, but the decisionmaking is ultimately synoptic.[39] Engineered systems are approved based on designs to handle a target event or provide an average performance over the long term. Outcomes are fixed, based on understandings at a specific moment in time, resulting in final administrative decisions and infrastructure designs that leave little room for subsequent learning and adaptation.

In recent years, the call for adaptive management has become intertwined with goals of system "resilience."[40] The term invokes various meanings and policy implications depending on the context.[41] In general, commentators using the term recognize that dynamic and complex events defy efforts to ensure static conditions.[42] Emergency managers, conjoining concepts of resilience and security, tend to focus on organizing human systems to help people "bounce back" quickly and recover essential services in the face of catastrophic events such as floods or hurricanes that are difficult to predict.[43] Questions about the resilience of ecosystems in this context are subordinate to questions about their useful-

30. *See, e.g.*, Fikret Berkes & Carl Folke, *Back to the Future: Ecosystem Dynamics and Local Knowledge*, *in* Panarchy: Understanding Transformations in Human and Natural Systems 121, 129–33 (Lance H. Gunderson & C.S. Holling eds., 2002).
31. *See* Robin Kundis Craig, *Legal Remedies for Deep Marine Oil Spills and Long-Term Ecological Resilience: A Match Made in Hell*, 2011 BYU L. Rev. 1863, 1896–97 (discussing sudden shifts caused by perturbations in aquatic ecosystems and implications for legal regimes).
32. *E.g.*, James Salzman et al., *The Most Important Current Research Questions in Urban Ecosystem Services*, 25 Duke Envtl. L. & Pol'y F. 1, 7–15 (2014) (summarizing literature on urban ecosystem services).
33. *See id.* at 2; *see also* Melissa M. Berry, *Thinking Like a City: Grounding Social-Ecological Resilience in an Urban Land Ethic*, 50 Idaho L. Rev. 117 (2014).
34. *See, e.g.*, Christina Hoffman & Sandra Zellmer, *Assessing Institutional Ability to Support Adaptive*, *Integrated Water Resources Management*, 91 Neb. L. Rev. 805 (2013).
35. C.S. Holling & Lance H. Gunderson, *Resilience and Adaptive Cycles*, *in* Panarchy: Understanding Transformations in Human and Natural Systems 25, 26 (Lance H. Gunderson & C.S. Holling eds., 2002).
36. *See, e.g.*, Alejandro E. Camacho, *Adapting Governance to Climate Change: Managing Uncertainty Through a Learning Infrastructure*, 59 Emory L.J. 1, 39 (2009) (noting the importance of information sharing and adaptive governance in natural resources management).
37. *See, e.g.*, A. Dan Tarlock, *A First Look at a Modern Legal Regime for a "Post-Modern" United States Army Corps of Engineers*, 52 U. Kan. L. Rev. 1285, 1312–13 (2004) (discussing the problems of preexisting entitlements).
38. *See, e.g.*, Craig Anthony "Tony" Arnold, *Resilient Cities and Adaptive Law*, 50 Idaho L. Rev. 245, 257 (2014) (noting barriers created by fixed concepts of private property).
39. *See* Karkkainen, *supra* note 25, at 906 (2002).
40. *See* Craig Anthony "Tony" Arnold & Lance H. Gunderson, *Adaptive Law and Resilience*, 43 ELR 10426 (May 2013).
41. *See* Tracy Lynn Humby, *Law and Resilience: Mapping the Literature*, 4 Seattle J. Envtl. L. 85 (2014).
42. Sara Meerow et al., *Defining Urban Resilience: A Review*, 147 Landscape & Urb. Planning 38, 39 (2016) (exploring differing perspectives and common themes in uses of the term "resilience" in the literature on urban environments).
43. *See* Nat'l Acads., Disaster Resilience: A National Imperative 16 (2012) (defining resilience as "the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events"); *see also* Gary Nestler & Andrea Jackman, IBM Corp., IBM Smarter Cities Thought Leadership White Paper: 21st Century Emergency Management (2014), http://public.dhe.ibm.com/common/ssi/ecm/lb/en/lbw03017usen/LBW03017USEN.PDF (discussing uses of smart technologies to facilitate agile response and recovery).

ness in promoting the recovery of human communities (e.g., through flood control and protection from storm surges).

The socio-ecological and "systems" literature acknowledges a broader scope to the term "resilience" that puts human and natural systems on an equal footing, with a longer term perspective.[44] Here, the key question is whether interdependent natural and human systems will both return to earlier self-organizing, regenerative patterns following disruption.[45] This perspective recognizes that ecological systems may shift suddenly from one dynamic equilibrium to another.[46] It sees human and natural systems as linked, and it emphasizes the dependency of human communities on underlying natural processes.[47] It inquires whether ecological, as well as societal patterns, will persist in ways that simultaneously support ongoing survival of people and nonhuman species.[48] This is the sense of the term "resilience" most pertinent to the current discussion about efforts to foster ecological integrity. Adaptive management of aquatic ecosystems is now understood to require efforts to ensure the capacity of aquatic ecosystems to respond resiliently in the face of disruptions, while at the same time empowering human communities to adjust flexibly to changing conditions.[49]

As various commentators have noted, an ecosystem that is impaired from a human point of view may nevertheless be resilient (returning readily to preexisting patterns of activity after disruption), without necessarily functioning as a biologically diverse community of organisms that people value and seek to maintain or restore.[50] The search for decisionmaking frameworks to interact wisely and adaptively with natural systems thus includes, but is not limited to, questions about how to foster resilience. Efforts to restore ecosystems to support diverse forms of life may entail disrupting current ecological processes in favor of a different dynamic equilibrium, while efforts to support the long-range sustainability of human communities may also necessitate embracing change rather than seeking a return to previous conditions.

C. *Institutional Myopia*

A third, closely related critique of relevant legal frameworks focuses on obstacles to perceiving or paying attention to relevant ecological information.[51] This critique views the inadequacies of decisionmaking entities as derived in part from fundamental obstacles to communication and information processing.[52] Adaptive learning and adaptive management mean that wise action over time ought to incorporate newly acquired information in responsive adjustments.

The power of landowners, water rights holders, and government regulatory agencies to pursue economic development does not necessarily go hand-in-hand with careful, responsive attention to disruptive spillover effects in aquatic ecosystems. Several commentators have pinpointed information gaps that pose particular challenges to learning and adaptation in water resource management.[53] Practical and legal obstacles to fully perceiving and responding to ecological information result in an institutionalized obliviousness that persists despite legislative and regulatory requirements to consider environmental impacts in administrative proceedings.

The criticisms of short-sightedness in water management encompass more than a failure of owners or administrative officials to "see" the ecological effects of human endeavors. The jurisdictional barriers and synoptic decisionmaking described above[54] produce, in effect, a sequence of failures: a failure to collect and transmit ecological information; a failure to invest in efforts to comprehend implications; and a failure to pursue responsive action to coordinate the operation of socioeconomic systems with ecosystem dynamics.[55]

44. *See* Lorenzo Chelleri et al., *Resilience Trade-Offs: Addressing Multiple Scales and Temporal Aspects of Urban Resilience*, 27 Env't & Urbanization 181 (2015); Meerow et al., *supra* note 42, at 39 (proposing a cross-cutting definition of "urban resilience" for use in a variety of policy settings) ("Urban resilience refers to the ability of an urban system—and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales—to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity.").
45. *See generally* Arnold, *supra* note 20; *see also* Lynda L. Butler, *The Resilience of Property*, 55 Ariz. L. Rev. 847 (2013); Robert L. Glicksman, *Ecosystem Resilience to Disruptions Linked to Global Climate Change: An Adaptive Approach to Federal Land Management*, 87 Neb. L. Rev. 833 (2009).
46. Barbara Cosens, Lance Gunderson & Brian Chaffin, *The Adaptive Water Governance Project: Assessing Law, Resilience and Governance in Regional Socio-Ecological Water Systems Facing a Changing Climate*, 51 Idaho L. Rev. 1 (2014) (introducing a series of articles, and exploring the connections between adaptive water governance and goals of resilience).
47. *See* Fikret Berkes & Carl Folke, *Linking Social and Ecological Systems for Resilience and Sustainability*, *in* Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience 1, 20–22 (1998) (noting the dependence of human society on the self-organizing capacities of ecosystems following disruptions.)
48. *See* Adell Louise Amos, *Developing the Law of the River: The Integration of Law and Policy Into Hydrologic Modeling Efforts in the Willamette River Basin*, 62 U. Kan. L. Rev. 1091 (2014); Stephen R. Miller, *Symposium Introduction: Resilient Cities: Environment, Economy, Equity*, 50 Idaho L. Rev. 1 (2014).
49. *See* Brian Walker et al., Perspective, *Resilience, Adaptability and Transformability in Social-Ecological Systems*, 9 Ecology & Soc'y, No. 2, Dec. 2014, http://www.ecologyandsociety.org/vol9/iss2/art5 (emphasizing the need for interactive adaptive processes to facilitate the sustainability of social and ecological systems); *see also* J.B. Ruhl, *General Design Principles for Resilience and Adaptive Capacity in Legal Systems—With Applications to Climate Change Adaptation*, 89 N.C. L. Rev. 1373, 1391, 1396 (2011) (emphasizing implications for change in legal systems to accommodate change in natural systems).
50. *See, e.g.*, Sandra Zellmer & Lance Gunderson, *Why Resilience May Not Always Be a Good Thing: Lessons in Ecosystem Restoration*, 87 Neb. L. Rev. 893 (2009).
51. *See* Dale D. Goble, *The Property Clause: As if Biodiversity Mattered*, 75 U. Colo. L. Rev. 1195, 1196–99 (2004) (noting that myopic decisionmaking by fragmented authorities disregards how landscapes function as whole ecosystems); Carol M. Rose, *The Several Futures of Property: Of Cyberspace and Folk Tales, Emissions Trades and Ecosystems*, 83 Minn. L. Rev. 129 (1998) (exploring fundamental problems of "myopia" in ecosystem problems); *see also* Holly Doremus, *Crossing Boundaries: Commentary on "The Law at the Water's Edge*," *in* Wet Growth: Should Water Law Control Land Use? 271, 295–312 (Craig Anthony "Tony" Arnold ed., 2005) (discussing informational and institutional obstacles to efforts to transcend boundaries).
52. *See* Cary Coglianese et al., *Seeking Truth for Power: Informational Strategy and Regulatory Policymaking*, 89 Minn. L. Rev. 277 (2004) (addressing broad issues of information acquisition and processing in administrative decisionmaking).
53. *See* Holly Doremus, *Data Gaps in Natural Resource Management: Sniffing for Leaks Along the Information Pipeline*, 83 Ind. L.J. 407 (2008); Alyson C. Flournoy, *Supply, Demand, and Consequences: The Impact of Information Flow on Individual Permitting Decisions Under Section 404 of the Clean Water Act*, 83 Ind. L.J. 537 (2008); Bradley C. Karkkainen, *Bottlenecks and Baselines: Tackling Information Deficits in Environmental Regulation*, 86 Tex. L. Rev. 1409 (2008); *see also* Robert L. Glicksman, *Bridging Data Gaps Through Modeling and Evaluation of Surrogates: Use of the Best Available Science to Protect Biological Diversity Under the National Forest Management Act*, 83 Ind. L.J. 465 (2008).
54. *See* discussion *supra* Sections I.A–B.
55. *See* Holly Doremus, *Adaptive Management as an Information Problem*, 89 N.C. L. Rev. 1455, 1467 (2011) (tracing steps in the acquisition of information,

Together, these observations go to the overall intelligence of management decisions.

Although obliviousness to ecological information is not unique to cities, nowhere are the problems more entrenched than in modern urbanized settings. Cities and other densely populated metropolitan areas depend on infrastructure and global market transactions to protect human health, safety, and welfare. Unlike individuals in subsistence communities that rely directly on the immediate environment for food, fuel, water, and other resources,[56] members of urban populations can avoid giving detailed daily attention to the patterns and functioning of local ecosystems as a matter of human survival.[57] Information processing in such urban contexts depends on multiple intermediary organizations that buffer the community from risks. Economic transactions deliver goods from distant places, and urban engineering provides transportation, energy supplies, drinking water, wastewater disposal, and flood control.[58] Ecological repercussions may occur far away. In these circumstances, information related to acquisition and consumption of economic goods may be readily available, while non-market values and ecological conditions escape attention.

II. Advances in Sensing and Monitoring Technologies

Part I sketched some fundamental obstacles to information acquisition, understanding, and adaptive response embedded in the decisionmaking frameworks affecting human use and management of aquatic ecosystems, particularly in urbanized areas. Recent advances in sensing technologies and information analysis promise to help overcome some of these challenges.[59] This Part considers ways in which smart technologies and analytical approaches facilitate wiser interactions of human and natural systems to promote ecological integrity, as the Clean Water Act and other laws envision, with particular focus on technological advances in the design and operation of "green infrastructure."

Much of the current attention to smart technology to solve urban problems focuses on ways in which people streamline and coordinate their activities with each other and with governmental entities without necessarily relying on centralized decisionmaking.[60] Availability on smartphones of real-time information about traffic and projected travel times allow people to adjust plans and select routes when driving their cars or taking public transportation. "Smart cars" armed with sensors to discern proximity to other vehicles and structures may, in the not-too-distant future, alleviate traffic jams, enhance safety, and replace error-prone human decisionmaking with algorithmic controls.[61] Public works departments providing services such as trash collection or snowplowing can gather and disseminate information and respond more readily to residents' changing needs or demands. Residents can more easily track and hold government officials accountable for observed problems.

While most discussions of "smart cities" focus on the coordination of human activities and human organizations to serve immediate human needs, a socio-ecological perspective invites attention to the broad roles that such technologies can play in understanding and shaping human interactions with ecosystems.[62] Innovations in the water management area are at the forefront of efforts to envision new ways of coordinating human and natural systems.

The urban design literature on smart cities broadly divides recent technological advances into three categories: (1) gathering data, (2) analyzing information, and (3) taking action based on insights.[63] Technological advances in each of these areas are relevant to the current discussion.

A. *Sensing*

The availability of small and inexpensive sensors for real-time, continuous monitoring and tracking of pollutants, water levels, or species in aquatic ecosystems has strikingly improved the capacity of water managers to understand aquatic ecosystem dynamics. Sensing technologies can now be widely and inexpensively distributed in a watershed or landscape to provide a multitude of localized measurements. Connected to modern wireless communications networks, sensing and monitoring technologies can collect and transmit fine-grained depictions of ecological conditions and dynamics, in situations where sampling and other measurements were previously far more labor intensive, expensive, slow, and imprecise.[64]

Parameters that can be tracked in this fashion have expanded rapidly. Sensors can keep tabs on water levels and temperatures, and they can measure a broad range of water pollutants and indicators of water quality such as turbid-

learning from information, and decisionmaking based on information that are involved in adaptive management).

56. *See* Elinor Ostrom, Governing the Commons: The Evolution of Institutions for Collective Action 205–07 (1990).
57. *See, e.g.*, Berkes & Folke, *supra* note 30, at 122.
58. *See* C.S. Holling, *What Barriers? What Bridges?*, *in* Barriers and Bridges to the Renewal of Ecosystems and Institutions (Lance H. Gunderson et al. eds., 1995).
59. Daniel C. Esty, *Environmental Protection in the Information Age*, 79 N.Y.U. L. Rev. 115 (2004); Karkkainen, *supra* note 25, at 907.
60. *See* Annie Decker, *Introduction, Symposium: Smart Law for Smart Cities: Regulation, Technology, and the Future of Cities*, 41 Fordham Urb. L.J. 1491 (2014); *see also* Ellen P. Goodman, *"Smart Cities" Meet "Anchor Institutions": The Case of Broadband and the Public Library*, 41 Fordham Urb. L.J. 1665, 1665–66 (2014).
61. Dorothy J. Glancy, *Sharing the Road: Smart Transportation Infrastructure*, 41 Fordham Urb. L.J. 1617 (2014).
62. Karkkainen, *supra* note 25, at 907–08 (noting how technological advances in information processing advance the understanding of complex natural systems and foster "a continuous information feedback loop that enables dynamic readjustment of policy and practice").
63. One formulation speaks of "three C's": collecting data, comprehending information, and compelling action through the use of new technologies. Dietmar Offenhuber & Katja Schechtner, *Protocols for Asking Hard Questions*, *in* Accountability Technologies: Tools for Asking Hard Questions 8 (Dietmar Offenhuber & Katja Schechtner eds., 2013); *see also* Dietmar Offenhuber & Carlo Ratti, *Introduction*, *in* Decoding the City: Urbanism in the Age of Big Data 6 (Dietmar Offenhuber & Carlo Ratti eds., 2014).
64. *See, e.g.*, David A. Hindin & Jon D. Silberman, *Designing More Effective Rules and Permits*, 7 Geo. Wash. J. Energy & Envtl. L. 103, 112 (2016); John Porter et al., *Wireless Sensor Networks for Ecology*, 55 BioScience 561, 561–62 (2005).

ity, dissolved oxygen, pH, and conductivity.[65] Data can be transmitted in real time via wireless technologies and Internet connections.[66]

Remote sensing of water resources by satellite has also become increasingly extensive and detailed. By correlating satellite or other remote sensing data with measurements obtained through localized sensing, researchers are able to garner far more precise depictions of regional and watershed conditions than ever before, and to trace the dynamic interactions across phenomena at multiple scales.[67]

While water resource managers have long engaged in field research to obtain extensive information about water quality and water quantities, and to map the results, these recent advances in technologies for gathering, transmitting, and storing data have greatly extended the scope of relevant information that is readily accessible and automatically transmitted without intermediate human action. Three aspects of recent advances in sensing technology stand out. First, sensors can be small and inexpensive, so that they can be feasibly acquired and installed with minimal costs, distributed widely in a landscape, and replaced easily if damaged. Sensors can also provide real-time monitoring, eliminating reliance on aggregate or grab sample data, providing the basis for more precise and fine-grained depictions of evolving phenomena. Finally, technologies for gathering and continuously transmitting data (autonomous sensors) perform work previously carried out through human effort, reducing labor costs in sampling and recording data, and substituting the operation of devices for human tasks.

B. Comprehending Information

Water resource managers have increasingly used geographic information systems to help discern ecological relationships and to understand ecosystem dynamics.[68] They have been at the forefront of scientific efforts to develop models, identify indicators, and formulate heuristics for characterizing ecological conditions. Now, rapid advances in information processing and mapping techniques are significantly expanding decisionmakers' capacities to visualize patterns in data and to understand and respond to the complexities of aquatic ecosystems.[69]

An ongoing "geospatial data revolution" enables individuals and organizations to coordinate human activities through rapid collection, transmission, and analysis of geographical information. Global Positioning System ("GPS") signal receivers in devices such as cellphones and cameras, paired with geographical information systems, allow precise mapping and tracking of locations and assembly of usable information.

The miniaturization of computing technologies and the availability of microprocessors have meant that information can often be analyzed and presented in usable form in distributed devices in the field, and exchanged through network connections, without necessarily depending on delivery of data to a central person and location to extract usable knowledge and make decisions. Meanwhile, capacities for rapid wireless transmission mean that cloud-based platforms provide workable approaches for rapidly analyzing and then disseminating information to dispersed locations. Significant advances in computing capacities and data analytics mean that the complex dynamics of aquatic ecosystems can be described and understood with more temporal and spatial precision than before, while weather forecasting services have improved projections of likely precipitation and weather-related events, with longer lead times and more granular delineation of locations than previously.[70]

C. Taking Action

The rapid recent advances in sensing and analytical capacities have also enabled advances in controlling and maintaining water infrastructure.[71] Innovations in information transmittal and processing, coupled with local water management devices, mean that engineered systems can respond automatically to new information without relying on intermediate human analysis and decisionmaking, once management protocols are put in place.[72] Smart technologies for taking action can evolve or "learn" from environmental events as they unfold.

In the arena of urban water management, advanced technologies have begun to streamline the steps from gathering sensor data, analyzing information, drawing conclusions, taking action, and tracking effects in an iterative process.[73] Systems of networked devices that receive, transmit, and use information to take action, drawing on algorithms to formulate measures based on informational inputs that are coordinated among multiple locations, have also become feasible, if not yet widely installed.[74] Such coordination among devices

65. Porter et al., *supra* note 64, at 564.
66. *See, e.g.*, John Porter et al., *New Eyes on the World: Advanced Sensors for Ecology*, 59 BioScience 385 (2009).
67. *See, e.g.*, Victor Klemas, *Coastal and Environmental Remote Sensing From Unmanned Aerial Vehicles: An Overview*, 31 J. Coastal Res. 1260 (2015); Victor Klemas, *Remote Sensing of Wetlands: Case Studies Comparing Practical Techniques*, 27 J. Coastal Res. 418, 424 (2011).
68. *See* Dave Owen, *Mapping, Modeling, and the Fragmentation of Environmental Law*, 2013 Utah L. Rev. 219, *reprinted in* 45 ELR 10796, 10798 (Aug. 2015) (excerpting and updating earlier article).
69. Nathan M. Torbick et al., *Assessing Invasive Plant Infestation and Disturbance Gradients in a Freshwater Wetland Using a GIScience Approach*, 18 Wetlands Ecology & Mgmt. 307, 308–09 (2010).
70. Richard Kerr, *Rise of the Forecasting Machines*, Science, Oct. 21, 2005, at 420.
71. *See, e.g.*, Michael E. Sullivan & Nitin Kapoor, IBM, Smarter Cities Thought Leadership White Paper: Employing Integrated Operations for Water Resources Management (2014), http://www.ibm.com/smarterplanet/us/en/smarter_cities/infrastructure; IBM, IBM Intelligent Water: Delivering Insights From Data to Better Manage Water Infrastructure, Assets and Operations (2015), http://www-03.ibm.com/software/products/en/intelligentwater.
72. *See* Marcus Quigley & Casey Brown, Water Env't Research Found., Transforming Our Cities: High-Performance Green Infrastructure (2014).
73. Jeff M. Miller & Mark Leinmiller, Schneider Elec., Why Smart Water Networks Boost Efficiency (2014), http://www.wwdmag.com/sites/default/files/998-2095-08-06-14AR0_EN.pdf.
74. *See* Tarleton Gillespie, *The Relevance of Algorithms*, *in* Media Technologies: Essays on Communication, Materiality, and Society 167 (Tarleton Gillespie et al. eds., 2014) (defining algorithms as "encoded procedures for transforming input data into a desired output, based on specified calculations"); *see also* J.B. Ruhl, *Sustainable Development: A Five-Dimensional Algorithm for Sus-*

without intermediate human intervention has sometimes been called an "Internet of Things."[75]

Water managers who oversee water infrastructure, particularly in large-scale projects and centralized metropolitan systems, have long relied on automated means for responding to changing natural conditions. In this respect, engineers dealing with water supplies, water pollution, storm surges, and flood protection have been innovators in coordinating the management of engineered structures in response to natural phenomena.[76] Computerized data-collection and data-control systems, until recently, have been installed primarily in large-scale, centralized facilities such as water and wastewater treatment plants. The most recent advances in smart technologies have opened new possibilities for coordinating smaller-scale structures and land uses, beyond the confines of industrial-scale facilities.[77] These technologies have begun to incorporate capacities to obtain and respond to predictions of future conditions, and to coordinate site-specific activities by linking them across a shared network.[78] These communication and coordination advances show particular promise in innovative landscape designs that incorporate "green infrastructure" and "low impact development" principles to cope with stormwater management and water quality impairment.[79]

Engineering consultants and contractors who specialize in facilities to control stormwater, harvest rainwater, restore modified aquatic habitat, or mitigate impacts on wetlands, have led the way in devising strategies in urban water management that capitalize on the emergence of smart technologies.[80] Smart stormwater systems, for example, use a suite of technologies that include distributed sensors, telemetry, cloud computing and web-based dashboards. These systems receive and process weather forecast information along with local sensor data. The systems estimate amounts of water retained on-site, and predict upcoming runoff and likely future water levels. Such systems may also rely on algorithmic instructions to actuate flow control devices, retain or release water over time to meet goals in water quantity and quality, and adjust valve operations as precipitation forecasts or local conditions change.[81]

Several aspects of these technological innovations for automatically actuating devices in light of estimated and actual conditions warrant attention here. Measures that would once have been costly or onerous have now become feasible and less expensive. Adaptive processes that actively control and adjust operations can replace passive engineered structures designed only to meet conditions during a fixed target event or to achieve static discharge rates.[82] Algorithmic operations replace management and control activities that previously would have required direct human decisionmaking and intervention. And finally, if distributed and networked across a landscape, such technologies offer possibilities for coordinating widely dispersed and fragmented human activities with regional goals and ecosystem dynamics, without depending on centralized management to take step-by-step decisions in response to changing conditions.

III. Implications for Legal Frameworks

For the moment, full-fledged examples of smart technologies that coordinate dispersed water management projects are not yet widely in operation. Within the regulatory framework of Clean Water Act permits, "low impact development" and "green infrastructure" initiatives that make use of such technologies often occur in situations where negotiated settlements have resolved enforcement actions in litigation or administrative proceedings, or where mitigation measures have helped an applicant reduce environmental impacts so as to qualify for less burdensome permit conditions.[83] Such arrangements, while not directly required by statute or regulation, have typically emerged through negotiation as alternatives to more onerous and costly requirements, spurred by federal enforcement actions against municipal permittees. Nevertheless, such pilot projects foreshadow possibilities for broader institutional innovations and process-oriented requirements in regulatory regimes.

On a site-by-site basis, smart technologies can facilitate monitoring and compliance with current permit requirements to use best management practices, to meet peak flow requirements, to offset water discharges or withdrawals, or to mitigate the impacts of wetlands alterations.[84] Within utilities, smart technologies can help manage services more efficiently, for example, by identifying leaks and automating responses. In these situations, smart technologies have made measures feasible that might have seemed impractical or too costly in the recent past. By tracking and analyzing real-time information, smart technologies can improve and automate auditing and reporting. At the same time, they may enable

tainable Development, 18 Stan. Envtl. L.J. 31, 44 (1999) (calling for "[an] algorithmic approach to adaptive, evolutionary [decisionmaking]" to solve complex optimization problems in pursuing goals of sustainable development).

75. The term is often used in describing networked consumer and household devices, and has received particular attention in the law review literature as presenting important issues of privacy and security. *E.g.*, Julie Brill, *The Internet of Things: Building Trust and Maximizing Benefits Through Consumer Control*, 83 Fordham L. Rev. 205 (2014); Scott R. Peppet, *Regulating the Internet of Things: First Steps Toward Managing Discrimination, Privacy, Security, and Consent*, 93 Tex. L. Rev. 85 (2014).
76. For example, dams can be opened or closed automatically when specified water levels are reached. Self-regulating tide gates can close automatically to protect urban waterfronts from flooding when surging water rises.
77. *See* Cameron Holley & Darren Sinclair, *Regulation, Technology and Water: "Buy-In" as a Precondition for Effective Real-Time Advanced Monitoring, Compliance, and Enforcement*, 7 Geo. Wash. J. Energy & Envtl. L. 52, 55–58 (2016) (examining the role of advanced electronic water metering, telemetry, and real-time data diffusion in a case study of a collaborative water management regime.)
78. Guy Dixon, *Kevin Mercer: A Smarter Rain Barrel*, Globe & Mail, http://www.theglobeandmail.com/report-on-business/innovators-at-work/a-smarter-rain-barrel/article18868882/ (last updated July 15, 2014) (discussing a coordinated system of dispersed rain barrels functioning as a municipal stormwater management utility).
79. *See* U.S. Envtl. Prot. Agency et al., Managing Wet Weather With Green Infrastructure: Action Strategy 2008, at 4 (2008).
80. *See* Quigley & Brown, *supra* note 72; Kevin Mercer & Stephen Braun, *Rain-Grid Networks: The Intelligent Community Stormwater Utility*, World Water: Stormwater Mgmt., Autumn 2014, at 32, 32.
81. *See* Quigley & Brown, *supra* note 72; Mercer & Braun, *supra* note 80, at 32.
82. *See, e.g.*, Quigley & Brown, *supra* note 72, at 19–20.
83. *See* Jack Ahern, *From Fail-Safe to Safe-to-Fail: Sustainability and Resilience in the New Urban World,* 4 Landscape & Regional. Plan., 341, 342–43 (2011).
84. *See* Holley & Sinclair, *supra* note 77, at 53–54.

project owners to install smaller facilities while still meeting existing requirements.

A larger issue, and the central one for purposes of the current discussion, is whether smart technologies, if introduced across dispersed locations at a landscape or watershed scale, can also help to overcome continuing institutional impediments at the regional or watershed scale to "seeing" and responding adequately to the complex dynamics of aquatic ecosystems, closing the gaps between legislative goals and the actual accomplishments of regulatory and management regimes.

If adopted at scale, smart technologies could facilitate some significant shifts in legal arrangements governing interactions between cities and aquatic ecosystems. One important effect might be to enable better integration of water, wastewater, stormwater, and wetlands management planning. As noted, in urbanized areas, water quality and aquatic habitat suffer from a combination of disruptions caused by many different aspects of the built environment and subject to multiple forms of administrative oversight.[85] Stormwater runoff from roads and parking lots, nonpoint source pollution, sewage treatment facilities, water withdrawals, and wetlands destruction combine to cause habitat destruction and species decline in aquatic ecosystems.[86] The design process for a development project or master plan is therefore an opportunity to build attainment of multiple goals and directives into the configuration of operations.

Advanced information gathering and processing technologies would facilitate the adjustment and coordination of activities affecting water in the landscape at dispersed locations over time, operating separate facilities as an integrated natural and human system. In particular, design of "green infrastructure" that mimics natural systems and extends the concept of infrastructure to include ecosystem services in landscape features can serve both human and natural communities.[87] By means of feedback loops for collecting new data, refining analyses and readjusting operations to coordinate with other locations within the landscape, without resorting to renewed administrative proceedings, smart technologies might be seen as offering an integrative process that can transcend jurisdictional boundaries. Through a networked structure of communication and response, such arrangements may facilitate the operation of polycentric, modular governance, corresponding to simultaneous needs for small-scale contextual management and large-scale coordination, and for interaction across administrative boundaries.

By facilitating the tracking of granular ecological information in real-time, recent advances in sensing, monitoring, information processing, and responsive action may be particularly valuable in expanding and streamlining the operation of market-like administrative mechanisms. Water banking and "no net loss" wetlands programs that rely on mitigation measures and careful ongoing efforts to account for tradeoffs in complex interactions are some such examples.[88]

Both federal and state laws governing aquatic ecosystems include mechanisms that authorize development projects if impacts are offset, either by mitigation at another location or by acquisition of credits derived from prior endeavors.[89] These projects, however, suffer from many uncertainties and may fail to fulfill projected functions. Enforcement is often difficult after initial approval.[90] Smart technologies for tracking and adjusting the operation of mitigation projects offer promising new means for measuring compliance, and for requiring and facilitating adjustments through adaptive management over time.

Reliance on smart technologies for coordinating the engineered aspects of the urban landscape could mark an important shift from fixed substantive requirements towards a more process-oriented approach. If configured to anticipate and respond to ecological conditions, the algorithms embedded in the operation of smart technologies can in effect serve as an adjustable mechanism for allocating water resources. Changing informational inputs would trigger alterations in water management through valves, pumps, gates, or other devices without the need to await further human decisionmaking. In this regard, algorithmic controls embody legal mandates and allocate responsibility while simultaneously foregoing static limits and conditions. They serve to automatically channel human activities while making adjustments in light of measured effects and advances in scientific understanding.[91] In essence, these technologies would replace direct human analysis and control with mechanisms organized in advance to address contingencies, and would cope with uncertainties in ecological understanding by pursuing ongoing investigation and adjustment.

Current stormwater management initiatives illustrate the potential operation of such algorithmic controls. Many current projects aim to reduce combined sewer overflows during wet weather events by anticipating and then timing

85. *See supra* Part I.
86. *See* Michael J. Kennish, *Environmental Threats and Environmental Future of Estuaries*, 29 Envtl. Conservation 78, 80–82 (2002).
87. *See* Alexandra Dapolito Dunn, *Siting Green Infrastructure: Legal and Policy Solutions to Alleviate Urban Poverty and Promote Healthy Communities*, 37 B.C. Envtl. Aff. L. Rev. 41, 41 (2010) (explaining concepts of green infrastructure and exploring ways in which such projects can simultaneously serve multiple urban planning goals for water bodies and city inhabitants).
88. Owen, *supra* note 68, 2013 Utah L. Rev. at 267–73 (exploring how modern techniques of spatial analysis can help make trading systems work); Dave Owen & Colin Apse, *Trading Dams*, 48 U.C. Davis L. Rev. 1043 (2015) (tracing history of environmental trading systems and describing how advances in information and communication technologies can facilitate the implementation of such systems).
89. *See, e.g.*, 16 U.S.C. §§ 661–666 (2012) (authorizing the U.S. Fish and Wildlife Service to provide technical assistance to restore aquatic habitat in the use and development of water resources); 33 U.S.C. § 1344(b) (authorizing guidelines for compensatory mitigation under the Clean Water Act); 43 U.S.C. § 2212 (permitting the U.S. Bureau of Reclamation to authorize projects to mitigate fish and wildlife losses during drought conditions).
90. *See, e.g.*, David L. Markell & Robert L. Glicksman, *A Holistic Look at Agency Enforcement*, 93 N.C. L. Rev. 1, 59 (2014) (noting difficulties in enforcing programs that seek to restore and maintain ecological functions over time).
91. *See* Ryan Calo, *Code, Nudge, or Notice?*, 99 Iowa L. Rev. 773 (2014) (discussing "architecture" or "code" as channeling behavior); Edward K. Cheng, *Structural Laws and the Puzzle of Regulating Behavior*, 100 Nw. U. L. Rev. 655, 692 (2006) (discussing variable "speed governors" for cars as an example of a technological innovation aimed at automatically adjusting human behavior to changing circumstances without depending on costly monitoring and enforcement to ensure compliance).

the retention and release of runoff on lands upstream.[92] If implemented across a landscape, the dispersed projects of multiple owners could be coordinated through networked and automatic operations to achieve desired results.[93] The overall goal—reduction of stormwater to prevent overflows—must be specified in advance, but subsequent operations can be adjusted as uncertainties are resolved and conditions change.

In the not-too-distant future, smart technology systems will likely be available for coordinating dispersed local projects in light of other potential water quality or ecosystem impacts. Cold-water fish populations, for example, are vulnerable in the face of rising temperatures, while withdrawals for municipal uses may significantly reduce cold groundwater inflow to streams. With dispersed temperature sensors, ecological models, and programmed responses to warm temperature forecasts, a fully coordinated system might be able to schedule or reduce withdrawals in response to ecosystem needs, assisting in the preservation of cold-water refugia for species survival, without waiting for emergency drought conditions to occur in a stream.[94]

Similarly, with autonomous sensors to measure an array of water quality parameters, data analytics to understand critical habitat parameters, and responsive devices for opening and closing tide gates, tide control structures might be automatically operated in a targeted way to reduce the combined effects of point source and nonpoint source pollution in coastal water bodies while at the same time protecting municipalities from storm surges.[95]

The possibilities for implementing smart technology systems at a landscape or watershed scale inspire both hopeful and cautionary observations. On the one hand, dispersed autonomous sensors and improved capacities for analyzing and visualizing data have enhanced the capacities of government entities and private owners alike to perceive and comprehend the dynamics and interactions of human activities and aquatic ecosystems.[96] Smart devices offer new mechanisms for responding with sensitivity to changing conditions and optimizing the attainment of multiple competing goals. In particular, they provide new hope for allocating and controlling water to simultaneously serve the welfare of human communities and aquatic organisms.

On the other hand, several caveats are in order. If the system relies on automatic operation of "smart" devices, it depends on the accuracy of the underlying ecological models and the wisdom of the ensuing algorithmic controls.[97] These are engineered solutions that routinize responses to contingencies in an engineered environment.

The management decisions expressed through the use of smart technologies inevitably embody judgments about how to optimize values from a human perspective and minimize risks in the face of likely tradeoffs between short-term human security and protection of aquatic ecosystems. The effort to engineer resilience for both human and natural systems, without subjecting human communities to any catastrophic risks, may easily slip into short-term planning for secure conditions in human communities, unless backed by strong regulatory commitments to coordinating human activities with the dynamics of ecological systems.

An additional critique focuses on the distributive effects of algorithmic controls and the implications for democratic processes and transparent decisionmaking. If fully automated, water management systems that rely on an "internet of things" substitute mechanistic information processing for ad hoc human decisionmaking. Will the distributional effects of such control processes be sufficiently apparent at the time of adoption to ensure fairness and participation by regulated parties and stakeholders? What if the algorithms themselves turn out to be insufficiently adaptive, or bring about unfair results?

One can imagine a situation in which a smart stormwater system might control overflows in one location but impose additional risks of flooding on low-lying neighborhoods. Or, a water delivery system might make allocations of water reductions in a time of drought, based on adaptive choices made in light of faulty instructions. The same technologies that streamline comprehension and provide flexible responses from an administrative perspective may also obscure the implications for regulated parties and stakeholders at the time of installation, while perpetuating unthinking reliance over time.

In short, there may be some dangers in turning increasingly to automated processes for sensing, analyzing, and responding to complex information about aquatic ecosystems, unless the administrative processes for adopting these systems are themselves made accessible, transparent, and subject to ongoing and meaningful review. Underlying algorithms may need to be changed, and ongoing public and private support for distributive decisions affecting the community will be important.[98] The "myopia" of current regulatory frameworks will only be thoroughly ameliorated if the new sensing technologies and analytical capabilities are also applied toward new and innovative efforts to communicate with members of the public and with stakeholders about ongoing processes. In this regard, the possibilities for visualizing data and making information about operations broadly accessible and understandable to the community at large will

92. *See, e.g.*, U.S. Envtl. Prot. Agency, EPA 832-B-95-002, Combined Sewer Overflows: Guidance for Long-Term Control Plan 128–30 (1995).

93. *See, e.g.*, Erik C. Porse, *Stormwater Governance and Future Cities*, 5 Water 29, 35–36 (2013).

94. *See* Dan J. Isaak et al., *The Cold-Water Climate Shield: Delineating Refugia for Preserving Salmonid Fishes Through the 21st Century*, 21 Global Change Biology 2540 (2015), http://www.treesearch.fs.fed.us/pubs/47740 (describing use of distributed sensors, crowd-sourced data sets, and development of collaborative networks to preserve cold water fish populations).

95. *See* William C. Glamore, *Incorporating Innovative Engineering Solutions Into Tidal Restoration Studies*, *in* Tidal Marsh Restoration: A Synthesis of Science and Management 277, 289–92 (Charles T. Roman & David M. Burdick eds., 2012).

96. Porse, *supra* note 93, at 43.

97. *See* Wendy Wagner, Elizabeth Fisher & Pasky Pascual, *Misunderstanding Models in Environmental and Public Health Regulation*, 18 N.Y.U. Envtl. L.J. 293 (2010) (warning against overreliance on computational models to provide fixed answers rather than insights into uncertain dynamics).

98. *See* Camacho, *supra* note 36 (noting the importance of information sharing and adaptive governance in natural resources management).

be key to the success of programs to expand the use of smart technologies in urban water management.

IV. Conclusion

Technological advances in sensing, information processing, and dynamic controls have facilitated adaptive management in watersheds and landscapes. Such advances promise to bring more communicative, interactive and streamlined coordination of human activities with natural systems. Fine-grained and flexible adjustments that once seemed impossible or costly are becoming feasible and inexpensive. Once in operation, automatic measures that evolve in response to ambient conditions may be able to substitute for protracted, step-by-step inquiry and decisionmaking.

That said, the algorithmic regulation that new technologies offer presents new challenges for wise governance. The systems offer new means for integrating fragmented management regimes and optimizing landscape-wide operations in a dynamic fashion, but success hinges on the configuration of the algorithms that govern learning, adjustment, and responsive action. Successful integration of algorithmic regulation also depends on continuing societal investments in the communications and information processing networks that make coordinated action and adjustment possible. Diligent efforts to ensure transparency and ongoing communication within accessible forums for deliberation and decisionmaking will be important in order to ensure that reliance on such systems over time continues to fairly and wisely enable insightful and responsive interactions between human populations and nonhuman communities of organisms.