The evolution of symbiotic innovation, water, and agricultural supply chains

David Zilberman, zilber11@berkeley.edu, University of California, Berkeley
Thomas A Reardon, reardpm@msu.edu, Michigan State University

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David Zilberman, Alice Huang, and Tom Reardon[1]

Modern agriculture and the food sector are characterized by a high rate of technological change that is supported by public and private research (Alston and Pardey 2021, Sunding and Zilberman 2001). Much of the value-added of food and other agricultural produced output is generated outside the farm gate through multi-stage agri-food supply chains. (Reardon et-al. 2009, Barrett et-al. 2020). There is a growing recognition that supply chains, e.g., of inputs and outputs, tend to be symbiotic and co-evolve (Reardon et al. 2009). Zilberman et-al. (forthcoming) investigated the relationship between innovation and product supply chains. A stylized innovation supply chain (ISC) includes research leading to a discovery, development testing, and refining of the basic concept and development an implementable project. The product supply chain (PSC) consists of multiple segments that generate products and services that implement the innovation. A styled presentation considers an upstream segment where inputs are produced or obtained, a midstream, where they process or distribute, and downstream where they are used. There are likely to be feedback loops linking the ISC and PSC, challenges of the PSC lead to new efforts for the ISC, and new discoveries will lead to modifications of PSC. The emerging bodies of research on supply chains emphasize their continuous evolution in response to changes in technology and policy, leading to the creation of new market structures and institutions. Most of the attention of this literature has been given to supply chains related to agricultural products, and much less to the supply of natural resources utilized in agriculture, in particular water. In this paper, we aim to delineate irrigation systems as supply chains and analyze the synergetic relationship between water and innovation supply chains, as well as product supply chains. Our analysis will show that water and irrigation innovations and the management of water supply chains tend to change the location and product mix of agriculture. It will also demonstrate that research policy and public investment and regulation affecting water supply chains have a significant impact on the evolution of food supply chains and the distribution of economic welfare among parties.

The next section will provide a broad overview of the evolution of water systems affected to a large extent by innovations and the economic impact of alternative water system structures. It will be followed by a more focused discussion of the impacts of modern irrigation technologies on agricultural systems and how the need for agricultural systems affected the evolution of technology. The third section will address some of the challenges facing agriculture, including climate change and salinization, and assess how innovation and innovation policies can affect the future of agriculture and its capacity to meet societal challenges.

The Evolution of Water Systems

Agriculture emerged about 8,000 - 10,000 BC and early agriculture was rain-fed. There is evidence of early irrigation systems in the Fertile Crescent and China about 6,000 BC. The early irrigation systems

[1] David Zilberman is a professor and Robinson Chair at UC Berkeley. Alice Huang is a Ph.D. student at UC Berkeley. Thomas Reardon is a University Distinguished Professor at Michigan State University.

were flooded irrigation systems, where land was managed so basins would be able to absorb excess river water, and later on, water can be extracted through siphoning of water or simple canals. These early water systems were riparian systems, diverting water from rivers or lakes to nearby land, and irrigation mostly occurred in water-rich regions. Over time, with improvement in scientific knowledge and engineering, societies developed systems to convey water over longer distances through canals and aqueducts, which allowed the irrigation of relatively dry regions and required a more complex engineering and management system.

Some early civilizations (around 2500 BC) relied on groundwater dug from shallow aquifers (10-20 m) and lifted by simple manual and animal-powered devices (Angelakius et al. 2020). This early development led to two major categories of water systems, surface water, and groundwater. Two main regimes of surface water development emerged, the riparian water right systems and the prior appropriation system. The riparian water right allocates water only to individuals who border a body of water. The prior appropriation system is based on two principles, first-come-first-served and use-it-or-lose-it. The prior appropriation system was established to encourage people to develop new areas, and it's an extension of the idea of homesteading to water resources. These water rights systems suggest that governments played an important role in establishing irrigation systems, and as a key element in the expansion of agricultural activities and providing livelihood. In most cases, individuals were given water rights for the water they were able to pump, which might have led to excess pumping and depletion of aquifers. The inefficiency of traditional water rights systems has been partially modified over time by the introduction of water trading.

Discoveries in physics and engineering, as well as technological developments in many sectors of the economy, have led to the further development of water systems. They include multiple applications of water systems that include non-consumptive use activities. For example, the use of water as a source of power and the use of water resources for recreation and transportation. Technological developments led to improved irrigation technologies that increase input use efficiency and expand the range of products that can be used with water. Development in pumping expanded groundwater use and increased pumping power led to the emergence of conjunctive use where water is stored during wet years to be utilized in dry years (Schoengold and Zilberman 2007). In recent years, research has led to the developments of technologies of reverse osmosis that allow recycling and reuse of water, as well as desalination of water. These innovations were outcomes of the innovation supply chain and led to modifications of the water supply chain. Below we will identify some of the major components of the water system, principles for optimizing it and discuss several patterns of supply chains that emerge in water systems. Later on, we will discuss how new technologies in some components of water systems affect the water supply chain and discuss some likely patterns for the future as we are likely to encounter climate change.

The Main Elements and Optimal Decision Rules for a Water System

Water systems have a strong element of both space and time. In these systems, water in the intermediary output and the final output is a variety of products. There are multiple variations in water systems. Here we will present one with many general elements. We will analyze the system where water is diverted from one region and moved to be utilized in another. The system is depicted in Figure 1.

The first element of the system is the water source. It can be a lake, river, or even a groundwater aquifer. The first activity of the system is the diversion of the water to canals or aqueducts. The second activity is the conveyance of the water to the destination where it will be utilized in agriculture or industry. The diversion of water requires an initial capital investment with incremental investment over time, as well as variable costs for the diversion activity. Similarly, the conveyance requires investment in infrastructure and maintenance and variable costs for operation. Both in diversion and conveyance, there is a tradeoff between capital and variable cost. A higher investment may increase the pumping capacity and pumping efficiency and a higher conveyance dimension will reduce conveyance losses, namely the fraction of water that is lost from the source to the destination. Water may be utilized for in-stream benefits (e.g., hydroelectric power, shipping). Some of the water may be also stored in a dam or underground. The water that will reach the destination region, where it will be used for production activities, will come directly from the source or storage facilities. A third element of the system is the distribution of water through a system of canals or pipes to final users. The fourth element is the use of water in production, which is farming in our case. Production requires expense in other inputs and investment in irrigation technology. It will produce an agricultural product, but water efficiency is likely to be below 1, and there will be water residue (drainage or runoff). In some systems, the drainage may be treated and reused as part of the production system, but in any case, the residue will have to be disposed of and generate waste. Altogether, we saw a system with multiple inputs and outputs, fixed cost investments, as well as variable costs that operate over a dimension of space and time. The technique of benefit-cost analysis was developed to optimally manage investment in water resources, and we will present a stylized optimization problem of a water system and present some of the optimal decision rules and these decision rules are used as benchmarks to assess actual decision rules under alternative supply chains.

The objective function of a socially optimal water system is to maximize the expected net present value of the benefit minus the cost over the life of the system. To overcome space limitations, we will consider a simple system without storage, intermediate output, or drainage treatment. During each period, the benefits include the benefit from the final (agricultural) products. If demand for the final product is not perfectly elastic, the benefits are larger than the price times quantity. Instead, they equal the aggregate willingness to pay for the quantity consumed, which is the area under the demand curve. At each period the cost includes the fixed and variable costs of diversion, conveyance, instream use, distribution, storage, production, treatment, and the externalities generated by the system. Derivation of optimal decision rules is available in an appendix. At the optimal solution, at each period the optimal level of water used with the final product is where the marginal benefit of the applied water is equal to the marginal cost of diversion, diversion, distribution, and externalities associated with one unit of applied water for production. Since there may be significant conveyance losses and distribution losses, each unit of applied water requires more than one unit of diverted water. The optimal level of output use is where the marginal benefit per unit of output is equal to the marginal cost. This marginal cost is based on the marginal cost of diversion, conveyance, externality, and production; investments in either diversion, conveyance, or distribution equipment are at the levels where the net present value of the marginal increase in the capital because of the investment throughout the life of the project is equal to the incremental cost of the investment. This result is consistent with Zilberman et-al. (2022). If we assume that producers can switch irrigation technologies (they may rent them), the optimal irrigation technology for each period is the one that yields the highest net difference between benefit and minus cost and the rent of the technology. One of the interesting features of the water system is the existence of multiple irrigation technologies with varying input use efficiency. A more advanced technology like drip irrigation tends to increase input use efficiency, namely the amount of applied water that is utilized by the crop, and reduce the amount of drainage and pollution of the system. Using the comparative statics in Caswell and Zilberman (1986) and Chakravorty et-al. (2009), it can be shown that:

1. Reduction in the variable or fixed cost of diversion, conveyance, and distribution will lead to increased production and water use

2. Increase in the efficiency of conveyance, distribution, or irrigation would lead to increased production but may lead to a reduction in actual water use. Such increases will reduce the residue of the system

3. Increase in the demand for the agricultural product would lead to increased production, but may lead to increased investment in capital goods, and may lead to reduced water use

4. Increase in interest rates may lead to a reduction of investment in the water system and a reduction in its production.

Other considerations affect optimal water system design. First, when adding in-stream use of water to an irrigation system, it may increase the investment, but it may also increase the profitability and may increase the likelihood that the system will pass the benefit-cost test. Indeed, some of the large water systems in the world are providing water to multiple constituents, e.g., both urban and rural, and provide benefits through hydroelectric power and recreation. Sometimes each activity by itself cannot justify a water project but combined, various activities integrated with a water project may make it economically worthwhile. Second, water systems are operating under conditions of seasonality and randomness. Storage facilities are constructed to extend the growing season and address intersectional variation in precipitation and climate. They may be used to extend the value of hydroelectric power and provide recreation and fishing benefits. The optimal use of inventory water during each season should equate marginal expected benefit with marginal costs. Optimal levels of investments are where the expected discounted marginal benefits over time are equal to the marginal costs of capital. The social-welfare optimizing decision rules are not necessarily followed by the various water-related supply chains.

Water Innovation and Water Supply Chain

Water systems are established through multiple supply chains. First, there are innovation supply chains that provide the knowledge and detailed designs of specific supply chains. Second, there are various supply chains that divert, convey, distribute water, and dispose of drainage. Finally, there are the product supply chains of different outputs that are produced with water.

The innovation supply chain includes research institutions that study various disciplines associated with water, including hydrology, physics, civil and environmental engineering, economics, geography, and agronomy. Researchers, as well as practitioners, will come up with ideas for new water-use technologies, as well as projects. These ideas may be further developed by institutions like government agencies, and multilateral organizations (e.g., The World Bank) that will assess water project design and obtain resources for it, as well as regulatory agencies that will approve water systems. Once a project is designed, a water supply chain emerges to execute and manage the water system. These supply chains have a symbiotic relationship with product supply chains.

Two major considerations that affect the design and performance of water supply chains are the political economy and credit. Political power distribution will give different interest groups different weights, unlike the social-optimization problem that will give the surpluses of consumers, producers, and government equal weight (Rausser, Swinnen, and Zusman 2011). Political power consideration may significantly affect the size of water projects and their design. Reisner (1993) argued that the political power of developers has led to excessive investment in water projects in the US West and some countries around the world. In the 1980s, the US government introduced principles and guidelines for project assessment that are based on the principles of benefit-cost analysis in order to optimize water project design (Water Resources Council 1983). The World Bank also developed criteria for project evaluations that embrace sound economics and sustainability considerations (Rodriguez et-al 2021). The impact of these guidelines on project design and performance needs to be evaluated. Water projects generally require significant investment and obtaining finance is a major constraint, and that gives governments, as well as international organizations like the World Bank, their say in project design and affects the resulting water supply chain.

We can identify several patterns of supply chains that control water systems. The first pattern is large water projects are quite frequently run by a public water utility that manages water diversion and conveyance, as well as the generation of hydroelectric power and storage, and then sells the water to regional water distributors who will sell it to the final user. This is a manner through which some of the biggest water projects in the world, including the Central Valley Project and the State Water project in California, the large water projects in China (South-to-North Water Diversion Project, Three Gorges Dam), etc. Agricultural water prices charged by these projects, especially in the earlier stages, are deemed to be quite low and not to cover even operational costs (Johansson 2000, Tsur and Dinar 1997). One reason is that at the early stages of the project, its management would like to create demand and induce businesses to use the water. Therefore, they will provide long-term contracts with relatively low water prices. Furthermore, in many cases, water rights are not tradeable and the rights to the water depend on use, which leads to underinvestment in water conservation. Over time there may be transitions to water trading that will enhance the adoption of modern irrigation technologies. The distribution of water within regions may be suboptimal without coordinated effort to manage canals effectively. If every farmer is responsible for building the infrastructure to convey water to their own plots, they will not consider the need of farmers downstream resulting in underinvestment in infrastructure and underutilization of water. Therefore, the establishment of regional water distribution centers that recognize the need of all users and invest in reducing conveyance loss within districts can even double the productivity of water in the region (Chakravorty et-al. 2009).

A second pattern is a water system that is run by water users. It may be a cooperative owned by final users and diverts and distributes water to individual members. This type of arrangement was typical in California and other parts of the world in the early periods before governments were able to finance water projects. In California, earlier water projects were used for mining, but over time, the infrastructure was diverted to irrigation. These water projects were early users of water resources. The members had relatively low water demand compared to the water availability, and therefore, they underinvested in conveyance and had high conveyance losses.

Figure 2 depicts California's network of water projects. The larger water projects are government-financed. The Federal projects are in blue, and the California State water project is in red. The federal project includes the Central Valley water project which moves water from Northern California to the Los Angeles area, and the Colorado River project which moves water through the American canal to Southern California. The state water project transfers water from Northern California to the south as well. The private water projects are smaller and shorter and tend to be older. They include longer projects that provide water to Los Angeles and the San Francisco Bay area, and smaller projects that were originally used for mining and are now used for irrigation.

A third pattern occurs when a private entity invests in the delivery and conveyance of water and then sells it to users. The water supplier has monopoly power and may overcharge and undersupply water to the farmers who use the water. There is evidence for such misallocation of the use of groundwater in India and Pakistan (Murgai, Jacoby, Rehman 2001).

Frequently, water projects are developed with low regard for environmental externalities. Without the inclusion of environmental and other external costs, projects tend to be bigger than is socially optimal (Zilberman and Lipper 1999). In some situations, deep peculating water from irrigation accumulates below the soil and results in water logging, which leads to abandoned agricultural land, or the development of drainage facilities that dispose of all the water. In the case of groundwater, there is a risk of salinization that requires disposal or recycling activities. Water systems eventually have a water disposal component that renders them more sustainable. The design and management of these disposal facilities, and possible conversion to new sources of recycled water, and even minerals are subjects of ongoing research (Anderson 2003, Dinar and Zilberman 1991).

Supply chains that implement new innovations tend to generate new products and transaction arrangements (Zilberman et-al. 2022, Reardon et-al. 2009). Indeed, the construction of the water supply chain led to the introduction of expansion of production and trading of various products and services, both inputs and outputs. They include pumps, pipes, water meters, and various components of irrigation technologies. Water projects may purchase many inputs in the market, but mostly they rely on specific contractual relationships to develop products to meet specifications (Matthews and Howell 2005)

Moreover, the introduction of water supply chains tends to modify crop supply chains, and these two supply chains co-evolved as technologies improve we will argue below.

The Co-evolution of Product Supply Chain and Water Supply Chain

The introduction of new water technologies and supply chains has tended to increase agricultural supply and led to the introduction of new products and production patterns. For example, Pueppke, Zhang, and Nurtazin (2018) document how irrigation in the Illi river in central Asia has changed over time with technological innovation and in response to political changes, from simple ditches to dams, and over time to pumping facilities and canal that allow expansion of irrigation to desert regions with fertile soils and minimal water. This expansion of irrigation enabled the production of high-value fruits and vegetables as well as rice. However, the quality of much of the land has not been maintained, drainage problems and desalination problems emerged and the Ill river agriculture is now challenged. There is ongoing research to develop sustainable practices that will enhance productivity and sustainability.

In this section, we provide specific examples of how the innovation supply chain affects the water supply chain, and how new technologies evolve and continue to affect crop production patterns. Specifically, we examine the impact of three active areas of innovation: optimal irrigation, the desalination of water, and the cleanup of drainage water.

Drip irrigation was a product of Israel and the public and private sectors in the 1960s and was exported to the US in the 1970s. The technology increases water use efficiency and thus tends to increase yield per acre and save water applied in most cases. It allows continuous irrigation compared to traditional flood irrigation where water was applied a few times during the seasons. The technology led to the introduction of multiple products and their own supply chains including emitters, pipes, and filters. These supply chains include producers, distributors, retailers, as well as consultants. Because drip requires some pressurization of water, it was applied earlier with surface water, where pumped water was pressurized, and users of surface water either developed storage or the water system was modified to have regional storage and continuous supply.

While traditional gravitation systems required relatively leveled fields, the expansion of drip irrigation allowed production to move to uneven lands, moderate hills, and sandy soils. Indeed, the production of the supply chain of avocado and grapes in California was expanded to the hills in the coastal area, and inside the state. Drip irrigation allowed high-value vegetables in sandy soils in California, Israel, and elsewhere. Drip irrigation technology has evolved over time. Drip systems have been adapted to the application of fertilizers and pesticides, which modified the product line and the supply chain of chemicals in California. Furthermore, university research led to the modification of the production of processing tomatoes and other crops to the use of drip irrigation (Taylor and Zilberman 2017). Drip irrigation became a key component of a modern production system and supply chain of strawberries, which combines planting nursery-grown plants in a mulch protected by plastic, and fumigated, drip irrigated, and fertigated. This high-yield system reduced the acreage of strawberries and led to concentration in a few regions in California and Florida where the ripe strawberries are chilled and then shipped in climate-controlled vehicles throughout the country and the world (Olver and Zilberman 2022). The continuous irrigation feasible with drip led to the introduction of more precise irrigation that is triggered by weather conditions frequently relying on the California information management system (CIMIS), an innovation of the University of California operated by the state. Some farmers rely on various monitors of soil moisture. Farmers may rely on members of a new industry, Irrigation Consultants, to manage their irrigation choices and water application. These consultants have been the major users of CIMIS (Zilberman et-al. 2019).

Drip and low-volume irrigation have been adopted gradually in the US and various European countries during the late part of the 20^{th} century benefitting from the effort of dealers, extension, and social networks (Genius et-al. 2014). More recently, they have been adopted in developing countries in Africa and Asia. Venot et-al (2017) document how the adoption of drip frequently supported by government subsidies and benefitting from the prestige of being “modern” led to the introduction and/or expansion of supply chains of fruits and vegetables. They emphasize that the adoption of drip irrigation was successful when its application adapted to local conditions and the products were rewarded by wholesalers, retailers, and consumers.

Water treatment and reuse supply chain

Increasing global demand for freshwater, as well as waste within the water system, has also prompted innovations in waste management systems. Globally, the use of freshwater generates large amounts of wastewater, of which more than 80% is discharged without treatment, with potential negative environmental and economic implications (Colella et al. 2021). Thus, wastewater represents a large “untapped resource” for clean water, and innovations to treat and reuse wastewater have large potential impacts on water supply chains.

At present, there are many types of wastewater treatment technologies, with the goal of recovering clean water, organic polymers, and various types of nutrients from wastewater.

In general, consistent with the threshold model of technological adoption, the adoption of desalination and waste management technologies tends to be faster in countries with acute water shortages. For instance, countries such as Australia and Spain, which face water shortages, have long-since adopted desalination technologies. Spain uses the highest proportion of desalinated water for agriculture, which is possible in large part due to financial support and government subsidies (Burn et al. 2015). However, as the costs of desalination and wastewater treatment decline, desalinated water will become more competitive for urban use, particularly given the higher cost of water in urban sectors relative to the agricultural sectors.

Two challenges of water systems are insufficient water and contaminated residues-resulting in salination and contamination of groundwater. One approach that can address partially this problem is water desalinization. While the process of water desalination has been around for thousands of years (e.g., the ancient Romans used clay filters to trap salt), new desalination technologies have emerged in recent years to preserve water resources and address the growing demand for fresh water. Desalination refers to the process by which salt and minerals are removed from seawater or brine, yielding fresh, drinkable water. Sedlak (2014) provides an overview of the innovation that led to the development of desalinization facilities. The first large-scale desalination plants were built in the 1960s, and today, over 300 million people globally get their fresh water from desalination plants (Robbins 2019). Many governments invest in desalination technologies due to water shortages. Saudi Arabia, for instance, with low energy costs and a limited natural endowment of fresh water, is now the world’s largest producer of brine and fresh water. Similarly, the Millenium Drought of 1997-2010 caused Australia to invest $15 billion in potable water recycling and desalination technologies (IWA 2016).

At present, the use of desalination technologies in agriculture is limited but growing. Desalinated water for agricultural production tends to have lower salinity and post-treatment requirements relative to desalinated water for drinking water since most crops can tolerate water with moderate salt content (Zarzo et al. 2013). Zarzo et al. (2013) find that the use of desalination in agriculture increases the productivity and quality of certain agricultural products. For instance, the study finds that with the use of desalinated water in the irrigation of citrus fruits, yields increased by 10-50% relative to the conventional water supplies, and the overall water use was reduced by 20%. Other studies have shown that the optimal salinity in water for agricultural production differs by crop (Zarzo et al. 2013). While some products (e.g., almonds, peppers, cucumbers) are highly sensitive to saline water, other products (e.g., celery) are less sensitive. Desalination technologies can in theory allow farmers to regulate the saline levels of water used in agricultural production.

Despite the benefits, the widespread adoption of desalination for agricultural purposes has been limited in large part due to the high cost of implementation, relative to the cost of water commonly used for agriculture (Burn et al. 2015). However, as desalination technologies become more efficient and costs of production decrease, the use of desalinated water may become more economically attractive. Furthermore, relatively high desalination costs may be offset by the adoption of efficient irrigation technologies (e.g., drip irrigation), particularly for higher-value crops. At present, there are a number of commercially-available desalination technologies, which vary in terms of cost and water recovery rates. Two of the most common desalination technologies are reverse osmosis (RO) and electrodialysis (ED). RO is a pressure-activated system that separates the salt and freshwater by driving water through a membrane; ED is a chemically-activated system in which, as water flows next to ion-exchange membranes, an applied current removes the salt from the water (Biesheuvel et al. 2021). RO tends to be more economical, although both methods are energy-intensive. Other emerging technologies for providing desalinated water include Forward Osmosis, pervaporation, and solar desalination techniques among others (Burn et al. 2015). As these innovations continue to evolve, in conjunction with efficient irrigation technologies and energy costs, water desalination processes may play a major role in agricultural production.

A final application relates to technologies that enhance the treatment of drainage water. As mentioned above, drainage can be a substantial source of water loss in agricultural production. Globally, nearly two-thirds of irrigated water is lost to drainage (Gregory 2012). Irrigation drainage water exhibits a high degree of salinity and tends to contain significant concentrations of nitrogen and phosphorus loads, which not only makes it unsuitable for reuse but also poses a challenge for proper disposal (Lichtenberg et al. 1988). Technologies that enable the treatment and recycling of drainage water may thus improve the water input-use efficiency in agriculture.

To date, innovations to aid in the treatment of drainage water are often initiated in the public sector. For instance, in 1985, following observations of avian teratogenesis in the Kesterson Reservoir, a repository for agricultural drainage flows in California, the state of California and the EPA established limits on the selenium concentrations in irrigation drainage (Green et al. 2003). In 1995, an Algal Bacterial Selenium Removal facility (proposed by Professor William J. Oswald of UC Berkeley) was designed and constructed at the Panoche Drainage District, which was able to remove approximately 80% of total soluble selenium and over 95% of nitrate from drainage water discharged to the San Joaquin River (Quinn et al. 2000). Similarly in the early 2000s, the San Luis Unit of the U.S. Bureau of Reclamation (USBR) conducted research on selenium-removal technologies. The agency issued a Record of Decision in 2007, which proposed the construction of a facility using reverse osmosis and selenium biotreatment technologies to treat drainage water (USBR 2011). A review of current treatment options for agricultural drainage wastewater finds that the most promising technologies include reverse osmosis, high-rate algal ponds, and chemical precipitation methods (Lee 2018). These technologies differ in the types and concentrations of metal and mineral pollutants that can be removed from drainage water, which offers greater optionality for farmers. Hejase et-al. (2021) identified multiple opportunities for the treatment and reuse of agricultural water in the United States. In eastern states, drainage water can be used to provide also fertilizers, while in the western US, they may be treated to eliminate minerals such as selenium. Ongoing research investigated the alternative structure of the water system. One option is centralized treatment facilities with drainage pipelines going to these facilities. An alternative option is a decentralized system where treatment is done by many small facilities located over space. There is ongoing research to address the technological challenges of both approaches and implementing each approach may necessitate design and investment in water treatment and reuse supply chain. Economic, as well as policy considerations, will determine the evolution of the supply chain for water using desalinization and other treatment facilities. The water supply chain will co-evolve with the desalinization supply chain and both will have symbiotic relationships with research and innovation.

Conclusion

This paper illustrates the linkages between water innovation and supply chain, as well as between water supply chain and supply chains of the products that the water contributes to growth. As water systems evolve over time, they provide multiple products and generate externalities. The public sector plays a major role in the research, investment, and management of water supply chains, and they rarely operate in a socially optimal manner. Agricultural water systems have relied minimally on market forces, but with increased water scarcity there is a transition from water rights to water markets. Increased knowledge and water scarcity led to the emergence of new technologies like drip irrigation that tend to modify water supply chains, as well as crop supply chains. Agriculture and society have to meet the challenges of food security and climate change, as well as growing water scarcity and reduction of water quality. Investment in research resulting in innovations leading to supply chains that can increase water availability, resilience, and productivity can meet the challenges.

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Figure 1. Flow chart of water systems

Figure 2. California Water Supply Project.