Chapter 12
Pump Tax, Basin Equity Assessment and Sustainability in Groundwater Management: Orange County Water District Experience

Takahiro Endo

Abstract The term "sustainable development" has become very popular among researchers, practitioners and policymakers since the 1980s. The sustainability concept is now applied in the field of groundwater management. Excessive groundwater pumping is taking place in many parts of the world and the means to achieve sustainable groundwater management has become an urgent need. The purpose of this paper is to analyze how to promote sustainable groundwater management, with a focus on Orange County Water District (OCWD), California, USA. OCWD faced excessive groundwater pumping in the 1920s. Since then, the district introduced various policies including a pump tax and basin equity assessment to tackle the problem, and continues to use groundwater as the primary supply. Investigation into the factors that enable OCWD to use groundwater continuously provides useful information to policymakers in other areas who are engaged in groundwater management. In addition, policy implications in terms of sustainability are drawn from OCWD's groundwater management.

Keywords Common-pool resources · Groundwater management · Sustainable development · Sustainability · Pump tax · Basin equity assessment · Orange County Water District · California

T. Endo (✉)
College of Sustainable System Sciences, Osaka Prefecture University, Sakai City, Osaka, Japan
e-mail: tte23042@osakafu-u.ac.jp

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12.1 Introduction

The term "sustainable development" has become very popular among researchers, practitioners and policymakers since a report by the World Commission on Environment and Development was published (The World Commission on Environment and Development 1987). The problem the term addresses is how to achieve economic development and environmental conservation at the same time (Pearce and Atkinson 1998). Although there have been controversies regarding the meaning of sustainable development, arguments for sustainability have gradually been directed at social problems in various fields, such as livestock control (Eisler and Lee 2014), fisheries (Heal and Schlenker 2008; Sampson et al. 2015) and transportation policy (Bruun and Givoni 2015).

The sustainability concept is also applied in the field of groundwater management. Excessive groundwater pumping is taking place in many parts of the world and the means to achieve sustainable groundwater management has become an urgent need (Wada et al. 2010). Although a variety of policy options are proposed in groundwater management, their effects remain to be investigated (Green et al. 2011). There are many economic tools to limit water uses such as water rate control, tradable permits and taxation. Taxation of natural resource utilization have been advanced theoretically as early as the 1960s (e.g., Dales 1968; Ruff 1970). However, their application to groundwater management has been limited, with a few exceptional cases such as Bangkok, Thailand (Lorphensri et al. 2011), Indonesia (Braadbaart and Braadbaart 1997), and the Netherlands (Schuerhoff et al. 2013).

The purpose of this paper is to analyze various means of promoting sustainable groundwater management, with a focus on the Orange County Water District, California, USA (hereafter referred to as OCWD). OCWD faced excessive groundwater pumping in the 1920s. Since then, OCWD has introduced various policies including a pump tax to tackle the problem and has continued to use groundwater as the primary supply. Investigation of the factors that enable OCWD to use groundwater continuously will provide useful information to policymakers in other areas who pursue sustainable groundwater management. It has been more than 50 years since OCWD initiated countermeasures. The history of economic tools in groundwater management in OCWD is much longer than the cases mentioned above. Thus, the OCWD case facilitates analysis of long- and short-term policy effects.

A brief history of the groundwater problem in Orange County is presented in the next section. OCWD's policy options including economic tools are explained in the third section. Then, policy implications in terms of sustainability drawn from OCWD's experience are described in the fourth section. Last, an overall summary is given in the fifth section. The paper does not deal with groundwater quality problems because of space limitations. Therefore, the term "groundwater management" herein means "quantitative control."

12.2 Orange County Water District

12.2.1 Brief History of Groundwater use in Orange County

Groundwater is a typical example of a common-pool resource, which has characteristics of difficulty of exclusion and rivalry in consumption. The former implies that controlling a range of beneficiaries through physical or institutional means can be prohibitively expensive, and the latter means that an individual's consumption of the resource reduces the potential consumption of others. Natural resources in general tend to have these common-pool characteristics (Ostrom et al. 1999).

Without adequate arrangements for exclusion, groundwater is left with an open-access status. In such a situation, no one has the incentive to conserve or replenish groundwater, simply because groundwater secured through such efforts can be reaped by someone else. Rather, a user currently has an incentive to pump groundwater as long as its private marginal benefit exceeds private marginal cost. Of course, such conduct generates external costs in the forms of cones of depression and groundwater table decline. Where the number of users is large, external costs caused by a single user may be very small. Nevertheless, the accumulation of such small effects cause clear groundwater depletion, land subsidence and seawater intrusion. Such "tragedy of the commons" (Hardin 1968) actually occurred in OCWD.

Orange County is in the most downstream area of the Santa Ana River, which runs southeast of Los Angeles (Fig. 12.1). This river begins in the San Bernardino Mountains and flows through Prado Dam to Orange County. The climate is dry, and average seasonal rainfall in the OCWD service area over a recent 5-year period (July 1, 2011 through June 30, 2016) was just 9.07 inches (230.38 mm) (OCWD 2017).

Artesian wells were put in use as early as 1868. Pumping machines gradually became popular in the 1890s, which resulted in the expansion of agricultural lands (California Department of Water Resources 1959). As demand for groundwater increased, negative effects were discovered. It was clearly observed in the 1920s that the groundwater table had dropped, resulting in the artesian area shrinking (Lippincott 1925).

12.2.2 Formation of OCWD

In 1931, water users in Orange County brought lawsuits against users in the upstream area. The intention was to make the upstream users curtail water diversion from the Santa Ana River to maintain instream flows, which were considered a primary recharge source of local groundwater. Water users in Orange County organized a body by which they collected property tax to raise revenue for the lawsuit in 1933. This was the origin of OCWD (Weschler 1968).

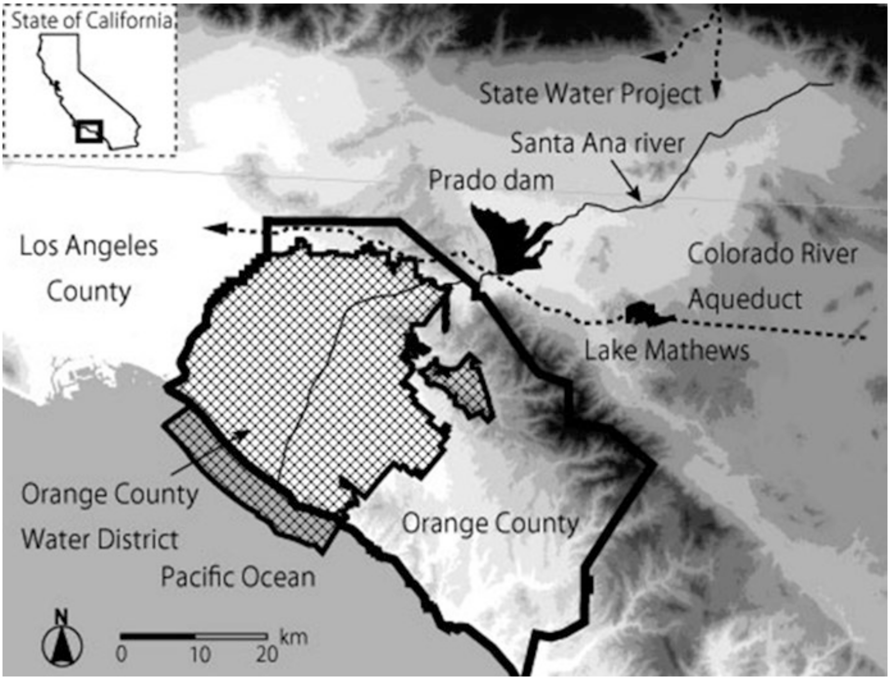

Fig. 12.1 Location of Orange County Water District

OCWD is a special district, a type of local government. When a county or city government provides various public services, it works for a specific purpose such as fire protection, park management or mosquito abatement. A special district that provides a water-related service is generally characterized as a special water district and is often called an "irrigation district" or "municipal water district" in accordance with its purpose. The service area of a special district does not always coincide with that of a county or city government. OCWD's jurisdiction is limited to the northeastern part of Orange County which is endowed with local groundwater (Littleworth and Garner 1995; Senate Local Government Committee 2010) (Fig. 12.1).

OCWD is given various authorities by the state legislature. These include powers to ① sell or store imported water, ② conserve and recharge local waters, ③ bring lawsuits against outsiders to secure a stable water supply for local users, ④ require a tax on groundwater pumping. Although OCWD's authority is wide-ranging, there are limitations. OCWD is not given authority to directly control groundwater pumping. All OCWD can do is control that pumping indirectly by managing the rate of the pump tax. In addition, it does not have power over groundwater quality. Therefore, if there is groundwater contamination within the OCWD service area, it would deal with the polluter using persuasion or lawsuits instead of directly ordering

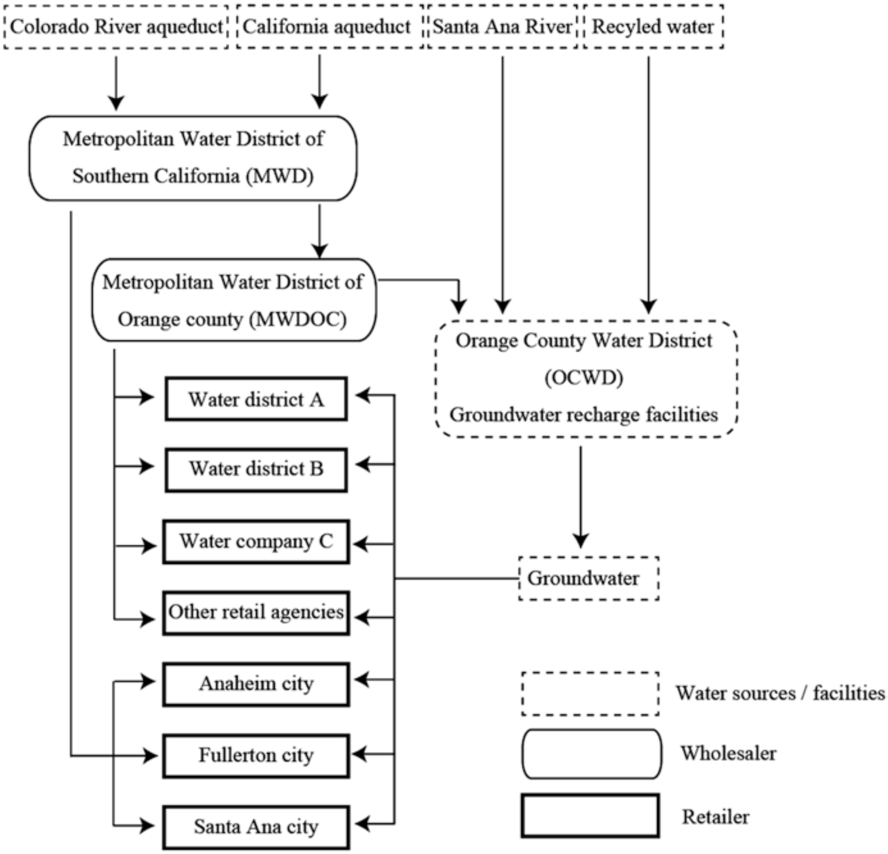

Fig. 12.2 Water supply system in OCWD

the polluter to cease and clean up the contamination (Crooke 1963; Weschler 1968; Blomquist 1992; OCWD 2015).

12.2.3 Water Supply System in OCWD

The OCWD service area is 243,968 acres and provides water to about 2.4 million people (OCWD 2015). Figure 12.2 shows the water supply system in OCWD. The sources of water supply are classified into surface water and groundwater. The former includes not only local water (e.g., the Santa Ana River) but also imported water, which is delivered from outside through long-distance aqueducts such as the California and Colorado River aqueducts.

The main local surface water is from the Santa Ana river. The river's water is rarely diverted for direct (potable) use now. Instead, it is stored in underground

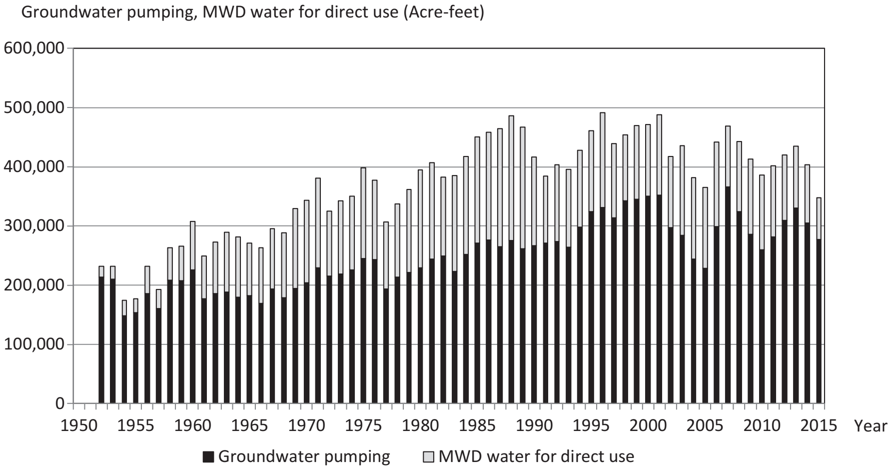

Fig. 12.3 Changes in volume of groundwater pumping and MWD water for direct use

space and then pumped out as groundwater. In other words, the river is used as a huge recharge facility. This approach is also applied to another local water source, recycled water. OCWD is famous for developing elaborate systems of water recycling. This highly advanced treatment changes local sewage into purified recycled water, which is used for groundwater recharge and water barriers against seawater intrusion in coastal areas.

Imported water is for direct use and serves as a recharge source. It is delivered to end users via a few steps. First, it is delivered to Orange County and other Southern California areas by a large wholesaler called the Metropolitan Water District of Southern California (hereafter referred to as MWD). Therefore, the imported water is often called MWD water. This water reaches end users in the OCWD service area mainly via two routes. First, MWD transfers water to a secondary wholesaler called the Municipal Water District of Orange County (hereafter referred to as MWDOC). The MWDOC service area covers all of Orange County and provides water to end users via subordinate retailers (e.g., water districts). Along the second route, as retailers, the cities of Anaheim, Fullerton and Santa Ana receive water directly from MWD and supply its water to citizens.

Groundwater is generally for urban uses. It is unevenly distributed in northwestern Orange County. Therefore, although there are many water districts across the county, only about 20 can access groundwater or imported water. They include the cities of Anaheim, Fullerton, Santa Ana and MWDOC's subordinate water districts, which are rich in local groundwater. OCWD consists of these districts. To put it another way, OCWD does not pump and deliver groundwater to end users directly. The main task is to aid member district groundwater pumping via groundwater recharge and other technical support (Herndon 2013).

Figure 12.3 shows changes in volume of imported water (for direct use) and groundwater pumping. Although imported water became an important supplemental supply after the 1960s, groundwater has been the main water supply. That means the supply has not fully switched from groundwater to surface water.

12.3 OCWD Groundwater Management

12.3.1 Groundwater Management in the State of California

Institutions of groundwater management are important in determining how scarce groundwater is allocated to competing demands (Tarlock 1985). In California, this allocation is determined traditionally by courts, not by administrative permission. The guiding principle is called the correlative right doctrine. First, it classifies groundwater users into two groups, those who use groundwater within or outside the basin. Members of the former group are called overlying users who are usually farmers. Members of the latter are non-overlying users, typically urban users. Then, the doctrine determines allocation priorities considering three cases: between overlying users, between non-overlying users, and between overlying users and non-overlying users. However, this rule does not promote efficient use of groundwater. This is because it plays a role only after disputes and has no preventative function (Sandino 2005).

Given such institutional failures in the region, groundwater is managed locally in diverse ways, reflecting its specific surroundings. The main approaches to groundwater management include formation of a special district, adjudication, and local groundwater management plans (Lipson 1978; Littleworth and Garner 1995). OCWD is considered a representative example of groundwater management by formation of a special district (De Lambert 1984). Nevertheless, this does not mean that any of the three approaches covers California entirely. There have been many locations called groundwater management vacuums, where there is no institution for groundwater (Governor's Commission to Review California Water Rights Law 1978). In 2014, the Sustainable Groundwater Management Act was legislated and many areas were required to establish groundwater sustainability agencies. This legislation was an attempt to fill the vacuums. OCWD has already been admitted as the exclusive local agency to manage groundwater within the district's statutory boundaries, with powers to comply with provisions of the Sustainable Groundwater Management Act (OCWD 2015).

12.3.2 Artificial Recharge

Excessive groundwater pumping can be counteracted either by recharge augmentation, pumping restrictions, or a combination of both. As mentioned in detail later, OCWD imports water from outside areas using revenue from the pump tax and

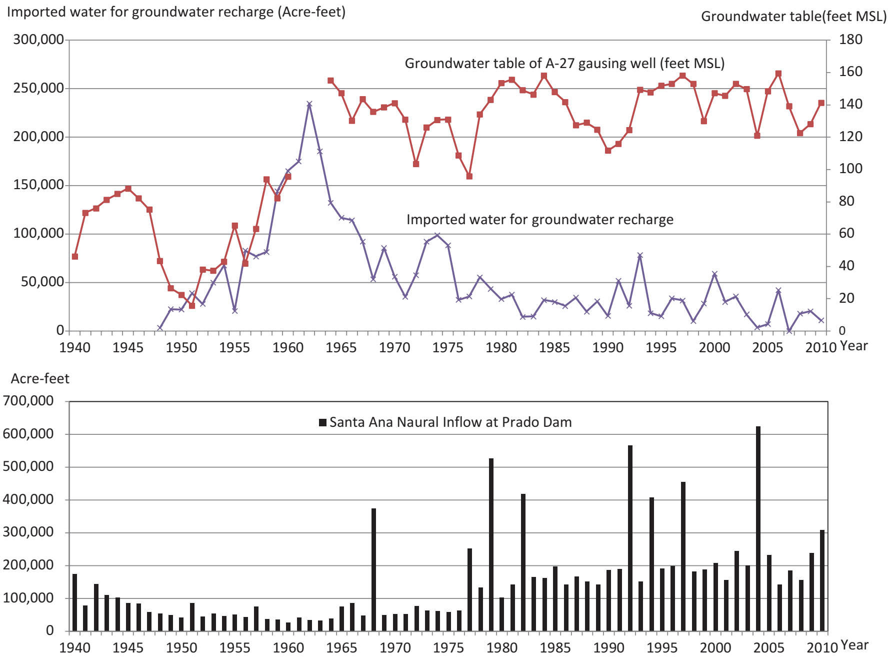

Fig. 12.4 Changes in the volume of imported water, groundwater table, and flow of the Santa Ana River (inflow at Prado Dam)

stores it in local basins to stabilize the groundwater supply. This concept is different from adjudication, which focuses on pump restriction. Rather, OCWD aims to avoid groundwater shortages by expanding groundwater recharge (Blomquist 1992).

The most downstream users of the Santa Ana River formed OCWD to engage in lawsuits with water users who diverted water in the upstream area. Although they won the lawsuit, they could not secure enough water. In addition, years with low precipitation have continued since 1942. This increased groundwater pumping and resulted in a decline of the groundwater table and expansion of areas suffering from seawater intrusion. To cope with this situation, OCWD began to recharge local groundwater using imported MWD water in the late 1940s (Weschler 1968).

Figure 12.4 shows changes in the volume of imported water, the groundwater table, and flow of the Santa Ana River (inflow at Prado Dam). From the late 1940s to 1964, the groundwater table (at A-27 gauging well) recovered rapidly. Flow in the Santa Ana River decreased during that period. Therefore, it may be assumed that artificial recharge by imported water supported the recovery. This supply-oriented policy was called “fill-the-basin”. However, this strategy was modified after 1964. This was because there was a great difference between regions in the rise of the groundwater table. Groundwater levels in some of the coastal areas did not recover as expected. Further, it was feared that some parts of the upper basin might revert to swamp because of a high groundwater table (Weschler 1968). The groundwater table recovered even after 1964 when the fill-the-basin policy ended. Figure 12.4 shows that the recovery corresponded with flow in the Santa Ana River. Therefore, it might be that the increase in natural groundwater recharge from the river had a role in maintaining the groundwater level after 1964.

12.3.3 Pump Tax

OCWD uses economic tools to manage groundwater. The district collected property tax for lawsuits against the upstream users in the 1930s and used the revenue to buy MWD water for artificial recharge. However, this revenue was insufficient to continue artificial recharge. Thus, another fiscal base became necessary. In 1953, the state legislature admitted a new authority to impose a pump tax (Crooke 1961). OCWD was the pioneering public water district to introduce a pump tax system in California (Weschler 1968).

The pump tax is levied on all groundwater users, whether the well is for irrigation or urban uses. However, tax rates per pumped acre-foot vary. The rate for irrigation wells has usually been set lower than that for non-irrigation wells. As mentioned above, almost all groundwater pumping is currently for urban uses. The tax rate for such uses was $322 per acre-foot in the 2015–16 water year (July 1, 2015 through June 30, 2016) (OCWD 2017).

Groundwater users are also required to install a meter to gauge pumped volume and report the data to OCWD every 6 months. The amount of tax is determined by multiplying the volume by the tax rate. There is one exception to this rule, i.e., the owners of “small wells” are exempt from the metering requirement. Here, “small” wells include those from which the discharge outlet is not greater than 2 inches (20.4 cm^2) in size and which provide domestic and irrigation water for an area not exceeding 1 acre (Crooke 1961; Weschler 1968).

Basically, the above information-gathering process is based on an honor system. Prevention of cheating is very important under this system. If necessary, OCWD checks the amount of electricity used to pump groundwater and the past pump record to improve their data accuracy. In addition, information sharing enables mutual checks among users to prevent cheating (Ostrom 1990). OCWD promotes mutual checks by publishing the annual pumping volume of major groundwater users (non-irrigation users of >25 acre-feet per year).

OCWD employs engineers who investigate groundwater conditions, especially the amount of overdraft, every year. Overdraft is the estimated quantity by which groundwater pumping exceeds its natural replenishment during a year (OCWD 2017). The engineers check groundwater conditions including the average annual overdraft over the past 10 years and the total accumulated overdraft of the preceding year. Then they consider the water quantity for artificial recharge necessary to mitigate overdraft and calculate the required budget to purchase that amount of water. Last, based on information of anticipated groundwater pumping in the ensuing year, they determine how much money should be levied on 1 acre-foot of pumped

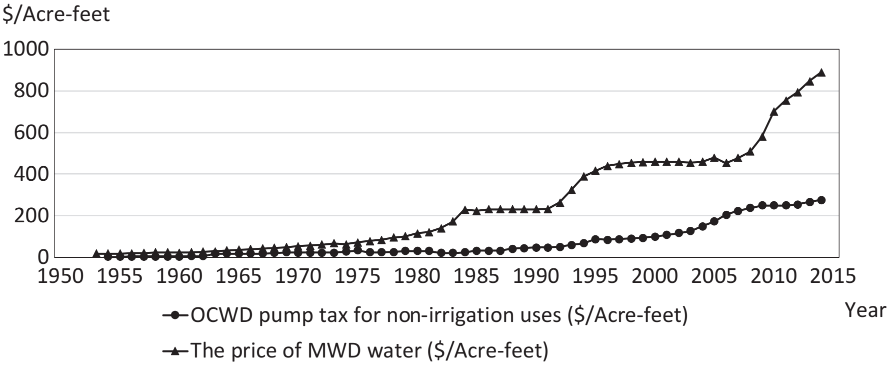

Fig. 12.5 Changes in the pump tax and the price of MWD water

groundwater. This is how the tax rate is determined each year. Therefore, the tax is imposed directly on water, not electricity. As mentioned above, each groundwater user is supposed to pay according to their pumped volume (Crooke 1954).

How OCWD allocates groundwater is different from the correlative right doctrine. Under this doctrine, when there is a dispute between an overlying and non-overlying user, the former is given the superior right to use groundwater. For allocation between non-overlying users, "first in time, first in right" is applied. That is, the party who began to use groundwater earlier is granted the superior right. However, OCWD does not utilize such classifications in terms of time and place of use. Local groundwater users are equal and they can pump groundwater freely as long as they pay the pump tax.

12.3.4 Basin Equity Assessment

The pump tax has been set lower than the price of MWD water (Fig. 12.5). Therefore, retailers in OCWD have had incentive to use groundwater instead of MWD water to satisfy customer water demand, which results in groundwater depletion.

To avoid the above situation, OCWD once asked retailers to use both MWD water and groundwater in a 50–50 ratio. However, this request did not work, simply because it was not mandated. A sharp decline of the groundwater table was observed in part of the OCWD service area.

The aforementioned problem was mitigated by an additional demand control tool called Basin Production Percentage (hereafter referred to as BPP), which was introduced in 1968. Under this system, OCWD established a percentage of water supply originating from local groundwater and supplemental water from outside the basin each year, using data on volume of groundwater storage and available MWD water. BPP is applied to a user who pumps groundwater at more than 25 acre-feet per year. Such users are often retailers like a city or water district, not individual well owners (OCWD 2009; OCWD 2017).

For example, when the BPP for a water retailer is set to 60%, it can satisfy as much as 60% of local water demand through cheap groundwater; the remainder should be met by expensive imported water. If the retailer pumps groundwater at more than the BPP rate, it is required to pay another assessment called a basin equity assessment for the excess. Conversely, when the retailer pumps at less than that rate, it benefits from the basin equity assessment paid by another retailer who pumps more than BPP rate. Thus, BPP is a system that regulates groundwater pumping by controlling the ratio of groundwater and imported water. The basin equity assessment was originally set equal to the difference between the prices of groundwater and imported water. However, it is now calculated so that the cost of groundwater production is higher than purchasing imported potable water. This means that a retailer who pumps groundwater at more than the BPP rate must eventually pay the same or more as it imports water from outside. This prevents retailers from pumping cheap groundwater as much as they want (OCWD 1970; OCWD 2009).

In summary, the pump tax and basin equity assessment are two primary economic tools for groundwater management in OCWD. Generally, the pump tax plays a role in preventing excessive groundwater pumping. However, this function cannot be exerted fully because OCWD has set the pump tax lower than the rate of imported water. This is why OCWD introduced a second tool of basin equity assessment. Simply raising the pump tax rate may prevent local retailers from excessive groundwater pumping but it would also deprive them of access to cheap groundwater, because the tax is imposed on all groundwater users. The aim of the basin equity assessment is to allow for utilization of cheap groundwater with some deterrents against excessive pumping; the additional assessment is only imposed on those who pump groundwater more than stipulated (Herndon 2013). OCWD's groundwater management approach has been considered primarily supply-enhancement (i.e. artificial recharge), but it also controls demand through the basin equity assessment.

12.4 Lessons toward Sustainable Groundwater Management

12.4.1 Sustainable Development and Capital

Various definitions have been proposed for the concept of sustainable development. Economists often define it in terms of capital accumulation. That is, they think sustainable development depends on how a stock of capital and technology should be carried over from one generation to the next. In the classical approach, the concept of capital was limited to produced goods or man-made capital such as factories, but more recent approaches include skill and knowledge embodied in humans (human capital), trust and social bonds between individuals (social capital), and natural resources in general (natural capital) (Pearce and Atkinson 1998).

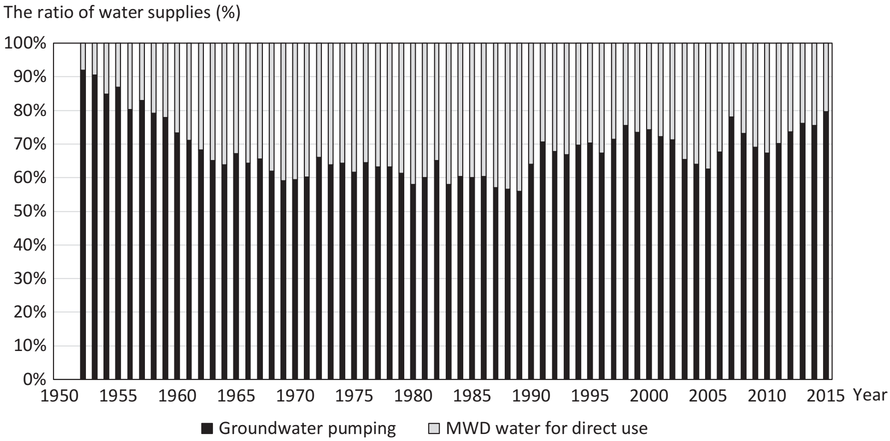

Fig. 12.6 Shares of groundwater and surface water in local water supply

The extent to which artificial and natural capital can be substituted has been controversial. Through debate, two approaches have emerged, weak and strong sustainability. The former assumes that the aforementioned two capitals are interchangeable. It is true that consumption of natural resources (especially non-renewable ones) is associated with costs such as resource depletion. However, if a part of the consumptive benefits can be invested to increase artificial capital which covers the loss of natural resources, the total volume of stocks can be maintained, resulting in sustainable development. However, strong sustainability does not take it for granted that the two capitals can be substituted without limit. Although natural capital is endowed with reproduction capacity, there are limits. Beyond a threshold, such capacity cannot be realized and the stock continues to decrease. In such a situation, artificial capital is no longer useful, so sustainable development cannot be achieved (Daily 1995; Pearce and Atkinson 1998).

12.4.2 Weak/Strong Sustainability in Groundwater Management

The concepts of weak/strong sustainability can be applied to groundwater management in OCWD in the following way. In the former, groundwater is fully consumed to depletion and then imported water is used as a substitute, which is delivered across natural hydrologic boundaries. In the latter, groundwater is used to some extent and the water supply is supplemented with imported water as needed.

Figure 12.6 shows shares of groundwater and surface water in the local water supply. This shows that the share of groundwater decreased from the 1950s to mid-1960s. This trend can be evaluated in terms of weak sustainability. Thereafter, however, OCWD implemented demand control through BPP and prevented further conversion. This can be interpreted as a departure from weak sustainability-oriented policy.

The method of groundwater use in OCWD sharply contrasts with that of Tokyo, Japan. Both areas have faced excessive groundwater pumping, but the countermeasures were very different. In Tokyo, the national Industrial Water Law of 1956 was enacted to cope with excessive groundwater pumping, promoting water supply conversion from groundwater to surface water. As a result, groundwater utilization has been restricted so severely that it has had an unexpected side effect, i.e., a high groundwater level causing floating pressure against underground infrastructure. In the short run, switching the water supply from groundwater to surface water would induce groundwater conservation. However, prohibiting groundwater use may have a completely negative impact on groundwater. This is because such prohibition causes people to potentially neglect groundwater and raises the risk of contamination. Nobody will take care of groundwater unless they use it constantly. The differences between OCWD and Tokyo include the subsidy system, legal definition of groundwater, and local governmental authority. This suggests that legal and administrative institutions influence the sustainable use of groundwater (Endo 2015).

12.4.3 Safe Minimum Standard

The irreversibility problem is often used to justify strong sustainability (Pearce and Atkinson 1998). The concept is that natural capital will continue decreasing to depletion once the stock diminishes beyond a threshold, because of human consumption. However, our knowledge of nature is so limited that it is very difficult to know that threshold precisely. Therefore, the maximum allowable consumption level should not be established by an assumptive threshold, but set within more restrictive levels, considering the uncertainty. This is called the safe minimum standard (Randall and Farmer 1995; Farmer and Randall 1998). However, constructing such a conceptual framework is one thing, while incorporating such an idea into policy is another completely.

The concept of "operating range," which OCWD introduced in 2007, suggests how the safe minimum standard could be applied to groundwater management. The operating range defines the upper limit of groundwater pumping. OCWD determines this limit considering the long-term groundwater budget (the difference between groundwater recharge and pumping), not a yearly one. When groundwater pumping exceeds recharge in a year, groundwater storage diminishes because of the deficit. If this occurs in the subsequent year, the reduction in storage will grow further. From past experience, OCWD engineers assume that seawater intrusion will become out of control once the accumulated reduction reaches 500,000 acre-feet. In reality, OCWD tries to recover groundwater storage using a preventive approach. That is, it takes countermeasures for increasing recharge and raises the pump tax when the accumulated reduction reaches 430,000 acre-feet. This operating range was made possible after the 1980s by a long-term monitoring system (Herndon

2013; OCWD 2017). Although OCWD sets the upper limit, it promotes groundwater pumping within the range. This suggests countermeasures alternative to complete prohibition of groundwater pumping.

12.4.4 Resource Characteristics and Sustainability

The extent to which artificial capital can be an alternative to natural capital is a focal point in the controversy surrounding strong and weak sustainability. Price has been considered an important factor in determining the substitution relationship. Generally, values of natural capital are not shown in the form of price. Therefore, even if natural capital becomes scarce because of depletion, price will not rise sufficiently to promote substitution (Barbier 1990).

However, the case of OCWD suggests that physical resource characteristics also influence the substitution relationship. For example, it takes time for forests to grow. Thus, once a forest is cut and we substitute the water storage function with artificial capital such as dams, it will be extremely difficult to use the forest again after a short period. In contrast, it is easier to switch groundwater with imported water in a short period, because the groundwater volume changes frequently through wet and dry seasons. As Fig. 12.6 shows, the ratio between imported water and groundwater changes every year. The method of switching the water supply between groundwater and surface water depending on precipitation is often called "conjunctive water management" (Blomquist et al. 2004).

Progress in artificial recharge techniques would make such substitution easier. Theoretical studies of sustainable development have not assumed that natural and artificial capital can be substituted frequently. The OCWD case suggests that such flexible uses of natural and artificial capital may be possible, depending on the resource characteristics of reproduction capacity.

12.5 Conclusions

The path to realizing sustainable groundwater management is now a global concern. This paper describes groundwater management in OCWD, with special emphasis on various policy options such as the pump tax and basin equity assessment. The following policy implications were deduced from the OCWD experience, within a framework of weak and strong sustainability:

First, legal and administrative institutions influence the sustainable use of groundwater. Whether local groundwater management is weak sustainability-oriented or not can be evaluated by how groundwater is used. OCWD and Tokyo faced excessive groundwater pumping during the same period, but the countermeasures were very different, resulting in sharply contrasting historical changes in groundwater use. While groundwater is used to some extent and the water supply is supplemented with imported water as needed in OCWD, imported water has almost completely replaced natural groundwater use in Tokyo. The differences between OCWD and Tokyo are partly caused by differences in the subsidy systems, legal definitions of groundwater, and local governmental authority.

Second, the safe minimum standard for strong sustainability can be applied to groundwater management. OCWD introduces the upper limit of groundwater pumping, called the operating range, to prevent seawater intrusion. The limit is established by an assumptive threshold, but set within more restrictive levels, considering the uncertainty. OCWD controls recharge volume and the pump tax rate considering this upper limit. This suggests that an upper limit based on long-term monitoring is necessary to establish organized countermeasures.

Lastly, the case of OCWD suggests that physical resource characteristics should be taken into consideration in the sustainability argument. The extent to which artificial capital can serve as an alternative to natural capital is a focal point in the controversy surrounding strong and weak sustainability. Unlike a forest resource, it is easier to switch natural groundwater with artificially imported water or vice versa in a short period. Theoretical studies of sustainable development have not assumed such a high frequency of substitution. This suggests progress in artificial recharge techniques would make such substitution easier, enabling flexible use of natural and artificial capital.

Comparative analysis of groundwater management in other regions remains to be investigated. It is well known that various experimental groundwater management approaches have been pursued in Southern California where OCWD is located. OCWD does not restrict groundwater pumping and promotes artificial recharge to compensate groundwater depletion. In contrast, Raymond Basin, which is northeast of Los Angeles, has introduced a court-appointed water resource manager, called a watermaster, who sets limits on annual groundwater pumping. Then the limits are divided and allocated to each user as groundwater decrees, which are tradable under supervision of watermaster. Although a few comparative studies have already been done by Lipson (1978) and Blomquist (1992), more should be done to evaluate the effects of each groundwater management framework from a longer-term perspective.

In addition, much attention should be paid to natural resources other than groundwater. As mentioned above, how artificial and natural capital can be substituted depends partly on reproduction capacities of the resources. These capacities vary among natural resources, including groundwater, fish and forest. Although there have been many theoretical studies on the concept of weak and strong sustainability, many case studies should be done to understand how to apply that concept to each natural resource management system. This paper is a starting point for such analysis.

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