Silicon Valley's Integrated Water System

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California's Santa Clara Valley, widely known as the Silicon Valley, manages its water resources admirably, integrating surface water, groundwater, artificial recharge, waste-water treatment, imported water, water conservation and public participation. As India seriously tackles its water challenges, the Silicon Valley's case history provides insights into how citizens of a hydrological basin may take control of their indigenous water resources based on an understanding of the essential attributes of hydrological systems, and drawing upon the best available science to achieve sustainable management. This case history also highlights the fact that even with the most sophisticated integrated water management, there are definite limits to the extent to which indigenous resources can satisfy water demands.

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Introduction

Webster's *International Dictionary* defines "synergism" as the "interaction of discrete agents, elements, or constituents in such a way that the total effect is greater than the sum of the individual effects". In this sense, the interaction between the citizens of Santa Clara Valley of California, widely known as the Silicon Valley, and a scientific understanding of the hydrological cycle qualifies as synergism. This synergism, as manifest in the evolution of the Valley's water management system over the past century, may provide useful insights to communities around the world that are confronted with the difficult challenge of water management. Accordingly, what follows is a narration of the water history and experience of the Santa Clara Valley, describing interactions among human attitudes, commerce, technology and governance.

This work begins with a description of the natural setting of the Santa Clara Valley, followed by a historical account of the Valley's water management system from the dry-farming days of late 19th century through irrigated orchards to modern urban geography dependent on high-technology manufacturing. Against this backdrop, the Valley's integrated water management system is then portrayed, including technical and governance aspects. The paper concludes with a discussion of water management lessons that may be learned from the experience.

Natural Setting

Santa Clara Valley, located about 60 kms south-east of San Francisco in California, is bounded on the east by the Diablo Range and on the west by the Santa Cruz Mountains, both rising to about 1,150 m. To the north, streams of the North County flow into the San Francisco Bay, and on the south, South County streams drain into Monterey Bay. Of a total of 23 streams, 19 belong in the larger North County. The administrative unit, the Santa Clara County, with an estimated population of 1.78 million in 2009, occupies an area of about 3,380 sq kms. Water information pertaining to the Valley can be accessed at the web site of the Santa Clara Valley Water District (http://www.valleywater.org/).

The Valley is generally arid, with an average rainfall of about 350 mm on the floor to more than 1,000 mm over parts of Santa Cruz Mountains on the west. In the Mediterranean-type climate, precipitation occurs during the winter, between November and April. Below-normal rainfall persisting for five years or longer (1928-34; 1944-50; 1987-92) is common (California History Centre and Foundation 2005: 263).

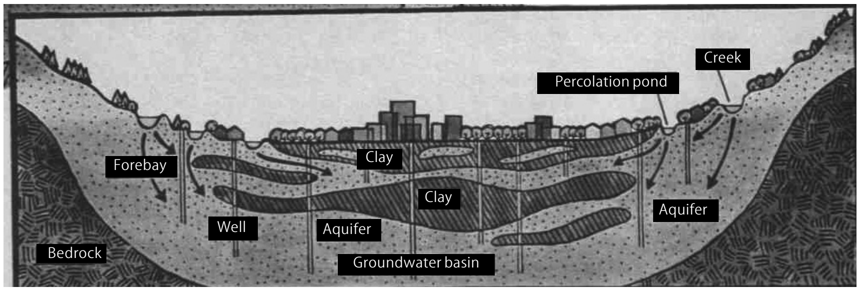
Geologically, the Valley is filled with several hundred metres of unconsolidated sediments with abundant pore space for water accumulation. Because water rushing down from the hills possesses higher energy, sediments along the foothills and upper Valley slopes comprise highly permeable sands and gravels down to considerable depths. Towards the Valley's lower reaches, the formations comprise layers of permeable sands (aquifers) separated by thick layers of silts and clays of low permeability but high porosity (Iwamura 1995). Known as "aquitards", these low-permeability layers keep groundwater confined under pressure in the aquifers, giving rise to artesian conditions of free flow at the surface. The consequence is that artesian aquifers of the lower Valley are sustained by groundwater recharge by streams that lose water by percolation as they traverse the foothills and the upper reaches of the Valleys (Figure 1, p 41).

The natural setting provides a basis for examining the evolution of water management in the Santa Clara Valley. The Valley is an uncommon natural laboratory where boundaries of surface water, groundwater and local administration (the county) coincide (Reynolds 2000: 7).

Society-Science Synergy

The water history of the Santa Clara Valley is influenced by and is reflective of understanding water as a natural resource,

Figure 1: Schematic Section Showing Areas Suitable for Artificial Recharge at Higher Elevations Where Permeable Sand and Gravel Assist Percolation



Towards the centre of the Valley, poorly permeable clays confine water under pressure in the aquifers.

including its scientific and technological aspects (ibid: 10). This recognition by the Valley's citizens, central to the society-science synergism, provides the motivation and the context for examining the evolution of the water management system, beginning with the second half of the 19th century.

Pre-railroad Beginnings (1850-1900): Following California's statehood in 1850, the early settlers of the Valley found themselves in an unusual climatic situation with rainfall occurring during the non-growing, winter season. Although the first artesian well had been drilled in 1854, the farmers of European origin, used to rain following the plough, did not practise irrigated agriculture of any significance. A strong eastern market for wheat (Bonanza wheat), aided by the completion of the transcontinental railroad during the 1870s, encouraged machine-assisted dry-farming over large acreage. But, the wheat market died by the 1880s. This, combined with intervening periods of drought, motivated the farmers to shift to irrigated orchards to take advantage of emerging markets for fruits and vegetables.

To help farmers pool their resources to harness water, the state legislature passed the Wright Act in 1887 allowing them to form "irrigation districts" to raise funds by issuing bonds, divert water from streams and locally manage water resources. With the growth of orchards and affluent towns, the Valley was popularly considered a Garden of Eden, a terrestrial paradise and a gift of god (ibid: 96).

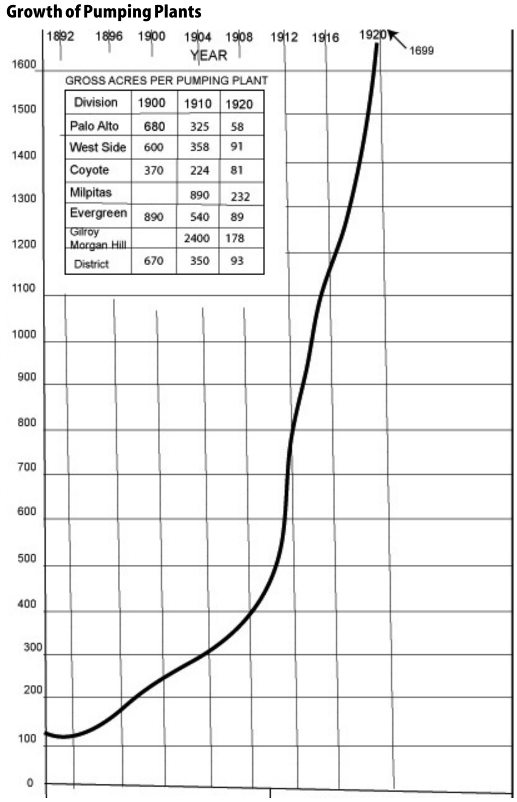
By the 1890s, scientific agriculture and systematic water surveys aided by the federal government had become common place. Scientists had established that confined aquifers sustaining artesian wells were being recharged by streams flowing over permeable beds in the foothills and upper Valley slopes. In southern California's San Bernadino County, this recognition led to the first successful attempt of artificial recharge, enabling storage of storm drainage in the groundwater reservoir for later recovery (Hilgard 1902). Underground storage was intuitively recognised to be a viable alternative to surface water storage. A major technological breakthrough during the 1890s was the invention of alternating current enabling long-distance transmission of electric power. Hydro-electric power plants soon began delivering power for industrial use.

Overdraft and Motivation to Conserve (1900-20): Prior to availability of electric power, windmills helped lift water from non-flowing wells. With the availability of electricity, horizontal-shaft centrifugal pumps became popular, but were limited to lifting water from within eight metres of pump setting. To overcome this limitation, the vertical-shaft turbine pump was invented which could be lowered into the well to lift water in wells with levels many tens of metres below land surface (Narasimhan 2009). Abundant availability of groundwater, combined with some years of below-normal rainfall made irrigated orchards a thriving industry. Between 1910 and 1920, the total number of wells increased nearly fourfold from about 450 in 1910 to 1,700 in 1920 (Figure 2). Concerned citizens of North County united to form a water conservation commission, and assigned to Fred Tibbetts, a civil engineer, the task of investigating the Valley's water resources and recommending a plan of optimal management.

At the turn of the 20th century, the citizens were already aware of the hydraulic connection between water-laden streams at higher elevations and artesian wells in the lower Valley. In 1904, in a court case against a private water company that planned to construct dams on some major streams potentially curtailing downstream flow, lower Valley farmers succeeded in convincing the court that decreased stream-flow would seriously affect well-yields downstream. The judge ruled that farmers enjoyed a right analogous to riparian rights (Reynolds 2000: 23).

Over 18 months starting in 1920, Tibbetts and Kieffer conducted a topographical survey of rainfall and stream-flow measurements, inventory of water wells and population projections. In their report (Tibbetts and Kieffer 1921) they concluded that by 1917, the Valley's water use had exceeded the annual replenishment. To meet escalating needs, they recommended an integrated water management system

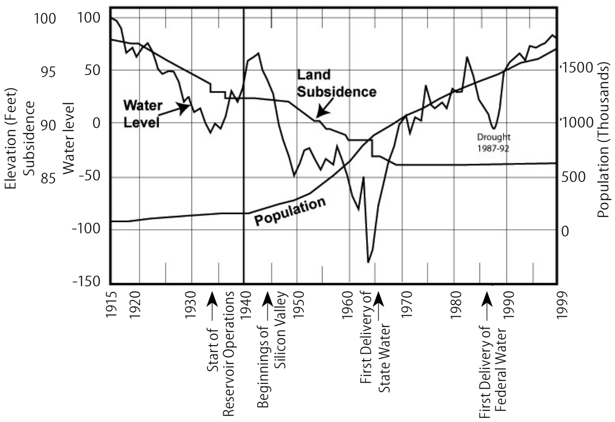
Figure 2: Santa Clara Valley Water Conservation Project: Growth of Pumping Plants



Division	1900	1910	1920
Palo Alto	680	325	58
West Side	600	358	91
Coyote	370	224	81
Milpitas		890	232
Evergreen	890	540	89
Gilroy Morgan Hill		2400	178
District	670	350	93

Between 1910 and 1920 Santa Clara Valley witnessed a dramatic increase in the total number of irrigation wells, combined with steep decrease in well yields, and alarming declines in water levels leading to escalating pumping costs (Tibbetts and Kieffer 1921).

Figure 3: History of Water Level Change, Land Subsidence, and Population Growth in Silicon Valley (1915-1999)



A dramatic rise in water level is seen immediately following the start of reservoir operations in 1935. The sharp decline in water level between 1943 and 1965 was due to increased water demand from a growing population of the emerging electronic industry. Importation of significant quantities of water from Northern California rivers commenced in 1965, leading to rising water levels and decreased land subsidence.

combining 17 surface water reservoirs, well-placed artificial recharge structures and groundwater extraction.

With the best available science counsel, the citizens of North County faced the challenge of implementing the plan for common good.

Creating an Institution (1920-30): The implementation of the plan required funding. To raise funds through bonds, local citizens had to seek an authorisation under the Wrights Act to form a "water district". A vigorous debate soon ensued on implementing the Tibbetts-Kieffer conservation plan. Despite a recognised need for water conservation, serious concerns emerged about the substantial costs involved, related tax burden and the potential for unaccountable government. Additionally, some believing in divine dispensation felt that in future, increased rainfall would render expensive water conservation measures unnecessary (Reynolds 2000: 28). Meanwhile, the proponents of the conservation plan obtained legislative approval for forming a water district, subject to approval by the county's citizens. In a 1921 referendum, the initiative was defeated by a narrow margin. In 1925, the initiative was once again brought for a public vote. This time, the defeat was overwhelming (California History Centre and Foundation 2005: 14).

Despite two failures, the conservation movement was revived. To demonstrate feasibility of conservation to the people, the leaders raised funds and constructed check dams and infiltration ponds on gravelly areas of several streams and in abandoned gravel quarries. These artificial-recharge experiments proved to be remarkably successful, raising the nearby water levels to highest levels in over a decade (Reynolds 2000: 43-44). This success, combined with active campaigning about economic growth and benefits led to the approval of the conservation plan by the voters in 1929, and the Santa Clara Valley Water Conservation District was formed, authorised by the Jones Act.

The district, as constituted, centred around utilisation of groundwater resources of portions of the North County. Citizens of the smaller South County formed their own district a decade later.

Brief Success (1930-45): This was the time of the Great Depression, and the district functioned over the next few years with limited resources, as it slowly raised funds for implementing a significantly scaled-down version of the Tibbetts-Kieffer plan. Finally, six surface water reservoirs were built between 1934 and 1936, along with a host of canals, check dams and percolation ponds to store excess flood waters underground. After protracted delays caused by land acquisition disputes, two more reservoirs were commissioned between 1950 and 1952. In 1938, people of South County formed a water conservation district along similar lines. They built two reservoirs and associated artificial recharge structures. This district later became known as Gavilan District.

Finally, citizens of North County had an integrated water management system. The beneficial effects of the conservation strategy immediately became evident as water levels began rising in wells in the Valley (Figure 3), peaking in 1943. However, the period of optimism was short – because the demography of the Valley changed for ever following the second world war.

Meanwhile, a routine high-precision survey by the US Coast and Geodetic Survey revealed in 1931 that large declines in water pressure in the aquifers had led to land subsidence over the Valley, attaining a maximum of about 1.3 metres in the city of San Jose. Some lands close to bay became vulnerable to inundation as they sank below the sea level.

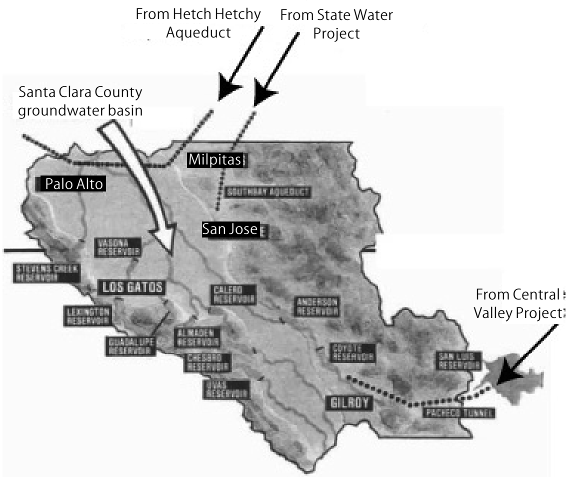
Post-war Urban Growth (1945-2000): During the second world war, the Valley was economically prosperous, being a major source of processed foods. Its indigenous water resources harnessed by the conservation plan were proving to be sustainable. This fortunate situation changed dramatically with the cessation of the war during the mid-1940s. A number of manufacturing industries producing defence-related and civilian hardware began proliferating in the Valley.

In 1939, Bill Hewlett and David Packard founded an electronic manufacturing company in the Valley, ushering in an era of hi-tech electronic industry that continues to this day. Santa Clara county's population expanded nearly eightfold from 1,75,000 in 1940 to 1.3 million in 1980. The phenomenal economic growth and demographic change, accompanied by vastly increased water demands, rendered the Tibbetts-Kieffer system inadequate, despite its technological sophistication.

Although the immediate need during the 1950s was to find adequate water supplies for the burgeoning population, the Valley also faced other problems such as flood-control, water pollution and habitat endangerment (California History Centre and Foundation 2005). The citizens of the Valley continued to creatively adapt to the ever-changing circumstances technologically and institutionally.

Institutional Multiplicity and Rivalry: In the early 1950s, North County witnessed an unprecedented flood damage. The eight reservoirs built under the Tibbetts-Kieffer plan were not designed for flood protection. Additionally, because of increased water demands, water levels had once again started falling dramatically after 1943 (Figure 3). There was no way to meet water demands from local sources. Water had to be imported. To meet these

Figure 4: Water Imports: Santa Clara Valley Water District



Of the total use in 2008, imports from the Central Valley Project was about 29%, from the State Water Project 9%, the Hetch Hetchy Aqueduct 16%, and miscellaneous 6%. Collectively, local surface water and groundwater accounted for about 40% of total use.

needs, the Santa Clara Valley Flood Control and Water Conservation District was created, independent of and in competition with the existing water district. Rivalry arose between the institutions due to competition for revenues to be raised. By the end of the 1950s, there were three independent water districts within the county, one for the North County, one for the South County and one for flood control.

Import Sources: To meet the Valley's escalating needs, three potential external sources were available. The first was the Hetch Hetchy Aqueduct, 270 km long, conveying municipal water from the Sierra Nevada Mountains on the east to San Francisco on the west. A portion of this pipeline, traversing the northern extremity of the Valley, would supply water to the municipalities of Milpitas, Sunnyvale, Mountain View and Palo Alto, subject to the restriction that the water be used solely for municipal purposes.

The second possibility was the federal government's Central Valley Project, designed around Shasta Dam on the Sacramento River in northern California. Completed during the 1940s, water from this facility was being delivered via the Delta Mendota Canal to agricultural lands in California's Great Central Valley. This source, although viable, posed engineering challenges because water had to be pumped through tunnels and pipelines across intervening mountains south-east of the Valley.

The third possibility involved the State Water Project, under construction during 1960, designed around Oroville Dam on northern California's Feather River, intended to provide water supply to southern California's metropolitan areas, via, the 700-km-long California Aqueduct. The proposal was to bring water, via, the South Bay Aqueduct, a branch of the California Aqueduct, entering the Valley from the north-east.

Based on engineering consideration and urgency, a decision was made to import water as quickly as possible from the State Water Project. The first deliveries, via, the South Bay Aqueduct came in 1965. It could not have come at a better time. As seen from Figure 3, water levels in some wells were more than 100 ft below sea level. The first deliveries were directly used to recharge groundwater and help dramatic water-level recovery (Figure 3). Import from the Central Valley Project, via, the San Felipe Project was implemented later, with deliveries starting in 1987.

Mergers and New Challenges: Even during the 1960s, many believed that coordinated water management over the entire county would be better achieved with a single district. However, achieving a merger of three different agencies was a slow process. In 1968, the Flood Control District merged with the Santa Clara Valley Water District. In 1987, the Gavilan Water District too merged, leading to the Santa Clara Valley Water District as it is constituted today.

As can be seen from Figure 3, water levels continuously rose with import of water, and the Valley appeared to be headed for sustainability insofar as water quantity was concerned. However, the 1980s brought to focus hitherto unforeseen problems of water quality and climatic uncertainty.

There emerged two types of water quality problems. In 1981, a report from officials of Fairchild Instrument and Camera Corporation in San Jose brought to light the leakage of substantial quantities of toxic organic chemicals from a leaky subsurface holding tank of a semiconductor fabrication plant. Investigation of the spill soon revealed an unacceptable contamination of nearby aquifers necessitating shutting down of water wells. Detailed investigations by officials of the Water District in collaboration with state officials soon revealed the leakage of toxic, hi-tech wastes at many more sites, leading to the creation of a Hazardous Materials Storage Permit Ordinance, that became a model for federal law. By 2005, some 3,200 sites contaminated by leaky storage tanks had been identified (California History Centre and Foundation 2005: 112-14).

The second water quality problem was related to imported water. Imported water, originating from the rivers of the Sacramento Valley, had to pass through the bay-delta, a vast low-lying wetland criss-crossed by myriad channels, subject to tidal effects in the bay. As a consequence, imported water from both the State Water Project (South Bay Aqueduct) and the Central Valley Project (San Felipe Project) was of a quality that required treatment. Unfortunately, this problem had no real remedy unless solutions were found to improve water quality at the delta. Between 1982 and 1992, the Valley was ravaged by two rare climatic extremes; first by floods between 1982 and 1986, and next by the century's worst drought between 1987 and 1992. The floods caused severe damage in urban areas of San Jose and Los Gatos, both located close to stream courses. The flood havoc accelerated the long-awaited implementation of plans for additional taxes and levies to carry out flood protection and restoration measures along the Guadalupe River. These efforts were rendered more complex and costly because they had to abide by Federal Endangered Species Act to protect vital habitats of fish (chinook salmon), certain species of frogs and other wildlife.

The unprecedented drought drove home the need for adding a new dimension to water management, namely, achieving usage reduction through public education, incentives and penalties. No other realistic way was available to sustain society with the finite endowment of water resources.

The onset of the 21st century witnessed the evolution of the Santa Clara Water

District from its groundwater-centred small beginnings in portions of the North County, to a mature organisation responsible for the entire Valley, integrating surface water, artificial recharge, groundwater, imported water, flood control, conservation, habitat restoration and public education.

The Present

The present-day Santa Clara Valley Water District is a noteworthy example of a public institution in which elected representatives use the best available scientific knowledge as a basis for equitable sharing of a finite, vital resource for human benefit and for the benefit of other living things.

Institutional Governance: The present governance is authorised by the Santa Clara Valley Water District Act passed by the California State Legislature in 1951. Accordingly, the county is divided into five geographic zones. The district is led by a seven-member board, serving overlapping four-year terms. In addition to a representative from each geographic zone, two members are appointed by the county government. The purpose of the board as articulated in the board's policy (2010) is,

> ...on behalf of the people of Santa Clara County, is to see to it that the District protects the public health and safety and enhances the quality of living within Santa Clara County by comprehensively managing water resources in a practical, cost-effective, and environmentally sensitive manner.

Among its values, the board is committed to transparency in its conduct, including timely sharing of technical data, and policy decisions. In addition to an administrative arm, the district is served by a technical arm with expertise in hydrological, ecological and environmental sciences and civil engineering, supported by an evolving network for monitoring water quantity, quality, ecosystems and water usage. The district is strongly committed to public education.

The district is entirely supported by taxes, bonds and other assessments on local citizens. Drawing upon ongoing monitoring of climate and water levels, the board approves strategies, on an evolving basis, for conjunctive management of surface water and groundwater. The county is served by 15 water retailers, of which nine are municipalities and the rest are privately-owned (California History Centre and Foundation 2005). The retailers buy water wholesale from the district. The price of water at various levels, as well as taxes, levies and assessments are decided through public participation and regulatory statutes.

In summary, governance, as practised, is a manifestation of a science-society synergism. The people own the water and government, acting as a trustee of the people, discharges its fiduciary responsibility to manage water beneficially, without waste.

The Integrated Water System: At present, the Valley's water system consists of 10 surface water reservoirs with an aggregate capacity of 210 million m^3. The Valley's underground storage is estimated to be about thrice as much as surface storage (Santa Clara Valley Water District 2010a: 3). Imported surface water (Figure 4, p 43) is treated at three water treatment plants before distribution to customers or diversion underground. The district operates four waste water treatment plants to treat sewage water. With an annual capacity of about 21 million m^3, processed water from these plants is used for irrigation or for environmental needs. High rates of artificial recharge are achieved through facilities located at sites chosen for favourable geological and hydrological conditions. These facilities comprise in-stream check dams and drop-structures and percolation ponds. Water management is closely coordinated with environmental and ecological protection, water conservation and public education.

In 2008, the Valley's water use was 470 million m^3. This was met by importing 282 million m^3 from the Central Valley Project, the State Water Project, the Hetch Hetchy Aqueduct, and water banks. The total groundwater pumpage was 209 million m^3. But, 109 million m^3 of the imported water was recharged underground. Thus, net groundwater withdrawal was 100 million m^3. Also, net withdrawal from local surface water reservoirs was 68 million m^3. Thus, local surface water and groundwater resources accounted for about 168 million m^3, or 36% of total use, the rest being met from imports. By conjunctively managing surface water and groundwater this way, the district has been able to maintain relatively high groundwater levels and maintain surface storage reserves at about two-thirds of capacity. The estimated population of the Valley for 2009 was 1.78 million. This implies that the annual per capita consumption is 264 m^3, or 0.72 m^3 (191 gallons) per day. An annual balance sheet is given in the following table.

Table: Annual Balance Sheet for Santa Clara Valley's Water (2008)

Description	Volume, Million m^3
Inflow:	
Imported surface water	282
Local surface water	68
Net groundwater withdrawal	100
Miscellaneous (water bank, trade)	20
Total inflow	470
Total water use	470
Per capita consumption	264 m^3

The general goal of water management in the district is to keep groundwater withdrawals moderate during normal and above-normal years, and increase groundwater production during below-normal years or when imports are cut back due to extraneous conditions. The management challenge arises from unpredictability of local annual rainfall variability, and uncertainties associated with availability of imported water. For these reasons, water conservation is assuming increased importance.

What May Be Learned

The Santa Clara Valley water experience is notable for its well-documented history spanning a century, during which local citizens continuously adapted to natural, demographic and technological changes. Despite confrontation by new challenges, they expanded their objectives to include environmental and ecological protection. Clearly, the philosophy and methodology of the Santa Clara Valley Water District are of educational value to communities elsewhere that grapple with the difficult task of equitable, judicious water management.

Perhaps, the most encouraging fact that emerges is that it is possible to achieve a synergism between science and water policy, within the framework of democratic governance. It makes a rational sense to manage water locally over well-defined watersheds, with the community taking ownership and control of water, and govern its sharing through transparent administration embellished by public participation. Local management is nourished and legitimatised by democratic values inherent in the state's constitution.

In the case of water, administrative notions of "local" and "regional" are relative, and depend on local physiographic and geological conditions. The Valley's experience shows that viable management can be achieved over a collection of watersheds, within which several communities will share a common resource. This sharing is facilitated by self-imposed regulation.

Despite the success, caution is needed in extrapolating the Valley experience to other areas. Because present water use in the Valley is mostly municipal and industrial, with minimal agriculture, per capita water consumption is relatively modest, about 0.72 m^3 (about 190 gallons) per day. The county's indigenous water resources are inadequate to meet even these needs. In larger watersheds, with more diverse water use including agriculture, it will be necessary to implement additional conditions of adaptation not reflected in the Valley's experience.

From a scientific perspective, the Valley experience has established the advantages of treating surface water storage and groundwater storage as complementary. The challenge is to manage groundwater levels judiciously as evidenced by data from key monitoring wells. In the Valley, there is a lower threshold to water levels dictated by triggering of land subsidence (Santa Clara Valley Water District 2010b).

If water level falls below this threshold, subsidence will occur at an accelerated rate. The district has successfully maintained water levels above this threshold since 1987 when the last drought occurred. Under other hydrogeological conditions different factors may determine the threshold. The lesson here is that carefully laid out permanent groundwater and surface water monitoring systems are essential for integrated water management.

REFERENCES

California History Centre and Foundation (2005): "Water in the Santa Clara Valley: A History", second edition.

Hilgard, Eugene W (1902): "Subterranean Water Supply of the San Bernardino Valley" in *Report of Irrigation Investigations for 1901* (Washington: Government Publication Office), pp 103-46.

Iwamura, T I (1995): "Hydrogeology of the Santa Clara and Coyote Valleys Groundwater Basins, California" in E M Sanginés, D W Andersen and A B Buising (ed.), *Recent Geologic Studies in the San Francisco Bay Area*, Society of Economic Paleontologists and Mineralogists, Pacific Section, 76, 173-92.

Narasimhan, T N (2009): "Groundwater: From Mystery to Management", *Environmental Research Letters*, 4, 035002, p 11.

Reynolds, J L (2000): "Water Resources Development in Santa Clara Valley, California: Insights into the Human Hydrologic Relationship", MS Dissertation, Environmental Science, Policy and Management, University of California at Berkeley.

Santa Clara Valley Water District (2010a): Protection and Augmentation of Water Supplies 2010/2011, 39th Annual Report, Santa Clara Valley Water District, San Jose, California.

– (2010b): Groundwater Condition Report, 25 January, Santa Clara Valley Water District, San Jose, California, p 14, Figure A1.

Tibbetts, F H and S E Kieffer (1921): "Report to Santa Clara Valley Water Conservation Commission on Santa Clara Valley Water Conservation Project", Santa Clara Valley Water District, San Jose, California, p 243.