



Evaluation of Combined Rainwater and Greywater Systems for Multiple Development Types in Mediterranean climates

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ABSTRACT

This paper explores the feasibility of combining rainwater harvest and greywater capture to meet urban water demands such as toilet flushing and landscape irrigation. In Mediterranean climates, rainwater harvesting is not a viable year-round alternative water supply. On the other hand, greywater has issues of quality, storage and plumbing costs. Three land uses (single-family house, apartment cluster, and mixed use site) were analyzed to determine the viability of rainwater and greywater in combination as a realistic water supply for non-potable uses. In all three development scenarios, rainwater and greywater combined were capable of offering sufficient volume of water to meet irrigation and toilet flushing demands. Several major impediments exist to the widespread adoption and use of combined rainwater and greywater systems the largest of which may be cost. An analysis of cost revealed that onsite use of rainwater/greywater in the single-family house scenario is nearly three times more than a municipal (City of Davis, CA) water bill. The discrepancies in cost do begin to level out at higher densities. Rainwater and greywater harvesting will be most successful if it is considered in the early planning stages. Additional areas for further investigation are suggested.

Keywords: Greywater; Rainwater harvesting; Reuse; Stormwater; Water conservation; Water management

1. INTRODUCTION

1.1 Background

Urban water demands are increasing at a rapid rate in California and throughout the American West. Despite recessionary times, population growth continues unabated; California alone is expected to increase its population to more than 44 million by 2020 (California Department of Finance 2007). Although there have been laudable strides in urban water conservation, especially in southern California and along the coast, all projections point

toward significantly increased urban water demand in the coming years. For example, under any of the future water supply/demand scenarios projected in California's State Water Plan, potential regional shortages could reach as high as 2.9 km³ in a normal year and 7.6 km³ in a dry or drought year (California DWR 2009). Add to this the potential impact of climate change on snow pack, reservoir capabilities and drought severity, and it is clear that future pressure on the State's urban water supplies will be great. This same scenario is playing itself out throughout the American West, and in many other parts of the developed world such as Australia.

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Where will “new” urban water come from? California’s State Water Plan is pretty clear: water use efficiency including various conservation practices, recycling, rainwater harvest, greywater use, and related efficiency measures like stormwater capture will make up the largest share of new urban supply. The State’s estimates for various future water sources includes off-stream storage, conjunctive use, and desalination, water use efficiency will be many water provider’s first (and perhaps only) option (Figure 1).

In years past, water source options involving “exotic” or “dispersed” technologies like rainwater harvest or greywater capture were dismissed as trivial or even undesirable. Their past unpopularity may be due to the perception that they are unhealthy, unreliable, and de-centralized and therefore cannot be considered on an equal par with other standard water supplies. They are difficult to quantify and turn into a marketable commodity. They offer variable supplies in terms of quantity and quality. Regulations for use, capture and clean-up are difficult to enact and enforce, and regional differences are significant. Yet, despite such arguments, interest in these water sources has never been higher. When considering the energy footprint of water use and wastewater treatment, sustainable solutions to new water demand become more attractive.

1.2 Purpose

This paper takes a critical look at how rainwater harvest and greywater capture might be used in combination for a variety of urban development scales and types in a winter-wet, summer-dry (Mediterranean) climate. Rainwater harvest alone is a difficult choice throughout most of the American West because of seasonal or sporadic rainfall patterns. The amount of storage and the length of time required for storage work against rainwater as a principal source. Greywater

systems suffer from difficulties in permitting, treatment and storage. Greywater use also carries a stigma with potential consumers. This paper suggests that the value of combining the two water sources can be enhanced by looking at new models for storage and designing treatment that work hand-in-hand with structures and the landscapes.

The potential benefits of a combined rainwater and greywater system are substantial. Rainwater and greywater are local renewable sources of relatively clean water that have the potential to serve a significant portion of non-potable uses. We use high quality treated water to flush toilets, irrigate landscapes and other “low value” uses, when a lesser quality water would be more than sufficient. In California, watering landscapes is the largest single use of urban water (California DWR 2002). There are also significant energy benefits from using these dispersed sources. Source water does not need to be pumped, treated, and conveyed. Wastewater does not need to be conveyed treated and disposed of. Energy, as well as water, is saved at every step.

1.3 Introduction to Rainwater Harvesting

Rainwater harvesting is the capture and storage of rainfall for later use. Most often, rainwater harvesting is associated with the capture of rainwater from rooftops or other impervious surfaces which is held in rain barrels or cisterns. Benefits of rainwater harvesting are numerous and include the use of water at its source, reduced demand on water supply, reduced energy use and reduced stormwater flows. Common uses of rainwater include watering plants and lawn, and washing cars.

Evidence suggests that water harvesting was practiced as far back as 5,000 years ago in Iraq, ranging from simple ways of diverting runoff for agriculture, to complex reservoirs

dug into mountains (Oweis et al. 2004). Romans directed runoff from impervious surfaces to sophisticated cisterns and collection systems (Figure 2) for future domestic water use (Kinkade-Levario 2007). Australia has a long history of rainwater harvesting and utilizes a combination of incentives and mandates (Queensland Water Commission 2007). Unfortunately, with few exceptions, many developed nations such as the United States have abandoned rainwater harvesting techniques due to the ready access to inexpensive clean water.

Climate change and interest in sustainability have renewed the popularity of rainwater harvesting and greywater reuse in parts of the United States. For example, the City of Tucson, Arizona recently passed the Commercial Rainwater Harvesting Ordinance (No. 10597) which requires new commercial development to obtain 50% of their landscaping water needs through rainwater harvesting. Additionally, Santa Fe County, New Mexico now requires all residences greater than 232 square meters to install cisterns (Ordinance No. 2003-6).

Despite the promise of rainwater harvesting, barriers and challenges exist. California and other areas with Mediterranean climates receive the majority of rainfall during the colder months (approximately October through April) and little to no rainfall during the warmer months (May through September). The seasonality of rainfall in Mediterranean climates poses the issue of larger scale water storage for months at a time. The large storage volumes needed result in unsightly tanks or expensive underground cistern systems. On smaller urban lots or in multi-family, commercial and higher density development, there may be little or no space available for storage. Issues can arise for stored water such as algal growth, mosquito breeding, anaerobic conditions causing odor, and bacterial growth, with

the latter two being more of a problem with greywater. The design of rainwater harvesting will need to take into account rainfall patterns that may include back-to-back storm events which are commonplace in California. As such, designs should accommodate the storage necessary for back-to-back storm events or identify a use for the rainwater that would empty the storage between storm events (Strecker and Poresky 2009). Moreover, adding the infrastructure to a project is a major increase in upfront development costs.

1.4 Introduction to Greywater Reuse

Greywater is wash water coming from showers, bathtubs, washing machines and bathroom sinks (Johnson and Loux 2004). For the purposes of this article, kitchen sinks and dishwashers were not included because of the organic matter commonly found in each; most regions that utilize greywater do not include kitchen sink waste. While not a mainstream idea, greywater is an underutilized source of water that is produced on a daily basis by any building that contains people. According to a nationally representative mail survey, more than 13 percent of California households reuse greywater (NPD Group 1999).

Without treatment, greywater storage should be limited to no more than 24 hours before it is completely drained (Melby and Cathcart 2002). This is because of the growth of bacteria that can cause septic conditions and unpleasant odors. Greywater requires a greater level of filtration than rainwater harvesting before use to break down pollutants and remove harmful bacteria. Greywater can also contain higher levels of salts and is therefore more alkaline. If greywater is used for irrigation, special attention should be placed on plant selection as salts can damage plants. Although it was found that when water is applied directly to the soil surface, many

salt sensitive plants show little or no symptoms of stress (Wu et al. 1999).

In addition to cost, perhaps the greatest barrier to the wide-spread implementation of greywater use is plumbing codes that prohibit or require a permit for the installation of a greywater system. Greywater is typically regulated locally, but codes regarding greywater can be found at the national, state, and local levels. Until recently, California required all greywater systems to be permitted and included extensive design and equipment requirements. In the face of a third year of drought conditions, California recently passed emergency legislation to provide flexibility in the greywater codes to encourage greywater reuse. Under the new code, some residential greywater systems can be installed without a permit (California Plumbing Code 2009). However, additional changes may be required in order to allow the use of greywater for toilet flushing.

Given the rainfall pattern of a Mediterranean climate, rainwater harvesting may not be a viable, year-round alternative water supply. Greywater is available and fairly reliable all year, but has issues of quality, storage and plumbing costs. In combination the two uses may present a viable, safe, cost-effective, year-round solution.

Three land uses, (a single family house, an apartment cluster and a mixed use site) were analyzed in depth to illustrate how rainwater harvesting and greywater may be used in combination for non-potable uses throughout the year. The development prototypes are adapted from a newly planned “sustainable community” being built in partnership with the University of California, Davis (UC Davis), known as West Village. The prototypes were analyzed to determine the viability of rainwater and greywater as a realistic future water supply for non-potable uses such as landscape irrigation and toilet flushing.

1.5 Combining the Two

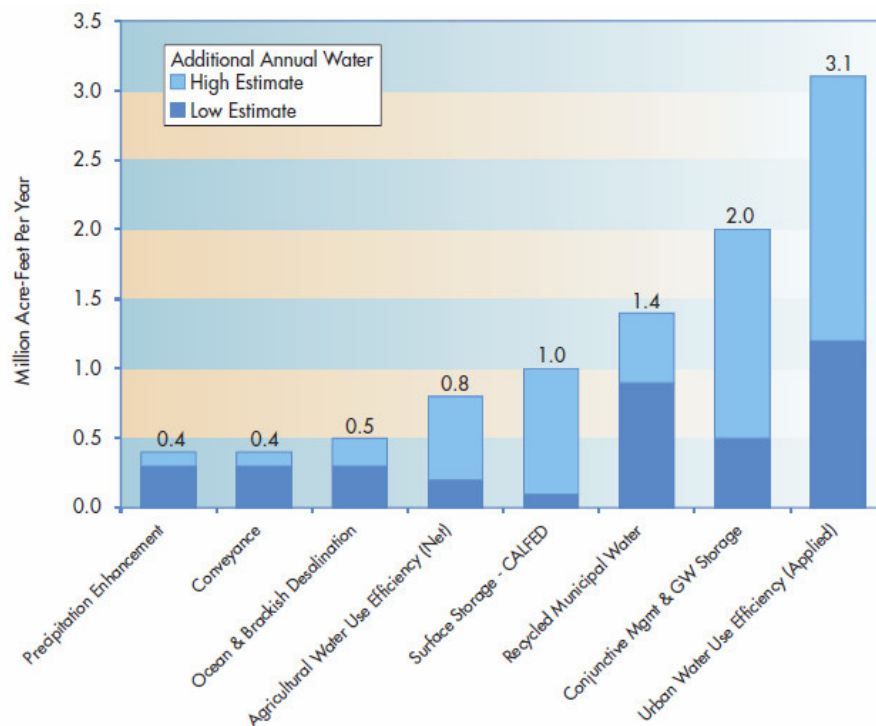


Figure 1 Estimates for Future Water Sources in California (California DWR, 2005)



Figure 2 Ancient Rainwater Harvesting Techniques in Pompeii Consisted of an Impluvium Designed to Direct Rainwater to an Underground Cistern (Photo Credit: Jan Walker)

2. MATERIALS AND METHODS

To determine the feasibility of combining rainwater and greywater use, several site and landscape design considerations were taken into account, including site and building conditions, soil parameters, planting selection, water source capture, storage, and treatment. These considerations were applied to three scenarios: a single family home, an apartment cluster, and a mixed use development project. Each is described in greater detail below. Simple spreadsheet models were developed to estimate rainwater and greywater volumes and seasonal fluctuations.

The UC Davis West Village project is unique in that it is a public/private partnership, on UC Davis land, designed to provide affordable housing and living arrangements for students, faculty and staff in a sustainable

manner. The project will use entirely locally produced renewable solar photo-voltaic, solar thermal and bio-gas from food and landscape wastes. West Village is also designed to have a limited transportation “footprint” by being located near UC Davis jobs. Most daily trips will be by bus, bicycle or walking. Likewise, the project is planned for water sustainability. All building plumbing and landscape are designed for low water use. All stormwater (from the 100-year storm and below) will be captured on-site in bioswales, rain gardens and artificial wetlands and used for irrigating recreational fields. The use of rainwater harvesting and greywater to augment the water supply is a logical extension of the “green” design concepts. The UC Davis plans to actively monitor and analyze the various innovative sustainable systems and features over time.

2.1 Site and Landscape Design

To be the most effective, the site building, landscape and water systems should be designed together from the outset. Like all sustainable innovations and “green” technologies, rainwater harvest and greywater systems work best when fully integrated into the design process.

2.2 Site and Building Conditions

The elevation of the building and surrounding landscape is a key consideration when designing for a rainwater or greywater system. The topography of the landscape and its elevation relative to the foundation of the building will determine if pumping is necessary or if gravity can be used to distribute the water. Gravity can be used if the landscape is below the grade of storage and pumps are required if part or all of the landscape is above the storage. Pumping may also be necessary if a spray irrigation system is required due to the pressures required to operate such an irrigation system.

As part of the landscape, the aesthetics of rainwater and greywater storage systems must be taken into account during the site planning stages. As discussed below in “Storage,” tanks can be placed underground and out-of-sight or designed to complement the landscape, but this is expensive. Storage can be incorporated into other design elements such as landscape walls, seat walls, or structural elements. Other features, such as shade canopies, offer multifunctionality and add an educational element by making rainwater harvesting a transparent part of the landscape. Storage can also be incorporated into building columns and walls. Water walls can be used for passive solar designs to moderate indoor temperatures by providing thermal mass (Bainbridge 2005). In public spaces, rainwater storage can double as public art, and act as an amenity for public space. As an added benefit, rainwater that is

visibly stored and used increases public awareness of water use.

2.3 Planting Selection

Drought and salt tolerant plants should be a priority when deciding on species for a landscape irrigated by rainwater and particularly greywater. Reduced irrigation requirements will not only take the rainwater and/or greywater system farther into the dry season, it also means that less storage is required, reducing costs and increasing space for other uses. Reducing the amount of turf will also drastically decrease irrigation needs and it can be argued that shrub and tree plantings are generally more attractive.

2.4 Capture

While most rainwater capture usually comes from rooftops, other functional architectural elements can be used to capture rainwater. For example, a shade canopy in public spaces can be designed to collect rainwater, thus enhancing civic spaces by creating cooler temperatures and adding an interesting design element. Another possible and often overlooked rainwater source is surface runoff from other impervious surfaces. Instead of being directed to a storm drain system, it can be guided to planters, swales, or underground storage tanks for later use.

2.5 Storage

As with anything else in a design, rainwater and greywater systems should be designed to complement the overall design scheme. One design consideration includes whether or not the storage will be above or below ground. Below ground storage incurs increased costs from excavation, maintenance and pumping, while above ground storage poses the problem of taking up potentially usable space, and

offers aesthetic challenges. Above ground storage will increase the likelihood that the irrigation can be gravity fed. When above ground storage is proposed, careful consideration should be given to the scale of the space and its other intended uses. Another item to consider when storage will be visible is what color and materials will be used. Storage comes in a variety of colors and the most common materials are metals, plastics, fiberglass, and concrete.

2.6 Treatment

While rainwater is generally fairly clean, greywater contains higher levels of particulate and organic matter and filtering and disinfection should be considered. This can be done with various types of filters and disinfecting technology, but there are other ways to filter greywater that can enhance the design of a space. One approach is to use the soil and vegetation of a planter to filter incoming rainwater and greywater, similar to typical low impact development projects. UC Davis recently completed a viticulture and fermentation science research lab in which rainwater is captured, drained through a bioswale and stored in four large metal tanks for use in irrigation of landscape and research/ demonstration vineyards. This has the benefit of combining filtering with an attractive landscaped seating element. This may lack applicability in a single residential setting due to lack of space and limited volumes of water produced. However, larger projects like apartment buildings and mixed commercial spaces could incorporate this idea more effectively. Depending on the use, additional disinfection and monitoring may be necessary. Other methods for disinfecting greywater include chemical treatments, ultraviolet light and ozonization (Kinkade-Levario 2007).

Chemicals should be avoided or used sparingly due to potential toxicity to plants.

2.7 Design Scenarios

The aim of West Village is to create an environmentally responsible community that provides multiple housing choices for students, faculty and staff, with networks of parks and open space (UC Davis 2006). West Village will be built out in phases, but ultimately will contain the number of units and non-residential uses as shown below in Table 1.

The City of Davis generally experiences a Mediterranean-style climate. Summers are very warm and dry while winters bring mild and cool weather to the area with substantial precipitation in sporadic storms. The average annual precipitation for the City of Davis is around 16.8 inches (Cunningham Engineers 2005). Rain tends to occur in clusters and back-to-back storms are common in the area. As illustrated in Table 2, evapotranspiration rates exceed precipitation amounts for eight months out of the year. These numbers illustrate that combining greywater and rainwater is essential to making rainwater harvesting work in a Mediterranean climate.

Three housing types from West Village were used to illustrate the potential for rainwater harvesting and the reuse of greywater at different building scales and densities. They include a compact single family home, a cluster of three apartment buildings, and a mixed use zone consisting of commercial uses on the ground level with housing above. The following designs were adapted from existing plans for the UC Davis West Village.

2.7.1 Single family home

Because single family homes are a prominent housing option in the United States, it was

critical to determine how efficiently greywater and rainwater can be incorporated into their design. This single family prototype consists of a 418 square meter lot with a 93 square meter building footprint, 55 square meter garage, and a total irrigated landscape of about 102 square meters. This lot would be considered small compared to a typical single family home in America, at about 10 dwelling units per 4,046 meters square (one acre). However, with the increasing cost of land, single family homes of this scale are becoming

more commonplace, and represent a more efficient use of land than typical older single family home densities.

In this design, rainwater is collected from the rooftops of the garage and the house and directed into above ground cisterns and into a series of connected tanks located below the deck in the back of the property. Two 379 liter (100 gallon) cisterns are located towards the front of the property and a 757 liter (200 gallon) cistern is located next to the garage as a back-up water supply (Figure 3).

Table 1 West Village Site Elements (Modified from: UC Davis 2006)

Site Element	Total
Faculty/Staff Housing	475 units
Student Housing	2,862 beds
Mixed Use	4,181 m ²
Educational	7,432 m ²
Public Safety Station	1,858 m ²
Buffer Landscape	121,730 m ²
Parks/Recreation	125,574 m ²

Table 2 Precipitation Amounts Compared with Evapotranspiration Rates (Source: Cunningham Engineers 2005)

Month	Precipitation (cm)	Evapotranspiration (cm)	Net (cm)
January	9.4	3.0	6.7
February	7.6	3.8	3.8
March	5.6	8.1	-2.5
April	3.0	11.9	-8.9
May	1.0	15.7	-14.7
June	0.3	19.6	-19.3
July	0.0	20.6	-20.6
August	0.0	18.0	-18.0
September	0.5	13.0	-12.4
October	2.3	8.6	-6.4
November	4.8	3.6	1.3
December	8.1	1.8	6.4
TOTAL	42.7	127.8	-85.1

All greywater produced by the residents is filtered and disinfected to allow for increased storage times and directed to the below deck tanks with a capacity of 2,271 liters (600 gallons). From here, water will be extracted as needed for landscape irrigation and to refill the above ground cisterns. These cisterns will be used to supply the house with its toilet flushing demands and some adjacent irrigation needs for the thin planting strips along the side of the house. When the below deck tanks become full, overflow will be directed to the sanitary sewer system. In contrast, cistern overflow due to rainfall will be directed to the below deck tanks to maximize the ratio of rainwater to greywater. Discharge to the sanitary sewer may require approval by the local wastewater authority.

2.7.2 Apartment Cluster

In the Master Plan for the West Village project, there is a substantial section of apartment style housing for students. The apartments are divided into clusters of three to four buildings that run along a pedestrian pathway. Each cluster is arranged around a central open space or courtyard and encompasses about 2,787 square meters with 827 square meters dedicated to building footprints, 326 square meters to paved surfaces, and 1,551 square meters to irrigated landscape. A single cluster, housing approximately 114 people, was analyzed and used as a prototype. The average density of this development type reflects the West Village plan specifications.

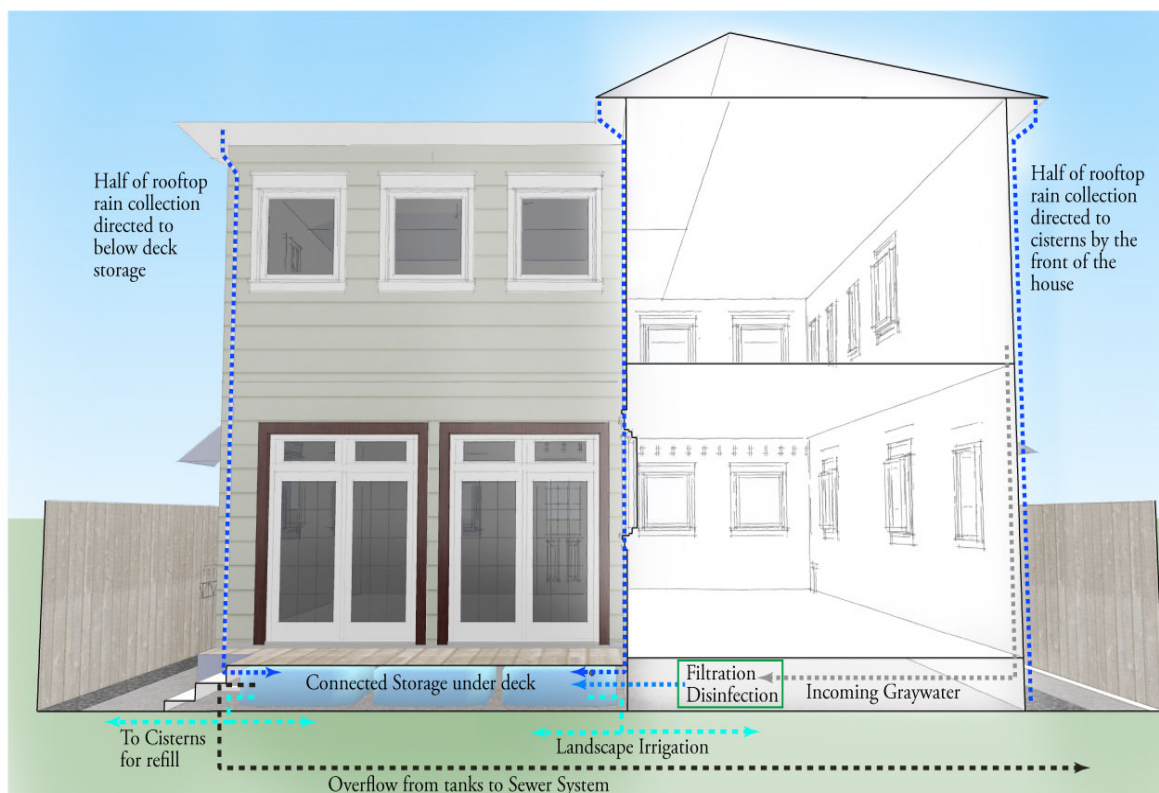


Figure 3 Single Family Home Scenario Illustrating a Combined Rainwater and Greywater Harvesting System (Graphic credit: Erik Gellerman)

As depicted in Figure 4, the apartment cluster has 11,356 liters (3,000 gallons) of storage in above ground cisterns and 41,640 liters (11,000 gallons) of storage located underneath the main courtyard. To celebrate the idea of water capture and reuse, two very visible and colorful cisterns are located at the entry, which can also be used to distinguish each of the clusters in the development. Four other cisterns are located on the courtyard side of the buildings. Greywater from the buildings is directed to planters located along the sides of each building, where it will filter through the plants and soil. The partially treated greywater will then go through another stage of micro-filtration and disinfection. After the final treatment, the water will then settle in the underground storage unit below main courtyard. The cisterns will be refilled from the underground storage unit as needed. Rainwater is collected from all the rooftops as well as a portion of the paved area in the central courtyard. Runoff from the rooftops will be directed to the above ground cisterns located along the courtyard side of the buildings where possible, while the rest will be sent

to the filtration planters to reside in storage with the greywater. Runoff from the courtyard will flow into the planters for filtration, then enter the below ground cistern. The above ground cisterns will provide the buildings with toilet flushing needs and be refilled when necessary from the underground storage unit.

2.7.3 Mixed Use

The West Village Master Plan also called for a mixed use town center called the Village Square. This space is approximately 151,417 square meters and will act as the commercial and social center for the neighborhood. It also incorporates housing units on the second and third levels of the buildings. As illustrated in Figure 5, Village Square has 7,571 liters (2,000 gallons) of storage in above ground cisterns and 41,640 liters (11,000 gallons) stored below the central courtyard. As the social gathering area of the development, it is important to have a larger area of turf grass in addition to a drought tolerant garden with pathways to enhance the space and create visual diversity.



Figure 4 Apartment Cluster Plan (Graphic credit: Erik Gellerman)



Figure 5 Village Square Plan (Graphic credit: Erik Gellerman)

Rainwater is collected from the rooftops as well as a portion of the adjacent parking lot. Runoff from the roof is directed into the cisterns where possible, while the rest is directed to filtration planters on the sides of the buildings. Runoff from the parking lots is graded towards planters on the backside of the buildings, where the water flows through curb cuts and infiltrates into the soil and piped to an underground storage unit located between the two buildings. Similar to the apartment example, all greywater is directed to filtration planters located along the sides of the buildings for preliminary treatment. Secondary treatment of the greywater is provided by micro-filtration and disinfection and then sent to the below ground storage unit where it is pumped as needed for landscape irrigation and refilling the above grade cisterns.

2.8 Determining Non-potable Water Supplies and Demands

A spreadsheet model was developed In order to determine the irrigation demands, rainfall-runoff volumes, and greywater supply and

demands. The methodology for calculating supply and demand is described in the following sections.

2.8.1 Irrigation Demands

Irrigation demands were calculated using the methodology outlined in “A Guide to Estimating Irrigation Water Needs of Landscape Plantings in California the Landscape Coefficient Method and WUCOLS III” (Costello et al. 2000). This method uses a landscape coefficient formula and landscape evapotranspiration formula to estimate monthly irrigation needs. The Landscape Coefficient (K_L) is based on the product of three factors: species (k_s), density (k_d) and microclimate (k_{mc}).

$$K_L = k_s * k_d * k_{mc} \quad (1)$$

The species factor is based on the watering needs of each species of plant. General values are specified using the WUCOLS list. The density factor is based on the existing or proposed densities of plantings. A value of 1.0 indicates an average density or about 70% - 100% canopy cover. The microclimate factor is based on specific or unique site conditions

like highly exposed areas, windy areas, shaded areas, etc. Areas like parking lots or south facing walls that absorb heat and increase evaporation are assigned values over 1.0, conversely protected areas would be assigned values less than 1.0. Table 3 further describes how landscape coefficient factors are assigned.

The Landscape Evapotranspiration Formula estimates water loss (ET_L) by multiplying the landscape coefficient (K_L) by the reference evapotranspiration (ET_o). Reference evapotranspiration is the amount of water lost due to evaporation and plant transpiration.

$$ET_L = K_L * ET_o \quad (2)$$

Total irrigation water (TWA) needed is estimated from two factors: landscape evapotranspiration (ET_L) and irrigation efficiency (IE). Irrigation efficiency is based on the idea that a typical system does not deliver all the water to made available to plants (i.e. some is lost to runoff, wind spray or leakage). To simplify the estimation, overhead sprays and rotors are estimated to be about 65% - 75% efficient, as opposed to drip systems which can work at greater than 90% efficiency.

$$TWA = ET_L / IE \quad (3)$$

Table 4 summarizes the landscape irrigation requirements as calculated for each of the West Village hypothetical development prototypes. These calculations are derived from the assumed landscape designs for each development type. The landscapes were all designed assuming native plants, mulches, soil preparation and other features that adhere generally to the recently passed Model Water Efficient Landscape Ordinance (California DWR 2009).

2.8.2 Rainfall-Runoff Volumes

The volume of runoff from rooftops and paving was calculated using the following formula:

$$\text{Runoff Volume} = \text{Area} * \text{Runoff Coefficient} * \text{Rainfall Amount} \quad (4)$$

For the purposes of this study, sloped rooftops and pavement were expected to have runoff coefficients around 90% and 80%, respectively. Table 5 summarizes the runoff volume amounts for the West Village hypothetical scenarios.

2.8.3 Greywater Supply and Demands

Greywater supply and toilet flushing demands were calculated using a methodology outlined in Appendix A of the 2007 California Plumbing Code. The Plumbing Code assigns a Water Supply Unit to fixtures such as sinks and toilets which can be used to determine water supply. Table 6, adapted from Appendix A, provides the Water Supply Units used to calculate greywater supply and demands. All sinks, clothes washers, showers and toilets were counted based on the floor plans provided for the West Village development.

Sixty-six percent (66%) of the total water used is greywater while approximately 31% is needed for toilet flushing. If each resident uses 322 liters (85 gallons) of water per day for indoor domestic use, 212 liters (56 gallons) per day per person will be greywater and 98 liters (26 gallons) will be needed for toilets per day. The monthly and annual amount of greywater supply and toilet flushing demands are provided in Table 7.

2.9 Cost Estimates

The costs of the major elements of each rainwater/greywater harvesting system in US Dollars are provided in Tables 8 – 10. Costs include price of tank, pumps, disinfection, pretreatment, plumbing and excavation. Costs for design, engineering and permitting, and landscaping and irrigation system installation were not included.

Table 3 Landscape Coefficient Factors

Landscape Coefficient Factor	Category	Value
k_s : Species (water needs)	Very low	< 0.1
	Low	0.1 - 0.3
	Moderate	0.4 - 0.6
	High	0.7 - 0.9
k_d : Density	Low	0.5 - 0.9
	Average	1.0
	High	1.1 - 1.3
k_{mc} : Microclimate (evaporative conditions)	Low	0.5 - 0.9
	Average	1.0
	High	1.1 - 1.4

Table 4 Landscape Irrigation Requirements

Month	Single Family Home (liters)	Apartment Cluster (liters)	Mixed Use (liters)
January	0	0	0
February	0	0	0
March	1,673	20,271	26,611
April	5,107	67,554	73,698
May	858	112,287	118,449
June	10,940	147,419	154,407
July	11,682	157,572	164,711
August	10,224	137,872	144,152
September	7,166	96,517	101,241
October	3,638	48,079	52,591
November	189	1,268	3,168
December	0	0	0
Annual	58,985	788,838	839,033

Table 5 Estimated Runoff Volumes

Month	Single Family Home (gallons)	Apartment Cluster (gallons)	Mixed Use (gallons)
January	3,359	24,662	52,016
February	2,790	20,484	43,204
March	1,973	14,487	30,556
April	1,129	8,288	17,481
May	404	2,965	6,253
June	128	943	1,990
July	18	135	284
August	28	202	426
September	138	1,011	2,132
October	854	6,267	13,217
November	1,707	12,533	26,434
December	2,891	21,225	44,768
Annual	15,419	113,202	228,762

Table 6 Water Supply Units

Fixture	Water Supply Units	# of Fixtures in West Village Scenarios	Total Water Supply Units
Sinks	1.0	24	24.0
Clothes Washers	4.0	5	20.0
Showers	2.0	10	20.0
SUBTOTAL (Greywater Supply)			64.0
Dishwashers	1.5	2	3.0
Toilets 6.1 L/flush	2.5	12	30.0
TOTAL			97.0

Table 7 Greywater Supply and Toilet Demand Estimates

Month	Greywater Supply			Toilet Flushing Demands		
	Single Family Home (liters)	Apartment Cluster (liters)	Mixed Use (liters)	Single Family Home (liters)	Apartment Cluster (liters)	Mixed Use (liters)
January	18,776	874,476	314,961	8,332	352,278	146,215
February	16,959	789,849	284,481	7,525	318,187	132,065
March	18,776	874,476	314,961	8,332	352,278	146,215
April	18,170	846,267	304,801	8,063	340,914	141,499
May	18,776	874,476	314,961	8,332	352,278	146,215
June	18,170	846,267	304,801	8,063	340,914	141,499
July	18,776	874,476	314,961	8,332	352,278	146,215
August	18,776	874,476	314,961	8,332	352,278	146,215
September	18,170	846,267	304,801	8,063	340,914	141,499
October	18,776	874,476	314,961	8,332	352,278	146,215
November	18,170	846,267	304,801	8,063	340,914	141,499
December	18,776	874,476	314,961	8,332	352,278	146,215
Annual	221,068	10,296,244	3,708,417	98,099	4,147,789	1,721,567

Table 8 Cost Estimates for Single Family Home Scenario¹

Rainwater/ Greywater Harvesting Component ^{2,3}	Estimated Cost (US Dollars)
2, 379 L (100 Gallon) Rainwater Cisterns (steel)	\$800
1, 757 L (200 Gallon) Rainwater Cistern (steel)	\$800
Greywater Filtration Disinfection (cartridge filter followed by UV light)	\$1,060
1, 2,271 L (600 Gallon) Greywater Tank (fiberglass) ^{4, 5}	\$2,050
Subtotal	\$4,710
Operation and Maintenance Over 20 years (est. 20% of subtotal)	\$1,884
TOTAL	\$6,594

1: Costs are one-time upfront costs

2: Cost estimates for cisterns and filtration/disinfection obtained from Texas Water Development Board (2005)

3: Cost estimates for Filtration Planters obtained using the Green Values National Stormwater Management Calculator

4: Cost estimates include a pump and costs associated with excavation in soils; values obtained from Pushard (no date) and Wallace-Kuhl and Associates (2006)

5: Includes cost estimates for greywater plumbing; Source: Whitney, et al. (1999)

Table 9 Cost Estimates for Apartment Cluster Scenario¹

Rainwater/ Greywater Harvesting Component^{2,3}	Estimated Cost (US Dollars)
2, 5,678 L (1,500 Gallon) Rainwater Cisterns (steel)	\$12,000
Filtration Planters (232 m ²)	\$60,000
Additional Greywater Filtration Disinfection (cartridge filter followed by UV light)	\$1,060
1, 41,640 L (11,000 Gallon) Below Ground Greywater Cistern (fiberglass) ^{4,5}	\$22,500
Subtotal	\$97,574
Operation and Maintenance Over 20 years (est. 20% of subtotal)	\$39,029
TOTAL	\$136,603

1: Costs are one-time upfront costs

2: Cost estimates for cisterns and filtration/disinfection obtained from Texas Water Development Board (2005)

3: Cost estimates for Filtration Planters obtained using the Green Values National Stormwater Management Calculator

4: Cost estimates include a pump and costs associated with excavation in soils; values obtained from Pushard (no date) and Wallace-Kuhl and Associates (2006)

5: Includes cost estimates for greywater plumbing; Source: Whitney, et al. (1999)

Table 10 Cost Estimates for Apartment Cluster Scenario¹

Rainwater/ Greywater Harvesting Component^{2,3}	Estimated Cost (US Dollars)
2, 3,785 L (1,000 Gallon) Rainwater Cisterns (steel)	\$8,000
Filtration Planters (65 m ²)	\$16,800
Additional Greywater Filtration Disinfection (cartridge filter followed by UV light)	\$1,060
1, 41,640 L (11,000 Gallon) Below Ground Cistern (fiberglass) ⁴	\$22,500
Subtotal	\$50,389
Operation and Maintenance Over 20 years (est. 20% of subtotal)	\$20,155
TOTAL	\$70,544

1: Costs are one-time upfront costs

2: Cost estimates for cisterns and filtration/disinfection obtained from Texas Water Development Board (2005)

3: Cost estimates for Filtration Planters obtained using the Green Values National Stormwater Management Calculator

4: Cost estimates include a pump and costs associated with excavation in soils; values obtained from Pushard (no date) and Wallace-Kuhl and Associates (2006)

5: Includes cost estimates for greywater plumbing; Source: Whitney, et al. (1999)

3. RESULTS AND DISCUSSION

Figures 6–8 compare the monthly volumes of water needed for irrigation and toilet flushing (demand), as well as the volumes produced by rainwater and greywater (supply) for each of

the three housing prototypes. As illustrated in the figures, rainfall occurs in an inverse relationship with irrigation needs, while greywater production and toilet flushing demands remain constant.

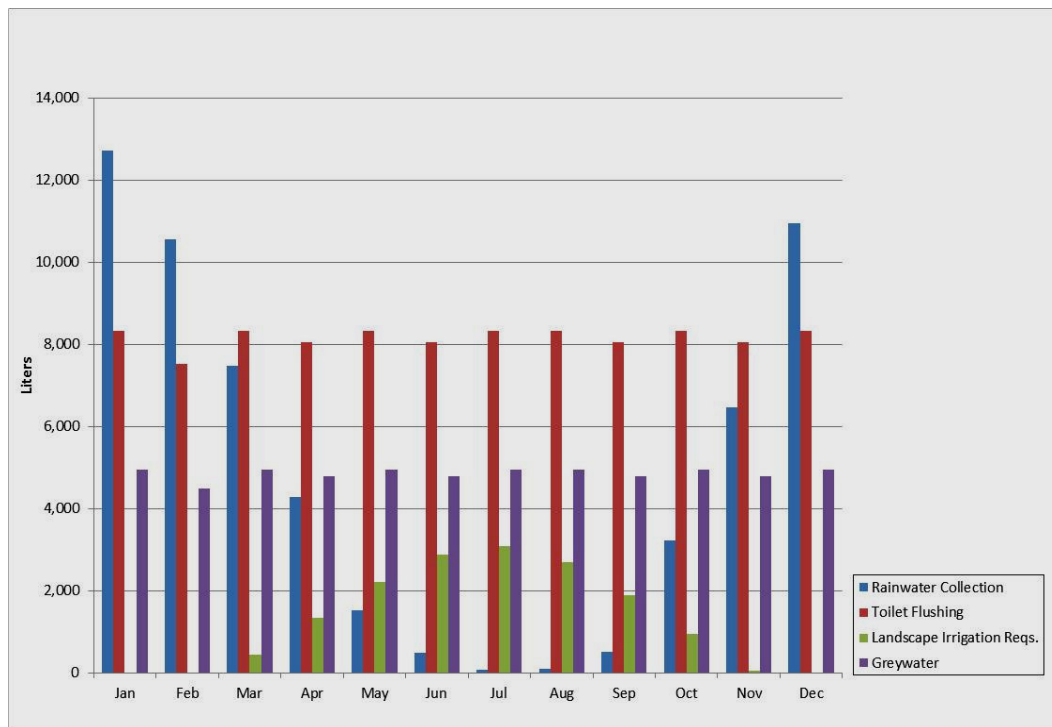


Figure 6 Single Family Non-Potable Water Supplies and Demand

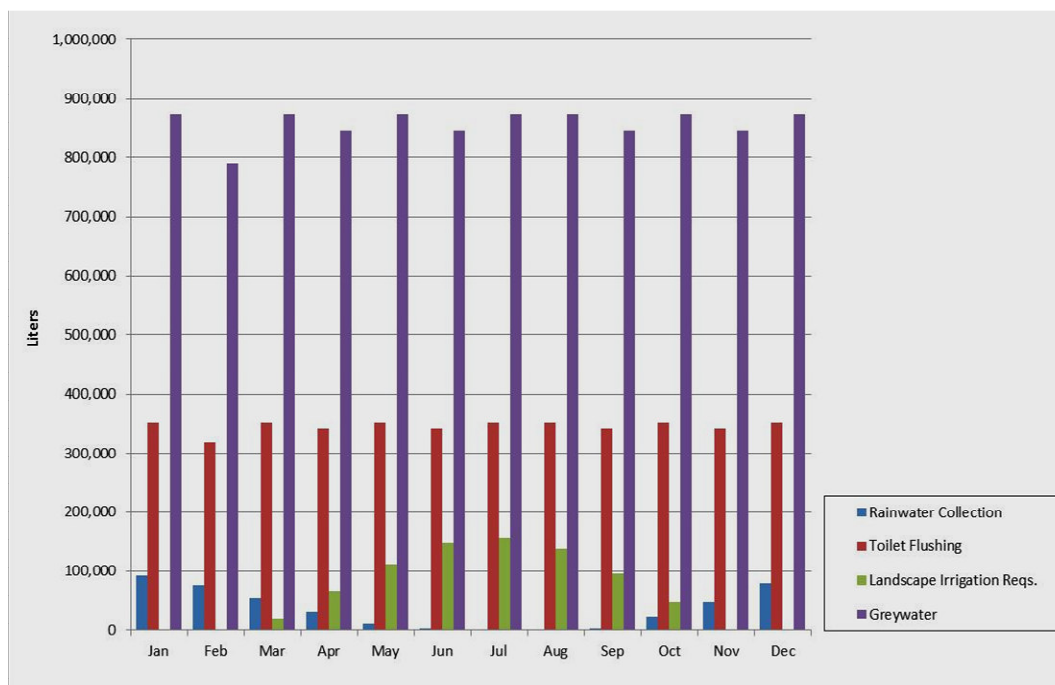


Figure 7 Apartment Cluster Non-Potable Water Supplies and Demand

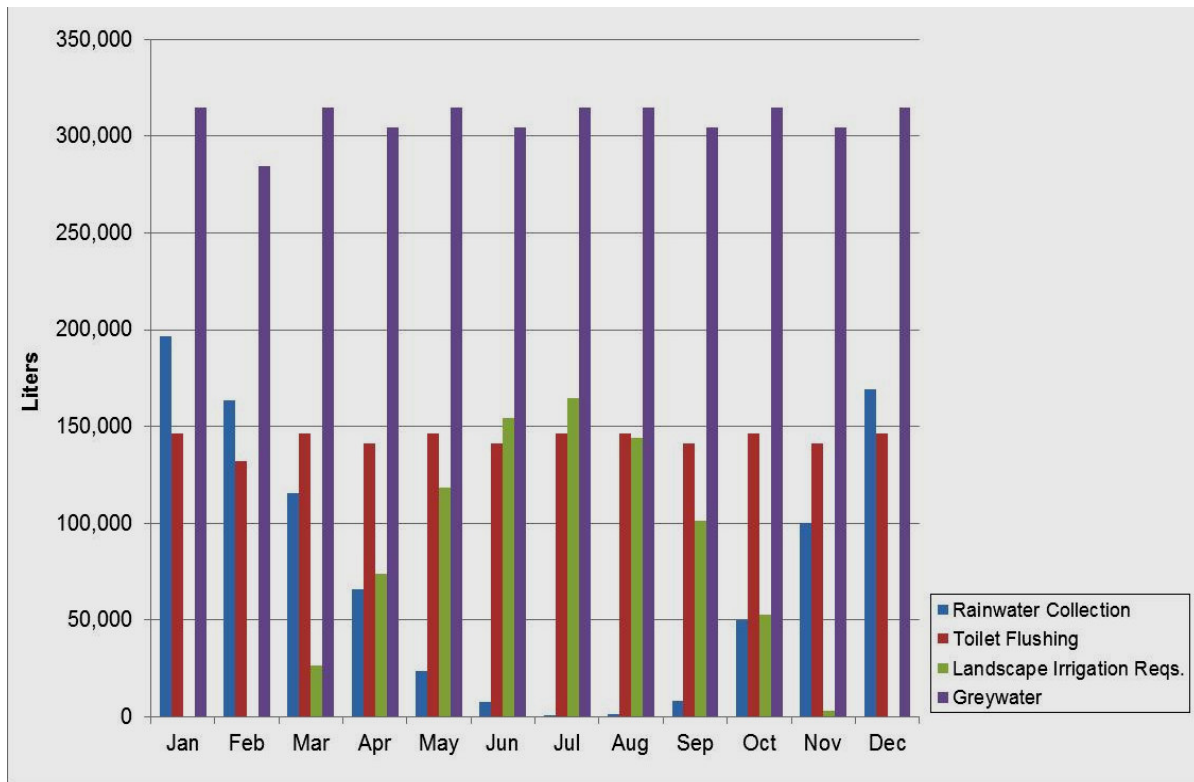


Figure 8 Mixed Use Non-Potable Water Supplies and Demand

Based on the research and calculations from these three scenarios, it becomes apparent that depending on the scale and density, rainwater and greywater vary substantially (Table 11). In the single family home and mixed use scenarios, rainwater can make up as much as 40% of total water production in the winter (Figures 9 and 10). This is in comparison to the apartment cluster where rainwater never makes up more than 10% of total water production, due to the higher number of occupants (Figure 11). For all three scenarios, rainwater contributes little to no supply during the summer months, meaning that the majority of the supply is greywater. Similarly, if a drought were to occur during the winter, the majority of the supply would be obtained from greywater sources.

In the single family scenario, on average only three months out the year (December – February) will not require supplemental irrigation. In the wet months the cisterns will

remain generally full with some fluctuations. May through September, when irrigation demands are higher, water levels in the tanks will drop to almost empty after an irrigation cycle then slowly be filled by the extra greywater throughout the week. The cisterns surrounding the house will provide all the irrigation needs except in June and July when the 757 liter (200 gallon) reserve tank by the garage will fulfill the remaining irrigation needs until demands decrease in the fall.

A number of trends are evident from the data. As density increases, greywater becomes even more prominent in overall production of water. In addition, landscape irrigation requirements decrease relative to toilet flushing demands and in comparison to total water production. Because of the increased amount of occupants per unit area, landscape irrigation requirements are easier to meet. If only landscape irrigation is the goal, then higher density, residential and non-residential, mixed

use and commercial development are relatively easy to serve.

Additionally, because California tends to experience back-to-back storms, rainwater must either be drawn-down to provide storage capacity for the next incoming storm or greater storage must be provided to prevent significant by-pass or overflow (Strecker and Poresky 2009). Rainwater harvesting should not be abandoned even though it might not be able to accommodate all non-potable needs. Harvesting rainwater is a responsible way of saving water resources and taking advantage of a relatively clean water source that can reduce the greywater treatment requirements.

Conversely, greywater remains a constant source of water throughout the year. Because of the constant water inputs there is a lower storage requirement. While rainwater has the problem of seasonal fluctuations, greywater has health and safety issues. This makes it difficult to implement greywater use on a large scale, partly because bacterial growth in greywater is a relatively unknown subject and

public opinions are generally unsure of greywater. Health issues are a valid concern and greywater should not be used if it will threaten human or environmental health. However, there has never been a report of illness due to exposure from greywater (Ludwig 2009).

Several major impediments exist to the widespread adoption and use of combined rainwater and greywater systems the largest of which may be cost. Compared to the relatively low cost of municipal water, implementation of greywater and rainwater systems are expensive. Tables 12 and 13 compare the cost of water supplied by the rainwater/greywater harvesting systems to the current status quo (groundwater supplied by the City of Davis) and desalination. These comparisons illustrate that onsite use of rainwater and greywater is nearly three times more in the single family scenario when compared with the City water bill. The discrepancies in cost do begin to level out at higher densities.

Table 11 Summary of Supply and Demand of Rainwater Harvesting/Greywater Scenarios

Month	Single Family Home		Apartment Cluster		Mixed Use	
	Total Supply (liters)	Total Demand (liters)	Total Supply (liters)	Total Demand (liters)	Total Supply (liters)	Total Demand (liters)
January	31,491	8,332	967,831	352,278	511,863	146,215
February	27,520	7,525	867,389	318,187	448,026	132,065
March	26,244	10,005	929,315	352,278	430,628	146,215
April	22,444	13,169	877,640	384,363	370,974	193,113
May	20,305	16,690	885,699	455,941	338,632	256,764
June	18,655	19,003	849,836	485,589	312,334	293,392
July	18,844	20,013	874,987	509,456	316,036	310,567
August	18,882	18,556	875,240	489,564	316,574	289,830
September	18,692	15,229	850,094	434,493	312,872	240,044
October	22,008	11,969	898,199	382,134	364,993	182,109
November	24,632	8,252	893,709	340,914	404,865	141,499
December	29,719	8,332	954,821	352,278	484,427	146,215
Annual	279,435	157,083	10,724,761	4,857,474	4,612,229	2,258,967

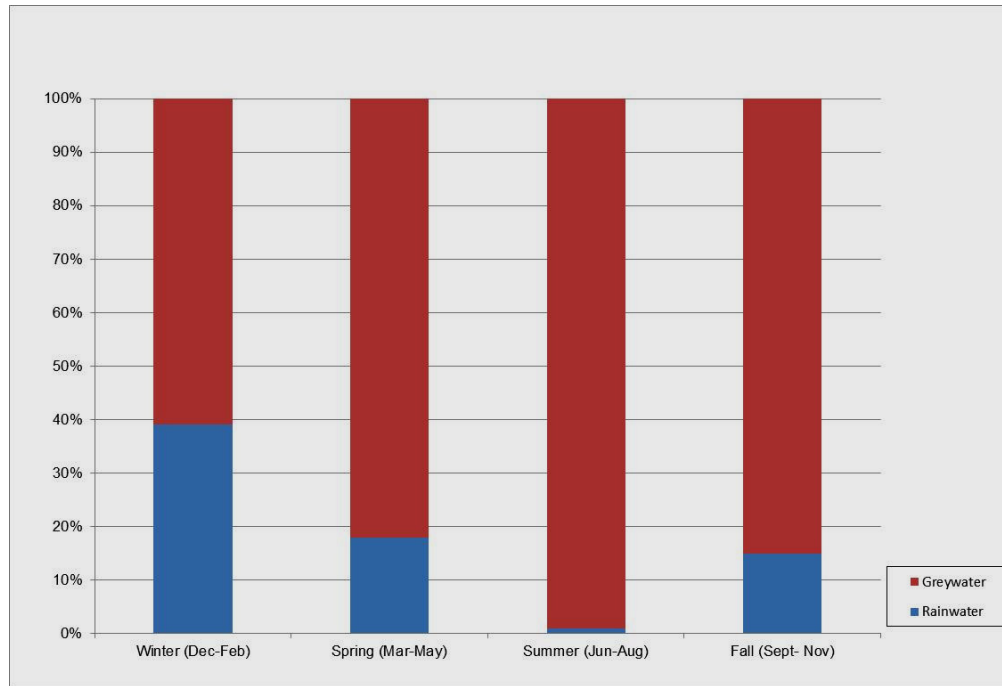


Figure 9 Single Family Home Water Supply Seasonal Variations

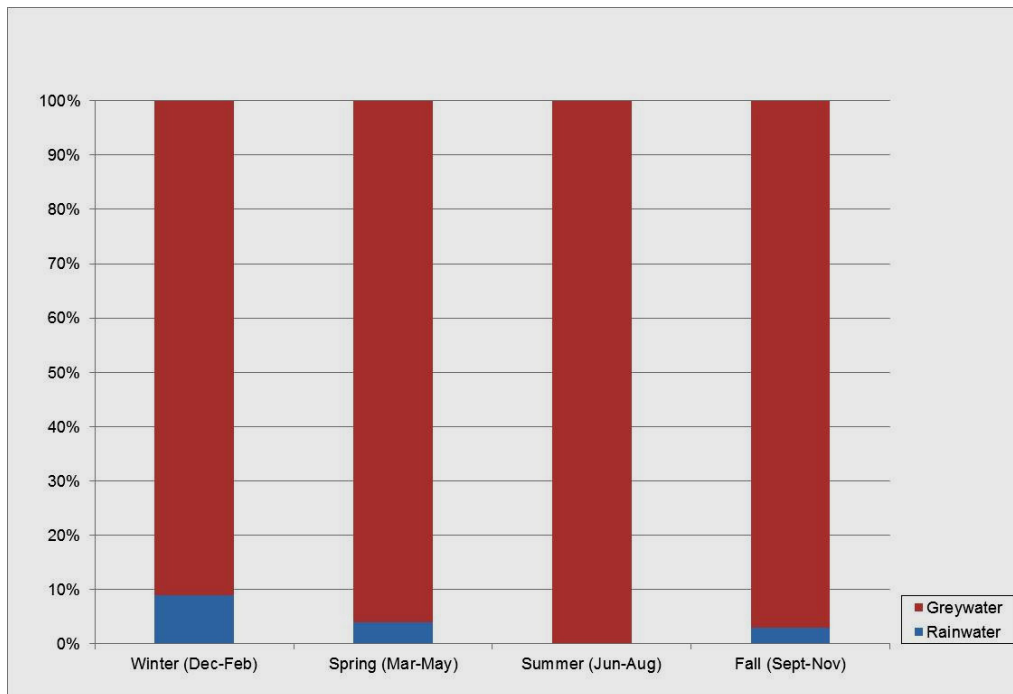


Figure 10 Mixed Use Water Supply Seasonal Variations

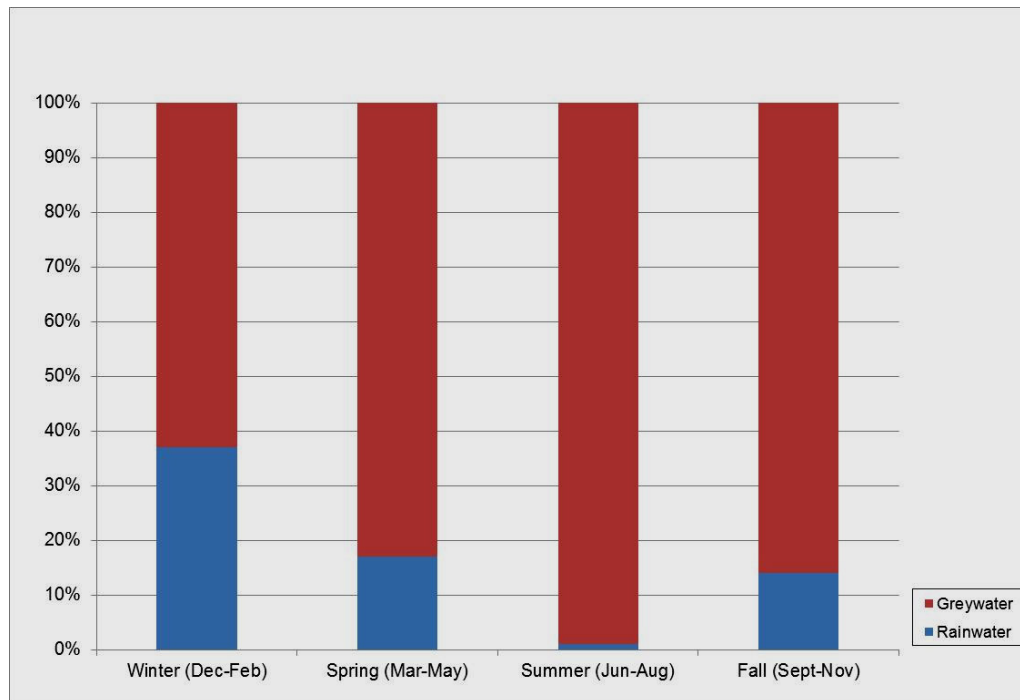


Figure 11 Apartment Cluster Seasonal Variations

Table 12 Total Cost of Water Supply Over 20 Year Period

Scenario	Water Demand Over 20-Years ¹	Rainwater/Greywater System	Status Quo (cost of City water bill: \$1.90 per 3,831 L) ²	Desalination (\$3 per 3,785 L) ³
Single Family Home	829,940	\$6,594	\$2,108	\$2,490
Apartment Cluster	25,664,180	\$136,603	\$65,190	\$76,993
Mixed Use	11,935,120	\$70,544	\$30,316	\$35,805

1: Annual Demand from Table 12 over 20 years

2: Source: <http://cityofdavis.org/pw/srvcs/services.cfm>

3: Source: http://deltavision.ca.gov/BlueRibbonTaskForce/July2007/Handouts/Day2_Item_2_Attachment_1.pdf

Table 13 Cost per 3,785 Liters (1,000 Gallons) Over 20 Years

Scenario	Rainwater/Greywater System ¹	Status Quo (cost of City water bill)	Desalination
Single Family Home	\$8.00		
Apartment Cluster	\$5.00	\$3.00	\$3.00
Mixed Use	\$6.00		

1: These costs do not factor in potential cost savings due to reduced stormwater drainage and/or wastewater treatment

However, in all cases, the full cost of externalities such as the environmental costs of a reservoir storage project or the “carbon-related” costs of the desalination project are not factored in to their assumed costs. Therefore the comparative water supply alternatives would be less attractive if all costs were taken into account. There are virtually no externalities for the rainwater-greywater combined system. In many regions of California and throughout the semi-arid western U.S., such systems have promise. They can save water, thereby also saving substantial amounts of energy in extraction, treatment, conveyance/pumping and waste water treatment, while staving off the need for significant capital (and potentially environmental) costs of major capital investment for water production.

Rainwater and greywater harvesting will be most successful if it is considered in the early planning stages. The aesthetics and placement of storage tanks are the keys to public acceptance and efficient rainwater and greywater collection. The best way to reduce water demands is by designing and implementing a water conscious landscape and in turn, reducing storage requirements and costs. Careful selection, design and placement of indoor plumbing fixtures and appliances can also significantly contribute to water conservation. Additionally, incentives for implementing rainwater and greywater harvesting systems may be provided by local governments through reduced stormwater drainage and wastewater treatment fees. Reduction in stormwater and wastewater fees could be directly tied to the amount of water used onsite. For example, the City of Camilla, Georgia recognizes the benefits of rain barrels through a crediting system that provides a reduction of up to 20% off the stormwater drainage fee for homeowners who install rain

barrels on their property (City of Camilla 2010).

California could expect to save 2.8 km³ of water per year if greywater and rainwater combined systems were implemented by every residence in California, based on 2010 United State Census numbers and the water savings documented in the hypothetical scenarios studied here (US Census Bureau 2010). This would result in more than a quarter (25%) reduction when compared with California’s overall urban water use (California DWR 2009). California and other communities concerned about water supplies are in great need of solving its water supply problems. Other likely alternatives to address water shortages include recycled water (treated municipal wastewater) and desalination of seawater. Both alternatives have economic and environmental consequences and may require a large carbon footprint to construct and maintain. Solutions will come in the form of not one, but many. Other solutions include the use of recycled water and conservation, both indoors and in the landscape. California and other communities should maintain a diverse water portfolio that adapts to growing needs and includes rainwater and greywater systems as part of the solution.

CONCLUSIONS

The development scenarios illustrate that rainwater and greywater combined offer sufficient volumes of water assuming a reasonable amount of storage and pre-treatment for irrigation and toilet flushing. In all cases, rainwater alone was not enough to satisfy the water demands for the development prototypes. The unpredictable nature of rainfall, coupled with its seasonal fluctuations would make it difficult to rely on by itself as a supplemental water source. Relying on rainwater systems alone in a Mediterranean

climate will require very large catchment areas and large amounts of storage to supply water into the dry months. Many single family residences simply do not have the space to accommodate large tanks, whereas apartment complexes might have more flexibility in this area. However, in dense urban settings, the storage space is still likely to be a significant barrier.

This research suggests several lines of inquiry for further investigation. Can we develop new technologies to reduce storage and treatment costs for small, dispersed systems, and can they be widely implemented? How can developers, builders and home owners be offered incentives to create dispersed systems by reducing water or waste water fees and saving utilities significant capital costs in new facilities or expansion? In what regions of the American west are these technologies most cost effective? Are there ways to incorporate storage directly into building and site design and therefore reduce costs, such as wall storage units? Are there “neighborhood” or building “cluster” solutions that can reduce cost, eliminate the aesthetic challenges of storage and centralize maintenance? These and similar questions could form the basis for more inquiries into these promising technologies.

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