

Sedimentation–upwelling: a model for the science–policy interface in the case of climate change and California water

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Abstract

This paper sets forth a framework to describe the science–policy interface. The “sedimentation–upwelling model” is a two-part process through which scientific information gradually becomes part of resource managers’ and policymakers’ agendas. In this paper, *sedimentation* refers to a gradual process through which scientific information slowly permeates a policymaking body, often slowly and through multiple sources. *Upwelling* is a process by which policymakers, having become aware of scientific concepts in a general way through sedimentation, independently devise policy actions consistent with the scientific body of knowledge. The framework was tested in the case of climate change science and California water policy through an analysis of historical data and interviews with key players on the science and policy sides of this issue. A remarkably consistent scientific message over the course of fifteen years before 2003 was not followed by corresponding changes in water management, as a “linear model” in which policymakers act directly on scientists recommendations would predict. Instead, both sedimentation and upwelling operated in this case and the importance of the linear pathway was minimal. Viewing science in the context of the upwelling–sedimentation model does not imply that science is ultimately any less influential on policy. On the contrary, this work suggests that policymakers rely on general, widespread cues that come both directly from scientists and through intermediaries and that these cues can influence policy choices in important, but often indirect ways.

Keywords: Adaptation; Complexity; Enlightenment theory; Water resources; Western water policy

Introduction

Science is a necessary tool for reducing uncertainties inherent to today’s complex resource management problems. However, actually incorporating science into management decisions has often proved difficult in the real world, particularly in organizations with complex structures. A better understanding of how the interface between science and policy can work could help both resource managers and environmental

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scientists. The purpose of this article is to describe theory and a case study for water researchers and policy practitioners interested in lessons on how the process can work.

This article proposes a framework to describe the transfer and digestion of scientific understanding across the science–policy interface, which is a critical part of a multi-faceted interaction (reviewed by Ingram & Schneider, 1998). It defines three terms describing movement of scientific knowledge into the policymaking process. *Sedimentation* here refers to a gradual process through which scientific information slowly permeates a policymaking body. *Upwelling* is defined as a process by which policymakers, having become aware of scientific concepts in a general way through sedimentation, independently devise policy actions consistent with the scientific body of knowledge. Both contrast a straw man *linear* pathway in which scientists deliver their message directly to policymakers and policymakers act to incorporate this knowledge into their management and planning.

The sedimentation–upwelling model, like the geological processes that inspired the metaphor, works over longer periods of time than a hypothetical linear model. Just as sediment deposits through the settling of fragmentary material of diverse origin, general awareness and understanding of scientific concepts in a management community requires multiple sources of information exchange. Transformation of novel ideas into adopted currency is a complex, non-linear process.

Similarly, the upwelling metaphor reflects the hydrological process of deep water rising to the surface, carrying with it nutrients, chemicals and particulate matter. Upwelling implies increasing visibility. Like deep water arriving at the surface, policy or management actions may appear after periods of invisibility to those outside a policy-making community. As upwelling water transports substances of various origins, it mixes them. Similarly, policy upwelling can generate novel mixtures of ideas with different compositions than the original ones.

These fluid metaphors suggest viscosity and resistance to movement. If they were applicable in a real world example, one would expect a time lag between the introduction of new scientific concepts and their application. The clearest demonstration of upwelling would involve a novel idea, motivated by diverse scientific knowledge, that lead to independent action by resource managers.

Both sedimentation and upwelling contrast a hypothetical linear process, which might seem more like a collision between two billiard balls—highly predictable, repeatable, transparent and targetable. Clearly, this straw man definition is not representative of most examples of the science–policy interface.

A case study of California's water management and policy response to climate change science from 1985–2003 supports this framework. For almost 20 years, scientists had sent a consistent message to policymakers that California's extensive, snowpack-dependent water system is vulnerable to global warming. They had also suggested management and policy changes for adaptation. Given California's historical leadership in environmental and progressive policies and the importance of water management in the state, one might expect that policymakers would want to use this information. However, integration of this science into water policy and management had been slow.

This paper briefly reviews relevant social science theory and describes the sedimentation–upwelling model. Analysis of a case study suggests that the sedimentation–upwelling model describes the science–policy interface better than a linear model.

The Sedimentation–upwelling model

Theoretical background

This article considers three potential pathways from science to policy, termed *linear*, *sedimentation* and *upwelling*. In a linear model, policymakers directly integrate science if certain threshold conditions are met. This straw man idea would suggest that use of scientific information should be straightforward. For example, if the information is relevant, compatible and accessible to policymakers, then the policymakers should adopt the science (Jones *et al.*, 1999).

This model suggests that science should have a direct, immediate influence on policy. The following is a hypothetical example of such a linear mode of the science–policy interface:

Policymakers define problem → Scientists identify missing research → Scientists conduct research → Scientists interpret research for problem solutions → Policymakers choose policy.

This model is consistent with a positivist view of effective scientific communication as “speaking truth to power” (e.g. Wildavsky, 1979, 1992). Weiss (1977) proposed an alternative framework that she termed “the enlightenment model” of social research. It suggests that research does not influence policy in a direct way. Instead, the gradual accumulation of new concepts and challenges to prevailing views ultimately do inform policymaker decisions, but only over the long term via their influence on broader paradigm shifts. This work is only one example of a broad range of constructivist studies (reviewed by Jasanoff & Wynne, 1998) that collectively recognize that a linear view is inadequate to describe processes that actually consist of dynamic scientific paradigms interacting with porous boundaries between science and policy. This is relevant in the field of climate change, as the linear model has been used by the most important global scientific collaboration on climate change, the IPCC, which “presupposed that scientific research could be targeted, in a linear fashion, to fill gaps in the existing knowledge base. Once the gaps were filled and uncertainties either reduced or eliminated, policymakers could rationally apply the products of science to formulating policy responses” (Jasanoff & Wynne, 1998).

Rational choice theory (Abell, 1991) is commonly invoked in sociological models of decision making indicting that individual decision makers are motivated to seek out and incorporate information that can make their decisions more effective. A large literature suggests it is problematic to apply rational choice theory to institutional decision making (Rayner *et al.*, 2005). In particular, information is not a “well-behaved” and easily transferred commodity (Diaz & Bordenave, 1972; Rogers & Kincaid, 1981) and information use in institutions requires the creation of collective meaning within the institution (Douglas, 1986). The complexity of the organizations, as well as the compartmentalized nature of responsibility and information flow within agencies, also hinder the application of rational choice theory. These observations are relevant to and consistent with the model presented in this article.

In research into organizational change, sources of change within organizations remains an understudied area (Barnett & Carroll, 1995). The study of innovation is a possible exception. Innovations such as ideas and technology provide creative and disruptive drivers of change in markets and society (Schumpeter, 1947). Empirical analyses of technological innovation on the scale of market sectors (e.g. agriculture, Griliches, 1960; or industrial, Fisher & Pry, 1971) suggest that diffusion of new technologies into widespread use follows a predictable pattern. Initial adoption happens slowly

as early adopters risk unproven reliability, followed by increases in the rate of adoption as solutions to initial issues arise and tapering as the sector reaches saturation. In some cases, innovation within organizations requires development of new capabilities (Tushman & Anderson, 1986; Henderson & Clark, 1990). Investigations of such phenomena from sociological perspectives have been slower to appear in the literature (Hage, 1999), but the above conclusions suggest parallels with the model presented in this paper.

Rayner *et al.*'s (2005) study of incorporating weather forecasting to water operations in the USA found that water resource managers had been reluctant to incorporate these new technologies into their day-to-day operations. They found that scientific and technical information is only one input into decision making and is mediated by institutional conservatism, such as reliance on familiar, traditional decision-making processes that modulates the impact of novel science. In addition, organizational conservatism, political disincentives to innovation and regulatory constraints all served to slow the potential uptake of new tools designed to increase the effectiveness of water management.

Model structure

This section outlines a metaphor informed by the above arguments. In this article, *sedimentation* refers to a gradual process through which a broad community of policymakers gains awareness of scientific concepts relevant to a particular topic. *Upwelling* refers to policymakers generating novel policy options based on a general understanding of the science. Upwelling allows for the generation of novel ideas in a policy context. That is, when policymakers take new scientific understanding gained through sedimentation, combine it with their knowledge of the policy realm and bring both together to bear on a problem, they can create policies that scientists may not have thought to recommend.

Sedimentation and upwelling are not mutually exclusive, but rather are likely to operate as a two-step process. For upwelling of new policy ideas to occur, policymakers need to understand scientific concepts first in order to apply them; this understanding might come through sedimentation. Innes (1998) has described the ideal case as “embeddedness of information”, suggesting that information is most influential when it exists as part of an everyday dialogue or consciousness, rather than as new and distinct from common knowledge.

While a linear, rational positivist model of the science–policy interface may appeal to scientists and indeed may form the basis for some scientists’ assumptions about how policy works, such models have been widely criticized by social scientists, who argue that such constructions are not widely applicable to organizational behavior. For example, “although information from natural scientists may often be claimed as authoritative, it is produced selectively. Therefore, it can never be understood solely from the perspective of the natural sciences. Scientists are but one set of players in the experience and interpretation of the environment” (Blaikie, 1995; quoted in Wallner *et al.*, 2003).

Indeed, the culture of natural science relies on positivist, rational thought in the construction and testing of deterministic models and the design of experiments. This mode of thinking may or may not spill over into natural scientists’ views of how their work should influence policy. Regardless, alternative notions may be useful for the scientific community and others who work at the science–policy interface in helping them plan their efforts at communication.

Methods

Scientific and agency documentation were reviewed and synthesized, and a comprehensive review of legislative history was conducted (Kiparsky, 2004). Participant observation during management and policy meetings and semi-structured interviews (Spradley, 1979) with scientists and decision makers involved in California water management complimented publicly available data. Informants involved with the issue of climate change were identified through previous research in a larger study of climate change science and California water management, including a scientific literature review (Kiparsky & Gleick, 2003), a comprehensive bibliography of water-related climate science (Kiparsky *et al.*, 2006), an analysis of policy recommendations by scientists (Kiparsky & Gleick, 2005) and a historical review of scientific milestones (Kiparsky, 2004). All respondents remain anonymous, in accordance with guidelines of U.C. Berkeley's Committee for the Protection of Human Subjects.

California water: complexity and vulnerability

California water is an interesting system for the study of climate change and the science–policy interface for scientific, historical and institutional reasons. California's water operations are extraordinary for their scale and complexity and for the clarity with which their vulnerability to global warming has been demonstrated by scientists. The state has historically been a leader in environmental policies, so one might expect its policymakers and resource managers to be forward thinking in their use of climate science in planning.

A complex system

California's water system is among the largest water conveyance operations in the world. The physical management of California's water is constrained both seasonally and geographically. Its Mediterranean climate delivers precipitation concentrated in the winter months, whereas demand for water is concentrated during the peak summer growing season for the massive agricultural industry that uses over three-quarters of the state's water resources and drives a significant proportion of its economy. In addition, precipitation falls most abundantly in the north of the state, while the bulk of the human demand for water is concentrated in the agricultural centers in the Central Valley and Southern California and in the population centers in the south.

California's water infrastructure is designed to deal with both of these issues. Dams store runoff, preventing peak flows from moving to the ocean and allowing the use of this water later in the year. The State is laced with major water conveyance facilities, the largest of which are the State Water Project (SWP) and the federally funded Central Valley Project (CVP).

The network of organizations that operate this infrastructure matches the physical size and complexity of California's storage and conveyance system. Statewide agencies such as the California Department of Water Resources (DWR) work in parallel with federal ones, such as the US Bureau of Reclamation (USBR). Many water districts are responsible for supplying their local service areas with water supplied either from local sources or purchased from one of the larger agencies. Stakeholders representing diverse

interests from agriculture to fish to social justice add further layers of complexity to these policy levels through their active involvement in planning.

Conflicts arise because the current system is oversubscribed—contractors to the SWP and CVP, for example, rarely receive their full allotment of water. Dividing water between the myriad interests would be difficult enough were hydrologic regimes fixed. Instead, they are moving targets that depend on the amount and timing of climatic events and demand in a given year. The challenges of water management in this state will only be exacerbated by changes in climate that alter hydrologic regimes that managers implicitly assume will continue consistent with historical patterns.

Projected impacts

Much of California's vulnerability to climate change lies in its dependence on seasonal snowpack in the Sierra Nevada Mountains, which acts as a natural reservoir by delaying runoff by locking precipitation temporarily in frozen form. Scientists have projected that climate warming will lead to a shift to earlier peak flows in California's rivers, and also measured such a shift in the historical record. This shift in timing, along with other projected effects, will have an impact on California water (reviewed by [Wilkinson & others, 2002](#); [Kiparsky & Gleick, 2003](#)).

As an illustrative example of such impacts, California's reservoirs in general are dual purpose. Operators keep water levels low in the winter and early spring to provide space for protection from floods. By the end of the peak runoff period in late spring, they will ideally have filled the reservoirs to capacity to maximize water storage and supply during the peak demand of the summer. A shift in the timing and magnitude of runoff will change the dynamics of their ability to balance the two purposes of these reservoirs. Expected climatic changes also have implications for a diverse suite of environmental characteristics, such as evapotranspiration, climate variability, runoff, soil moisture, water quality, aquatic and terrestrial ecosystems, groundwater and other issues (reviewed by [Wilkinson & others, 2002](#); [Kiparsky & Gleick, 2003](#)) and many of these changes could directly influence water management.

Policy implications

Unlike in many other regions, for over a decade, scientists were producing formal, peer-reviewed recommendations for the Western states (see [Kiparsky & Gleick, 2005](#) for an in depth review). Recommendations included suggestions for managing existing infrastructure in light of projected changes, improved water planning and site-specific application of climate change science. Scientists also recommended “no-regrets” options such as traditional and alternative options for new supplies, demand management and conservation and efficiency.

A linear process?

Again using the straw man defined above, where a linear pathway from science to policy followed, policies would have been put in place to begin concretely integrating climate change into water planning and management, because investments in infrastructure and operations have decade-to-century time

horizons. However, an overview of historical documents and interviews with key players suggests that the science–policy interface did not operate via the linear model in this case.

One remarkable element of regional climate research in California is the degree to which many of the early scientific conclusions have been supported by a growing body of research. One of the first, and still most consistent, projections of the impacts of climate change on California water is that warming trends will lead to earlier melting of snowpack (Gleick, 1987; Knowles & Cayan, 2002). The result for water managers will be runoff with higher peak flows that come earlier in the water year. Each of these effects is relevant for water managers¹. Significant uncertainty exists in the specifics of all climate projections and will be likely to remain in future reports as well. However, the message from this science has been broadly consistent over the past 15 years (Kiparsky, 2004).

All the reports reviewed by Kiparsky & Gleick (2005) have consistent lines of argument on similar themes of policy recommendations. None of the reports contradict each other on any specific recommended measure, paralleling the general scientific consensus on global climate change (Oreskes, 2004). Although these conditions were seemingly conducive to a linear pathway from science to policy decisions, the present research suggests that the influence on decisions was less direct.

Sedimentation

Sedimentation of scientific ideas occurred in this case. Against the backdrop of mounting scientific evidence for changes in hydrologic regimes, a critical mass of awareness of the issue developed within water management agencies and recent years have saw increasing sedimentation in many levels of California government.

Respondents suggested that there was broad acceptance of the main scientific concepts: scientists and managers who are generally informed about California's water system found the idea that rising temperatures will lead to melting snow intuitive and accessible. Respondents all demonstrated not only an understanding of this concept, but also of its implications.

At DWR, a broad awareness developed among employees there that climate change will be important in the future. DWR traditionally had a hierarchical, engineering-based culture typical of many water agencies (Rayner *et al.*, 2005), which implies a strong top-down route for policy decisions. Awareness of climate science seemed to have built among technical staff through sedimentation, suggesting that bottom-up influence is an important component of management.

Similar broad awareness developed among urban water districts. Water districts arguably have the most direct responsibility to deliver water supply and quality to the end user and thus may feel the most pressure to plan well. The Metropolitan Water District (MWD), which serves 14 million Southern California customers, mentioned climate change in several press releases and held a climate forum in 2001 for its board of directors. The Contra Costa and Marin water districts' boards of directors also discussed climate change, mentioning it as an issue that could affect their ability to deliver on their water commitments in the future. The Director of Marin Water District said "we need to take this into

¹ Climate change most often refers to changes in the average weather over time, often in a directional way (e.g. hotter or wetter) and often implies human-caused effects, rather than purely natural cycles. Climate variability most often refers to natural climate cycles that deviate from some pattern or expectation. Engineers have been concerned with climate variability for many years and many solutions addressing climate variability also apply to climate change.

consideration in long-range water sustainability for MMWD and the rest of the state”, according to its Board’s meeting minutes. This Board discussed supporting measures to reduce greenhouse gas emissions in response. Although this mitigation would not directly affect future impacts on their water supply, the suggestion of a willingness to act was forward thinking for that time period.

In sum, sedimentation of knowledge of climate science took place throughout much of California’s distributed water management structure. The beginnings of upwelling of novel policy responses to climate change may suggest that we can expect an increase in the pace of actual integration of this scientific knowledge into meaningful actions in future².

Upwelling

Had anything come of the sedimentation of scientific knowledge with management ramifications into the California water policy community? Interviews suggest progress was made. Respondents repeatedly indicated that relatively few concrete water management policy actions, such as changes in infrastructure or altered operations of water projects, had been taken. By this metric, climate change science had not yet been integrated into California water policy. However, such a definition of policy success may be premature. If one instead defines successful integration of science to policy as an active dialogue and tangible consideration of science in planning, this case study reveals examples of great success.

For example, at DWR, the main policy manifestation of this sedimentation was the inclusion of climate change in the most important statewide water-planning document, its California Water Plan Update for 2005 ([California Department of Water Resources, 2005](#)). This document, updated about every five years, had only made cursory references to climate change in its past two versions, but included a major section on climate change in a chapter on uncertainty. The idea to include climate change in this document is an example of upwelling—respondents acknowledged that the idea came from within DWR, although the process of preparing the initial drafts involved stakeholders (including this author) participating in a Climate Change Working Group.

Sedimentation of knowledge of climate change to district managers led to upwelling, as awareness of uncertainty in California’s hydrologic future motivated an increase in flexibility in their future planning. District managers said publicly that climate change is an issue of concern. Legal requirements mandate that districts ensure reliability of the water supply 20 years into the future and provide motivation for a forward-looking view. Interestingly, this may inform how some district managers would like to view climate change largely from an economic, risk management perspective. This seems in keeping with the pragmatic way that they typically plan, for example, to meet demand from projected population growth. Projections for population growth have a range of uncertainty, which can be integrated into projections for future demand and current policy actions and districts would like to use this same risk management model for future climatic changes. Recognizing the increased uncertainties, a top manager at MWD cited climate change as a driver for their decision to make their planning at this high level a more flexible, iterative process.

² Between completion of the present research and its publication, this statement has proven true. Attention to climate change has grown globally and California has continued to be a leader in mitigation measures and has been actively considering consideration of adaptation policies. Details await future study.

Novel scientific problems in complex natural and organizational systems can be expected to require novel solutions. With climate change as a novel scientific and conceptual addition to the world view of water managers, they may be expected to respond by developing new tools in response—the ultimate form of upwelling.

Urban water districts, with pressure to provide consistent supply and high water quality, provide an example. While population growth has historically been predicted with reasonable accuracy (Landis, 2003), water quality is influenced by complex processes such as biogeochemical cycling and land use. Any of these factors are difficult to model independently and correspondingly more difficult to combine. Thus, the information and tools desired by districts may not be available from the scientific community in the near term, making it more difficult for them to integrate climate change into their planning in spite of their publicly stated eagerness to do so. However, the process of upwelling allowed for action based on this science.

An ideal case of upwelling would involve a novel idea from a practitioner, directly motivated by scientific understanding, that leads to independent policies devised by practitioners. The potential use of modern portfolio theory by water managers provides a clear example. Modern financial portfolio theory weighs the rate of return, volatility and correlation among a set of financial instruments (stock, bonds, etc.) and provides standard methods for balancing risk and return for investors. No formal hydrologic analogue exists. Motivated in part by projections of increased hydrologic variability, Buehler (2003) applied this concept to water supply. To illustrate the concept, groundwater supplies may be less affected by drought and non-traditional sources such as desalination or indoor conservation can be almost completely decoupled from the hydrologic cycle. A water agency might be able to hedge against increasing climatic variability through such portfolio diversification, which is innovative because it could provide a way to adapt to the uncertainties of increasing climatic variability.

This example satisfies the criteria of upwelling as a new idea proposed by a manager independently of the scientists who produced the original studies. While it may provide a vehicle for district managers to work with more variable future supplies, the idea was not among the recommendations made by scientists. Instead, it represents a novel policy idea devised by policymakers and influenced by a general understanding of the science. Climate change science thus helped motivate an alignment of interest in non-traditional water sources with the recommendations of scientists, through the vehicle of risk reduction. The upshot is that a manager synthesized scientific information in a policy-relevant way that had not been suggested by scientists—a strong example of upwelling.

While the example of portfolio theory first involved technical staff, upwelling can also work through the highest levels of management. A senior California Resources Agency official actively encouraged her subordinates at DWR to work on the issue. She described a sedimentation process for her and others' awareness of the science, saying that climate change science "just seems to be part of the atmosphere". Others described her role, suggesting she acted as a catalyst for turning existing interest within the agencies into policy action, rather than directly dictating specific actions. Some prominent California water managers had been interested in issues of global climate change before this official was appointed, but had been unsure of how and whether to act given the lack of a legislative mandate. This key player effectively encouraged these people to surface and look for ways to become active on the issue.

The importance of a broad understanding of the science through sedimentation was important in this case. As described above, DWR was "internally primed" through sedimentation for receptivity to these suggestions. This may have increased its ability to act on the suggestions of the Resources Agency. Executives at DWR had wanted to include climate change in the Water Plan Update, but were unsure of

whether it would be appropriate without higher-level direction. The Resources Agency official approved of the idea in an active way, noting that “even if they were criticized for it, the science was adequate to justify making that a part of their considerations”.

Thus, sedimentation at several organizational levels set the stage for upwelling of policy action. Understanding of climate change at the agency level, coupled with understanding of the science by a higher level decision maker allowed for a step forward in the official integration of climate change science into state water planning.

The bottom-up process is also reflected in funding for climate work. As of 2003, there were no large-scale programs at the state level devoted to climate change. Instead, smaller ones were pieced together by interested people. The amount of money being spent on a particular issue can be a good measure of its perceived importance. Top officials described the overall amount as “miniscule” relative to overall budgets. Climate initiatives are mostly pieced together through existing programs, as may be fitting for agencies in the exploratory steps of learning how to integrate climate change with their policies from the bottom up.

Since high-level policymakers have not included budget line items for the issue of climate change in water resources, organizations “piggy-back” on work done in other contexts. For example, currently a group of water managers at DWR takes on responsibility for interpretation of climate change modeling for the agency on a “voluntary” basis, adding this work to their regular duties. This group of self-described “research engineers with interest in policy” works to communicate modeling results to other branches of DWR and pushes scientists to make their results more relevant to water managers. For example, their explanation given to a climate scientist that probability distributions of likely climatic changes are more useful to water planning than presentations of a range between two extremes led to a report that synthesized modeling data in this way (Dettinger, 2004). Here, managers at lower levels have pushed policymakers to a broader view of this issue, motivated by their awareness of the overall significance of the science. It is also consistent with the suggestion of Rayner *et al.* (2005) that this group includes some younger hires, who may bring familiarity with climate science, openness to new ideas and/or the ability to “translate” from a broader scientific body of knowledge to higher level management.

Mechanisms of sedimentation

Sedimentation of scientific knowledge into a management community implies that pathways for this information come from a variety of sources. Relevant decision makers have a broad range of scientific expertise and varying levels of familiarity with the hydrologic or climatologic information needed to grasp the concepts and implications of climate change for water management. Communication tools beyond publication in peer-reviewed journals are necessary. The following are some examples of different mechanisms or pathways through which scientific information had been transferred from the scientific to the policy communities.

Knowledge brokers and key players

A central difference in information transfer between a linear pathway and sedimentation is that ideas need to reach a broader audience. A critical difference in upwelling compared to a linear pathway is that

policymakers act based on scientific ideas, as opposed to the policymakers acting as a conduit for the policy ideas of the scientist.

The sedimentation metaphor implies a dispersion of knowledge to a large number of people over a broad spectrum of a policy community. This implies a corresponding need for a broader variety of conduits for knowledge beyond primary scientific literature and scientific conferences. “Knowledge brokers”, defined as those with a role in translation between scientists and policymakers, played a critical role in increasing the understanding of climate science among policy and resource managers. They did so through a number of avenues, including personal contact, talks at meetings and conferences, and writing reports and syntheses of science. Knowledge brokers are necessary because the primary scientific literature reflects values such as conceptual precision and density of idea content, often at the expense of accessibility to audiences outside a particular discipline. In many areas where science influences policy, particularly those with implications reaching across traditional disciplinary boundaries, some translation and synthesis has proved to be necessary.

The actions of such knowledge brokers helped transfer scientific knowledge from the academy to the policy and management communities. Decision makers at all levels of California water policy cited the influence of scientists from academic and non-profit institutions, who communicated to them the concepts of climate change and its potential importance. Such intermediaries act to bridge scientific and policy communities.

Knowledge brokers tend more often to be scientists working towards informing the policy community, rather than policymakers actively seeking to communicate policy problems within the scientific community. However, this generalization broke down as the dialogue increased through public forums hosted by policy-making bodies. There, it was common to hear policymakers expressing their perspective and desire for specific information directly to climate scientists. In a linear model of the science–policy interface described above, this would lead to targeted research by scientists, who would then deliver directly useable information to policymakers. Instead, policymakers demanded information at a greater level of certainty than scientists could deliver given the development of this field of science. Policymakers at the agency and district level directly and publicly expressed their interest in incorporating this information in more substantive ways to their management plans. Scientists were not able to deliver data of the type the policymakers demand, because of the state of uncertainty in the science. This suggests that a reliance on the creativity of policymakers, coupled with their general understanding of what the science does indicate with confidence, may not be a bad or inefficient thing. Since scientists actually do not have all of the policy answers, upwelling may be the most effective route to policy formulation in the face of uncertainty.

That the linear model did not operate in this example does not diminish the importance or impact of scientific results, or the actions of the scientific community. Rather, it suggests that gradual paradigm shifts in a fairly conservative institution or set of institutions are necessary before collective buy-in can be had into new ways of operating. The question is not whether science influences policy—it is how. In an unwieldy, interdisciplinary body of science, part of this mechanism may be reliance on a larger number of individuals than in better-developed, more discrete fields.

Knowledge brokers may or may not also have status as “experts”. The literal dictionary definition of expertise relates either to skill in or knowledge of a certain subject. The traditional home of science expertise is in academia, in the form of researchers who establish their *bona fides* through original research in particular disciplines.

As science becomes complex enough and its policy ramifications have high enough stakes, problems may grow such that traditional academic disciplinary researchers no longer monopolize the status of experts (Funtowicz & Ravetz, 1992). The actions and identities of knowledge brokers in this case support this assertion. For example, the lead author of a major synthesis of the potential effects of climate change on California (Wilkinson & others, 2002) was a university lecturer who had not yet obtained a PhD credential or a tenure-track faculty position. His strength lay in knowing who the experts were, bringing them together and synthesizing complex information in a readable way, rather than in a natural science track record.

Interviews indicated that key players cited as influential by policymakers were not always those with the strongest or most current academic publication records. This emphasizes the importance of knowledge brokers, as managers who developed an interest in the topic through sedimentation often used these key players as conduits for knowledge. However, they often did not know where to turn for information because of the conceptually novel nature and daunting scope of the problem of climate change. It is important to acknowledge that many scientists who *had* done cutting-edge and directly relevant research actively participated in efforts to educate managers. However, observations and interviews suggest that there were influential “experts” in this area who do not fit the profile of the academic researcher.

To extend this argument, managers, in their search for descriptions of the problem, have sometimes “borrowed” experts from other fields. In the climate change session of a major regional science conference, two noted biologists spoke to the topic of potential ecosystem effects. Each one introduced his talk with a caveat along the lines of “they asked me to talk about climate change. I don’t really know anything about it, but here goes”. Expertise took on a malleable quality in the case of climate change and California water, perhaps owing to the topic’s complexity (Funtowicz & Ravetz, 1992).

In keeping with this malleable quality, knowledge brokers may actually come from within the agency side. Such key individuals can be important in both sedimentation and upwelling, as was a key individual at DWR who had taken a personal interest in the issue of climate change. He became interested in climate change at the time of the earliest projections of snowmelt timing change and identified some of the empirical data on changes in streamflow showing possible evidence that snowfall and snowmelt patterns were changing (Roos, 1987). Largely out of personal interest, he tracked scientific developments in the field and DWR officials say that the institutional respect he commanded effectively primed the department for acceptance of climate change science. Others within DWR cited his involvement as having facilitated their thinking on the issue of climate change.

In sum, while sedimentation and upwelling are on the whole best described on the level of communities (e.g. scientific and resource management communities), individuals matter at the interface between these communities. This reflects in part the intrinsic difficulties inherent in communication between epistemic communities.

Presentation of abstract science

If knowledge brokers are *who* mediates effective transfer of scientific information, methods of communication help describe *how* such transfer happens. Over a decade ago, Ingram *et al.* (1991) noted that whether climate change science would reach the policy agenda was dependent on “how abstract and

theoretical scientific information is interpreted by key political leaders and institutions”. The flip side of this statement is the nature of how such concepts were communicated to these leaders.

Top policymakers garnered understanding through multiple channels, instead of through a few well-placed presentations. As none of them were professional climate scientists, their understanding came through several different pathways.

Within the different formats for communication (basic research publications, reports, conferences, journalism), there exist different ways of communicating concepts such as changes in snowmelt timing. With available computing power paralleling the increased sophistication of modeling and its graphical output, scientists have increasing ability to deliver research results which are more relevant to water managers’ needs and also to communicate the relevant impact of climate change on California’s water.

Heretofore impossible visual representation had become more common, increasing the conceptual effectiveness of scientists’ communication as it begins to approach the level of regional specificity desired by policymakers. One example was the increasing specificity of geographical information available with increasing computing power and modeling sophistication.

Early work (e.g. Gleick, 1987) captured the essence of the problem of change in snowmelt timing (Figure 1) and respondents cited it as influential. The basic conceptual information has only been supported by subsequent research. The ability of models to attempt increasingly regionally specific projections was growing (Knowles & Cayan, 2002; Snyder *et al.*, 2002), but the basic premise of earlier timing of runoff remained similar to early work.

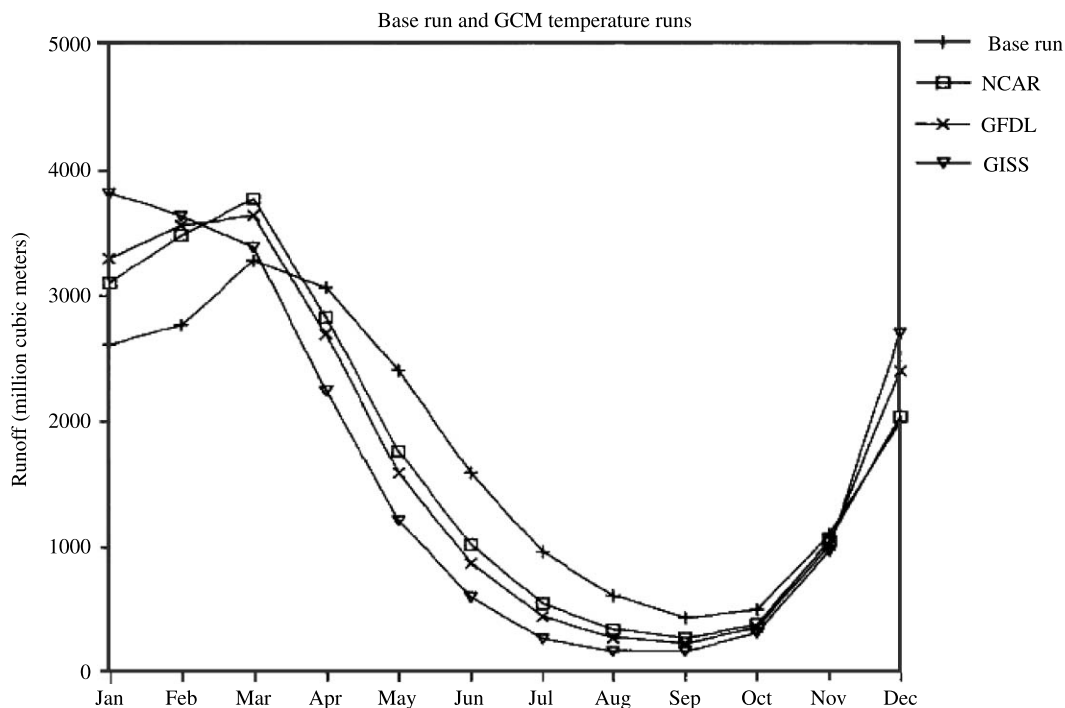


Fig. 1. Average monthly runoff in the Sacramento Basin, California, and its sensitivity to climate change as originally modeled by Gleick (1987). The shift in hydrograph represented here might interest a trained hydrologist, but might not excite a manager who was not as intimately familiar with the importance of runoff timing for the functioning of California’s water management system.

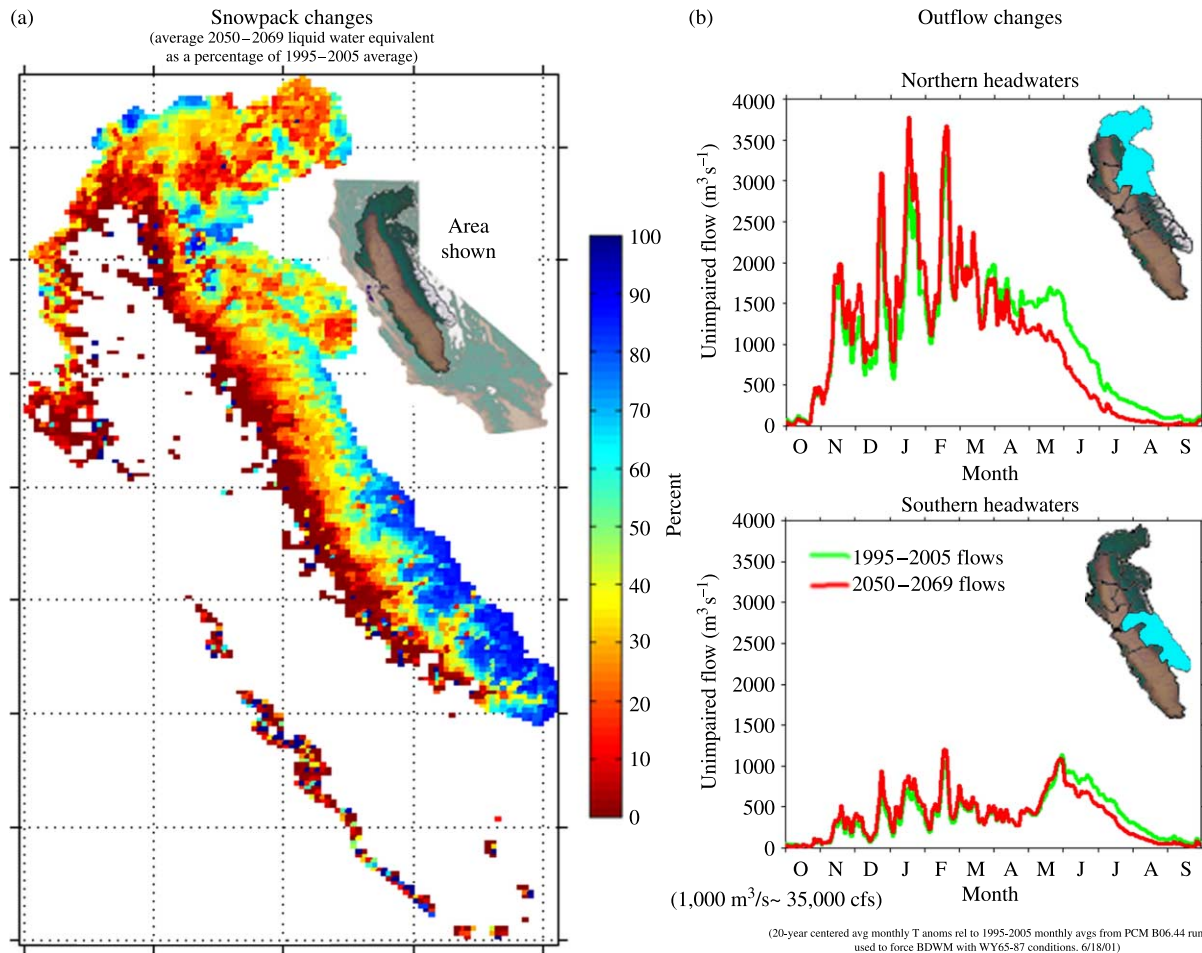


Fig. 2. Projected changes in California's hydrology by 2060. (a) Snowpack changes, (b) outflow changes. Presentation of recent modeling results on timing of snowmelt change in the San Francisco Bay-Delta watershed (Knowles & Cayan, 2002, figure courtesy of Dr Noah Knowles).

However, along with increasing specificity of model results, the graphical delivery of this information has also increased in sophistication and in its impact on policymakers. Respondents cited the results of Knowles & Cayan (2002, Figure 2) as influential. The information most salient to water managers in the more recent figures is the comparative hydrographs contained on the right of Figure 2. In this sense, the information contained in the two reports has the same utility (the hydrograph variability shown in Figure 2 may not be statistically or practically significant given the uncertainty in these sensitivity analyses). Sophisticated presentation of data is critical to spanning the boundaries between science and policy, regardless of the merit or idea content of the science being communicated³. This echoes

³ Notably, the authors of this study acknowledge water managers at the DWR as inspiration for their work, supporting the notion that DWR was receptive or primed to learn about climate impacts, and a cyclical, positive feedback loop between sedimentation and upwelling over time.

the impact that visual images of the ozone hole had in motivating policy action on another complex, abstract environmental issue (Roan, 1989). While the specifics of how communication happens are important in many cases, the overarching lesson appears to be the importance of multiple forums, for multiple audiences, with multiple forms of information. The need for a broad base of understanding among a variety of different decision makers suggests that a final requirement of sedimentation and upwelling is a diverse effort on the part of scientists and knowledge brokers to communicate their work across the science–policy interface.

Conclusion

Between the late 1980s and 2003, resource managers in California began to lay the groundwork for adapting to the projected impacts of climate change on water resources in the state. A broad understanding of climate change science had permeated disparate segments of California water management communities. This fits a model of *sedimentation*, the gradual, broadly distributed increase in scientific understanding within a policy community. In addition, there were signs that this broad increase in understanding may be tangibly influencing water management through *upwelling*, the development of novel policies informed by general scientific understanding. The present study generally supports the sedimentation–upwelling model for the science–policy interface in this case and revealed no evidence of direct “linear” integration of climate change science to water management in California.

Overall, while the actual policy activity was modest, a more positive outlook for the integration of this science to policy may be warranted⁴. Climate change science has produced information that has begun to convince California water managers of the need to investigate possible changes in future water policy. An active dialogue was underway within the water management community. This constituted the first step in the integration of climate change science to water policy: awareness and willingness to exchange information with scientists.

The next steps may involve attempts to integrate the more actionable recommendations into actual changes in water operations. Ideally, scientists will alter existing policy recommendations such that they more directly target different levels of policy and management. This would involve an additional dimension not explored deeply here: more direct feedback between scientists and policymakers.

Generality

Generalizing aspects of this case for climate science to other regions could prove problematic, but some lessons do emerge. Geographical and seasonal aspects of California’s water resource system result in some relatively clearly defined issues resulting from climate change projections, such as change in timing and storage of water. This may not be the case in areas where model projections may be limited, for example, to an increase in the kinds of climate variability that already exist. Also, this case study considers a time period over which concerted effort was made by knowledge brokers to brief policymakers directly about science.

⁴ See footnote 2.

Conversely, the general public, including managers, is becoming better educated about the concept of climatic change through increased attention in the mass media. Further, a younger generation of engineers entering service in the water sector may be more aware of climate science, as it has become more frequently discussed within academic institutions than it was during the education of their predecessors. Thus, other regions may have a head start on integration of climate change science to their policies because of general awareness of the issue, but their issues may be difficult if a clearly defined hydrologic alteration is lacking.

Nonetheless, how California water managers eventually integrate climate change science could prove informative for other parts of the world, as California has traditionally been an environmental and policy leader. While the process may at times seem slow, this may be a pioneering case of adaptation to climate change in the water sector. This case study may inform the use of science in other resource management fields affected by complex problems of the future.

It is, of course, possible to extend further the sedimentation–upwelling model. For example, it is worth noting that just as external forces (such as wind blowing across the water’s surface) drive upwelling, upwelling of decisions from a management community can be profoundly affected by political forces, to take just one example. Similarly, sedimentation and upwelling can affect their surroundings. The movement of water can change the course of the very channels that determine how it flows in the same way that both scientific information and policy decisions can change the framing that constrains the parameters of a debate. These and other extensions of this idea are subjects for future work.

Implications

Viewing the science–policy interface through the lens of sedimentation and upwelling supports and extends theory suggesting that policy is more than the sum of its scientific parts. Awareness of the sedimentation–upwelling model presented above, along with other alternatives to idealized linear pathways from science to policy, could help scientists who seek to have their work influence policy processes. Some scientists still conceive science–policy as operating with a linear model, as it is more consistent with the rational positivist mode of thought favored in natural science training. Science, while essential for informing policy, often does so indirectly. An understanding of this alternative view could help scientists to target their efforts more effectively towards broader audiences.

A broadening by scientists of their role as educators from targeting the highest levels of policy to including wider management communities could increase the speed of the sedimentation process. This is happening in California water in the form of increasingly frequent appearances of the topic in general forums for managers. Scientists divide their limited time between theoretical and applied research, disseminating that research to the scientific community and helping to transfer it to policy and management, but are not always given professional credit for the latter function. Because transfer of knowledge may be a bottleneck in the adoption of science into policy, both the science and policy communities could benefit from an increased role for knowledge brokers. Resource managers and policymakers might do well to increase support for scientific communication designed to speed up the sedimentation process.

Finally, a message for both communities: patience is a virtue. Sedimentation of new scientific ideas and the resulting policy upwelling, each take time. This applies even when institutions are receptive to new ideas. While some suggestions have been made about specific strategies or “response modes” for

effective coping with water problems (Lach *et al.*, 2005), scientists and managers each need to realize that openness, persistence and collaboration are key to success, but that success at shifting paradigms may take years. Data in this study considered the time period through 2003. Since then, the issue of climate change has received much attention in the scientific and policy communities. Formal examination of these more recent developments is ongoing.

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Dedication

I dedicate this paper to the memory of Professor Alex Farrell of the Energy and Resources Group, who passed away as this paper went to press. Among many other accomplishments, Alex was instrumental in helping California move forward in its leadership in climate mitigation policy. His legacy will live on in his ideas, his research, and in the future work of his students and colleagues.

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