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Nasser A. S. Tuqan SEFFICIENCY APPLICATION IN WATER (RE)ALLOCATION POLICIES

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Master Dissertation
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Abstract

Water is globally scarce and highly competitive among several users. In fact, UN estimates that more than 40% of the global population is projected to be living in areas of severe water stress through 2050. The only foreseeable way to deal with this scarcity is by well-managing the available and accessible resources. The objective of this work is to promote water efficient use through systemically measuring the performance of a defined water system (WS) using sustainable efficiency ($S_{efficiency}$) as a tool. The general framework of $S_{efficiency}$, which is an advanced efficiency indicator that considers the usefulness criterion (water quality and beneficence characteristics), was suggested and detailed by Haie, et al. in their 2012 paper. In order to achieve the final efficiency results after the selection of a WS, data collection and acquisition processes are needed to characterize the WS under consideration quantitatively, qualitatively and beneficially. Tomato crop farmlands located in Davis City, Yolo County at the west bank of the largest river in California State, Sacramento River, were selected as a WS because of the seriousness of water drought series in addition to the distinguished economic value of agriculture there. The $S_{efficiency}$ results of the WS under consideration showed relatively inefficient performance at the local level inside the system; symptoms of polluting impacts by the WS on the river; and considerably satisfactory recharge to the main source.

Resumo

A água está globalmente escarça e altamente competitiva entre muitos usuários. A ONU estima que mais de 40% da população mundial deverá viver em áreas com graves problemas hídricos até 2050. A única maneira previsível para lidar com essa escassez é por meio da boa gestão dos recursos disponíveis e acessíveis. O objetivo desse trabalho é promover o uso eficiente da água através da medição sistemática do desempenho de um determinado sistema hídrico (*water system*/WS) usando como ferramenta a eficiência sustentável (*sustainable efficiency*/$S_{efficiency}$). A estrutura geral de $S_{efficiency}$ — um indicador avançado de eficiência que considera o critério de utilidade (características de beneficência e qualidade da água) — foi sugerido e detalhado por Haie, et al. em seu artigo de 2012. A fim de alcançar os resultados de eficiência finais após a seleção de um WS, são necessários processos de aquisição e coleta de dados para caracterizar o WS segundo considerações quantitativa, qualitativa e benéfica. Foram selecionados como WS fazendas de cultivo de tomate localizadas em Davis City, Yolo County, na margem ocidental do Rio Sacramento, o maior rio do estado da Califórnia, por causa dos graves e constantes períodos de seca, além do notável valor económico da agricultura naquele local. Os resultados de $S_{efficiency}$ do WS sob consideração mostraram um desempenho relativamente ineficiente no nível local de dentro do sistema: sintomas de impacto de poluiçãoo no rio pelo WS e recarga consideravelmente satisfatória para a fonte principal.

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Abbreviations

℃	Degree Celsius
3ME	Macro, Meso and Micro-Efficiency
af	Acre-feet
AU	Agronomic Use
BEA	Bureau of Economic Analysis
CA	California State
CCME	Canadian Council of Ministers of the Environment
CCSCE	Center for Continuing Study of the California Economy
CE	Classical Efficiency
CGE	Computable General Equilibrium
CIA	Central Intelligence Agency
CIMIS	California Irrigation Management Information System
cm	Centimeter
CWQG	Canadian Water Quality Guidelines
CWQI	Canadian Water Quality Index
dS/m	deciSiemens per meter
EE	Effective Efficiency
ET	Evapotranspiration
FAO	Food and Agriculture Organization
$ft.$	Feet
GDP	Gross Domestic Product
GDWQI	Global Drinking Water Quality Index
GIS	Geographic Information System
ha	Hectare
IHP	International Hydrological Program
$in.$	Inch
IS	Irrigation Sagacity
km	Kilometer
kPa	Kilo Pascal
LR	Leaching Factor
m	Meter
MCM	Million Cubic Meter
MDG	Millennium Development Goals
mg/L	Milligram per Liter
mm	Millimeter
N.T.U.	Nephelometric Turbidity Units
NR	Non-Reusable
OS	Other Sources
OSP	Occupied State of Palestine
PM	Penman Method
PP	Precipitation
PWA	Palestinian Water Authority
rad	Radian
RF	Return Flow
RP	Potential Return
S_A	Abstraction Savings
S_C	Consumptive Savings
SDG	Sustainable Development Goals
UN	United Nations
UNEP	United Nations Environmental Program
UNESCO	UN Educational, Scientific and Cultural Organization
USA	United States of America
USD	United States Dollar
USGS	United States Geological Survey
VA	Volume of water Abstracted
VD	Volume of water Downstream
VU	Volume of water Upstream
W_{q_X}	Quality weight of variable X
W_{b_X}	Beneficence weight of variable X
WB	West Bank
WQI	Water Quality Index
WS	Water System
WWAP	World Water Assessment Program
WWDR	World Water Development Report

1 INTRODUCTION

Water is a life main component that guarantees creatures' continuity. It is widely known that scientists have always indicated life existence by dihydrogen monoxide existence. Indeed, water is commonly considered as the most essential sector among natural resources (Vörösmarty, et al., 2010). Furthermore, water is undoubtedly a wealth indicator, a vital element for human health and hygiene, an important factor for renaissance, a war cause, and a peace seeder.

1.1 Water on Earth

On our mother, earth, water covers 70.90% of its surface (CIA, 2013). As shown and detailed in figure 1-1, 96.50% of the planet's water is found in seas and oceans, while 1.70% as groundwater (0.77% fresh and 0.93% saline). There are 1.70% in glaciers and the ice caps of Antarctica and Greenland, a small fraction in other large water bodies, and 0.001% in the air as vapor, clouds (formed of solid and liquid water particles suspended in air), and precipitation. Only 2.50% of the Earth's water is freshwater, and 98.70% of that water are ice and groundwater. Less than 0.30% of all freshwater is in rivers, lakes, and the atmosphere, and a smaller amount of the Earth's freshwater (0.003%) is contained within biological bodies and manufactured products (Gleick, 1993).

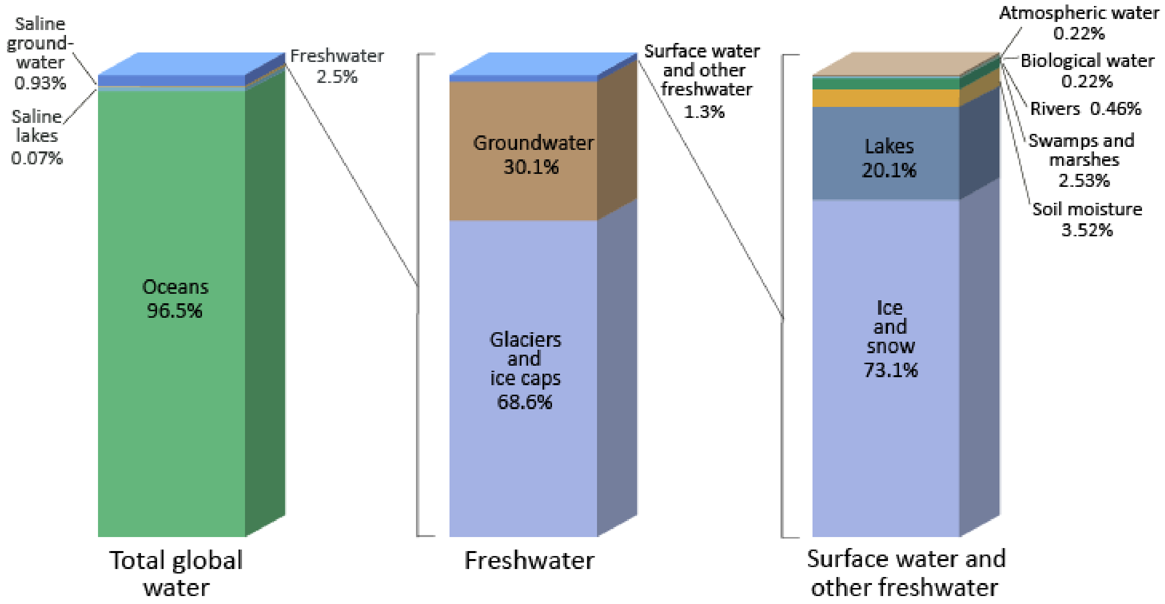


Figure 1-1: Distribution of Earth's Water
Source: (Gleick, 1993)

It is important to understand that freshwater is continuously moving, flowing in rivers, evaporating and spreading as water vapor, falling as rain or snow, or being infiltrated slowly through the soil as groundwater (BIDLACK, et al., 2004). Water evaporates annually from the oceanic surface ($502{,}800\ km^3$) and from lands ($74{,}200\ km^3$). The same amount of water falls as atmospheric precipitation ($458{,}000\ km^3$ on oceans and $119{,}000\ km^3$ on lands). The difference between precipitation and evaporation from the land surface ($44{,}800\ km^3/year$) represents the total runoff of the Earth's rivers ($42{,}700\ km^3/year$) and direct groundwater runoff to the ocean ($2{,}100\ km^3/year$). These are the principal sources of fresh water to support life essentials and human activities (Shiklomanov, 1998).

1.2 Water Scarcity

Freshwater is absolutely an essential element for human well-being and sustainable socio-economic development. According to the UN World Water Development Report of 2014, major regional and global crises – of climate, poverty, hunger, health and finance – that threaten the livelihood of many, especially the three billion people living on less than $2.50\ USD/day$, are somehow interconnected through water (WWAP, 2014).

In many regions of the planet, water shortage is considered as one of the most crucial unresolved issues. One fourth of the world's population lives in dry or semi-arid areas, where water supply chain management is evolving as one of the most difficult and urgent problems, since water demand and supply are significantly varying from year to year, seasonally and even daily (Kondili, et al., 2009). On the word of some estimates, the number of people whose right to water is not satisfied (regardless the reason) could be as high as $3.5\ billion$, while $2.5\ billion$ remain without access to improved sanitation. Figure 1-2 shows the global physical and economic surface water

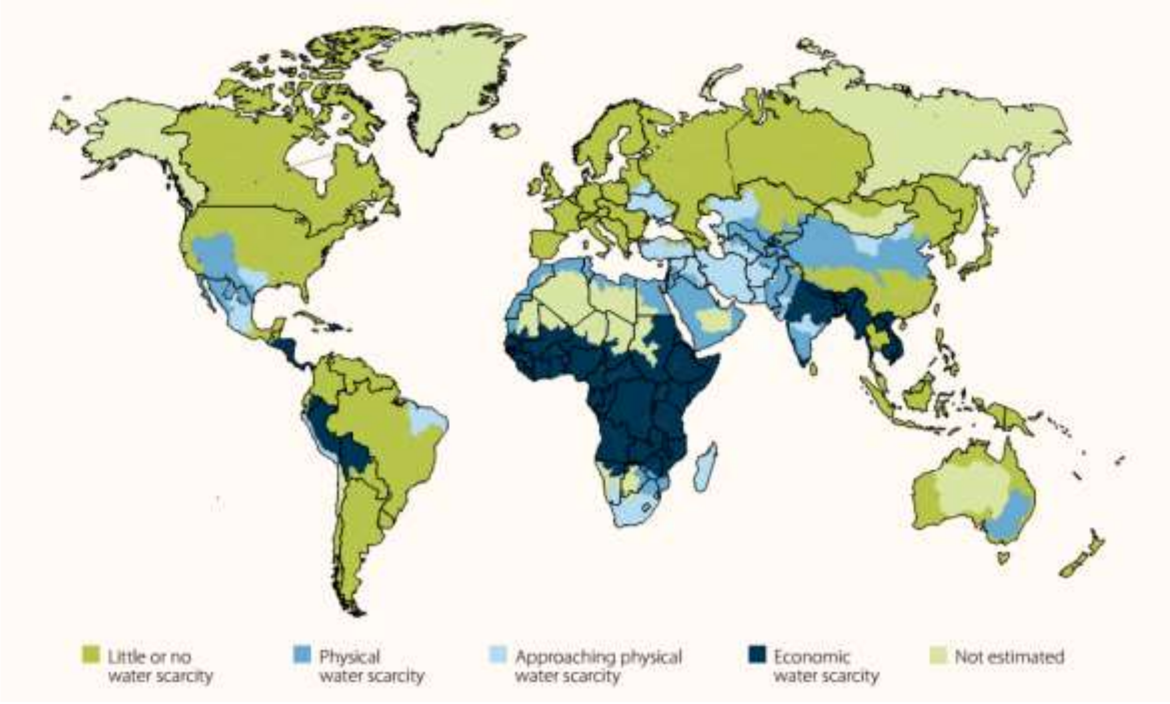


Figure 1-2: Global Physical and Economic Surface Water Scarcity
Source: (WWAP, 2014)

scarcity classified into five different classes regarding the type of water scarcity worldwide. The five classes, according to (WWAP, 2014), are defined as:

1. Little or no water scarcity: abundant water resources relative to use, with less than 25% of water from rivers withdrawn for human purposes.
2. Physical water scarcity (water resources development is approaching or has exceeded sustainable limits): More than 75% of river flows are withdrawn for agriculture, industry and domestic purposes. This definition – relating water availability to water demand – implies that dry areas are not necessarily water scarce.
3. Approaching physical water scarcity: More than 60% of river flows are withdrawn. These basins will experience physical water scarcity in the near future.
4. Economic water scarcity (human, institutional and financial capital limit access to water even though water in nature is available locally to meet human demands): Water resources are abundant relative to water use, with less than 25% of water from rivers withdrawn for human purposes, but malnutrition exists.
5. No available estimation.

The challenge which has had to be met by today is to extend the coverage of water services to the unserved areas worldwide. This challenge was stated in the 7th development goal (target 7.c) of the Millennium Development Goals (MDGs): *"Halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation"* (UN, 2014). The MDGs were adopted at the United Nations Millennium Summit in New York in 2000, and it reaches the target date by the end of year 2015 (UNESCO, 2014).

Figure 1-3: MDG 7 Infographic
Source: (UN, 2014)

On the other hand, there are several future water-related challenges humans should overcome. The main challenge is, according to the UN, that demands for water will continue to increase considerably over the coming years to meet the needs of growing populations and economies (WWAP, 2014). Thus, as the MDGs program is concluding by the end of 2015, the 192 Member States declared the Sustainable Development Goals (SDGs) agenda beyond 2015 at the United Nations Conference on Sustainable

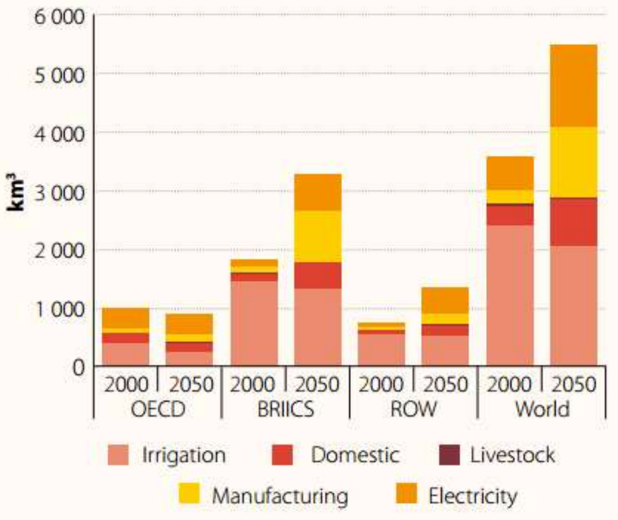
Development in 2012 (Rio+20) outcome document *"The Future We Want"*. In accordance, the International Hydrological Program of UNESCO (UNESCO-IHP) proposed a stand-alone sustainable development goal dedicated to water in order to *"Ensure **Water Security** for Sustainable Development"* (UNESCO, 2014).

That challenge will be most severe in regions going through accelerated development and rapid economic growth, or those in which a large portion of the population lacks access to modern services. In fact, UN estimates that global water withdrawals are projected to increase by some 55% by 2050, mainly because of growing demands from manufacturing (400%), thermal electricity generation (140%) and domestic use (130%). As a result, freshwater availability will be more and more stressed over this time period, and more than 40% of the global population is projected to be living in areas of severe water stress through 2050. Moreover, there is clear evidence that groundwater quantities are shrinking, with an estimated 20% of the world's aquifers being over-exploited (WWAP, 2014).

1.3 Water Use Sectors

Since water essentially contributes to all human development activities, it is highly competitive among several users. Categorizing water use by sectors has considerable significance for management-related purposes. In fact, water use sectors can be classified into several classifications. For example, a suggested classification can be as the following: domestic; agricultural; industrial; and commercial water use.

In that context, UN-Water had different classifications in their consecutive World Water Development Reports. Lately, the WWDR of 2014 classified water use sectors into: municipal; industrial; and agricultural, and also into: irrigation; domestic; live stock; manufacturing; and electricity. The second classification appears in figure 1-4 (extracted from WWDR 2014), which represents the global water demand as baseline scenario of 2000 and 2050.



Note: BRIICS, Brazil, Russia, India, Indonesia, China, South Africa; OECD, Organisation for Economic Co-operation and Development; ROW, rest of the world. This graph only measures 'blue water' demand and does not consider rainfed agriculture.

Figure 1-4: Global Water Demand (2000 & 2050)
Source: (WWAP, 2014)

Following the first UN-Water classification, most of the available waters, generally speaking at the global scale, are used by the agricultural sector (69% in year 2006). The rest is shared between the industrial sector (19% in year 2006) and the municipal sector (12% in year 2006) (WWAP, 2014).

Regardless the sectors named and classified, the idea of classification itself is the most important here, keeping in mind that most classifications have the same theme in common. Actually, such variability comes from the idea that differentiating water use sectors is of massive importance for planners and decision makers. Also, the variance made it harder for data collectors, researchers and scientists to unite their deliverables.

It is worth mentioning here that each of the water use sectors is in continuous competition to enlarge their shares on the expense of the other sectors. Indeed, this competition becomes more obvious and meaner the more the water is scarce. In such cases, it is the duty of high-level decision makers and the sovereign managerial bodies to maintain the equitable sharing of this precious resource, in which the demands of each sector are satisfied according to predefined prioritization process.

1.4 Objectives

This work is a trial of exploration and better understanding of a specific part of the human scientific knowledge related to the integrated water resources management and the better practices of water use. It is directed under the purpose of completion and meeting the degree seeking requirements of the Master Program of Urban Engineering - Environmental Hydraulics at the University of Minho, in Braga and Guimarães, Portugal. Indeed, the leading purpose behind this effort is to light another candle in the long road towards overcoming the global water crisis.

As discussed in the previous sections of this introduction, water is scarce in our globe and highly competitive among several users. Hence, and because humans cannot increase, by any means, the quantity of the available water on earth, the only way to maintain the recent life standards is to better manage our water resources.

Key tools in this regard are the indicators of water use performance. The concept behind these tools is to measure how much efficient the available water has been used. The aim of this work is to highlight and achieve the fundamental objective of water management of promoting water efficient use. This will be approached through systemically measuring the performance of a defined water system (WS) according to the applied management alternatives (allocation) using ***sustainable efficiency*** $\boldsymbol{(S_{efficiency})}$ as a tool.

The main aim is approached in this work through the following objectives:

i. **WS Selection:**
Selection among several alternatives of suggested water systems has to be made at the initial stage of the work progress. The hypothesized methodology will be implemented

later on the selected system in order to approach the other objectives, achieve results and draw conclusions.

ii. **Characterizing the WS:**

A process of defining, calculating, estimating or quantifying the system's variables of interest:

- Hydrologically (precipitation, evapotranspiration, infiltration, etc...);
- Qualitatively (pollution); and
- Socially (values: monetary or otherwise, usually by stakeholders).

iii. **Presenting the multi-level performance of the WS:**

This objective encompasses several tasks including: the development of a computerized model of the performance indicators; the quantitative estimation of the multi-level performance indicators; and performing sensitivity analysis to evaluate the effects of the different variables on the developed indicators.

iv. **Analyzing (re)allocation policies:**

Allocation or reallocation policies of water resources are subjected to a prioritization process between three main competitors: agriculture, urban/industry, and nature. The last objective of this work is approached by suggesting the most convenient allocation alternative(s) of the available water resources according to the presented results of the multi-level performance of the WS in objective iii.

2 LITERATURE REVIEW

When it comes to water resources management, this term refers not only to one complete science, but it refers to a group of sciences ranging from conventional sciences (such as supply management) to more modern and complex ones (such as integrated water resources management). However, the scope of this work is directed toward interconnected fields, including basically water (re)allocation policies and water use efficiency.

2.1 Management Approaches

As already discussed in the previous sections, water quantity is finite, while world's population keeps increasing and the human life style develops rapidly. Moreover, due to the possible changes accompanied with climate change, uncertainty of the potentially upcoming scenarios is absolutely high. As the demand of water increase while the supply does not increase, the challenge is to utilize the available – and limited – quantity of water supplies in order to meet the minimum requirements of water demand. The variables of this utilization process – more importantly water demand among highly competitive users – are normally address by different management approaches in order to achieve the most efficient utilization. However, allocation decisions are taken by relevant policy makers.

For example, Pakistan suffered a severe flood in 2010, while trying to feed a population of over $180\ million$ (2010). Bangladesh as well, which records the world's highest population density, suffered in 1988 its most devastating flooding, covering around two thirds of the country, with an estimated loss of over a hundred thousand lives. Despite the apparent 'excess' of water, even if both countries improved all the agricultural water use efficiencies to the maximum possible extent, neither Pakistan nor Bangladesh would be able to feed their own populations in the year 2050, nor protect them from the prospective increased floods and droughts (Stakhiv, 2011).

Figure 2-1 illustrates the paradigm shifts or evolution of water management levels regarding the population increase in relation to water availability, and the increase of problem variables complexity.

Management approaches, such as the traditional water supply enhancement approach, proved inadequacy to address increasing water related challenges and meet the newly resulted standards in water allocation. In addition, demand management is important but unsatisfactory for growth, development, and adaptation to climate change for most developing countries (Stakhiv, 2011). As a result, issues such as quality management, environmental integrity, efficient allocation of water resources and cost effectiveness are introduced in integrated water management (Kampragou, et al., 2011).

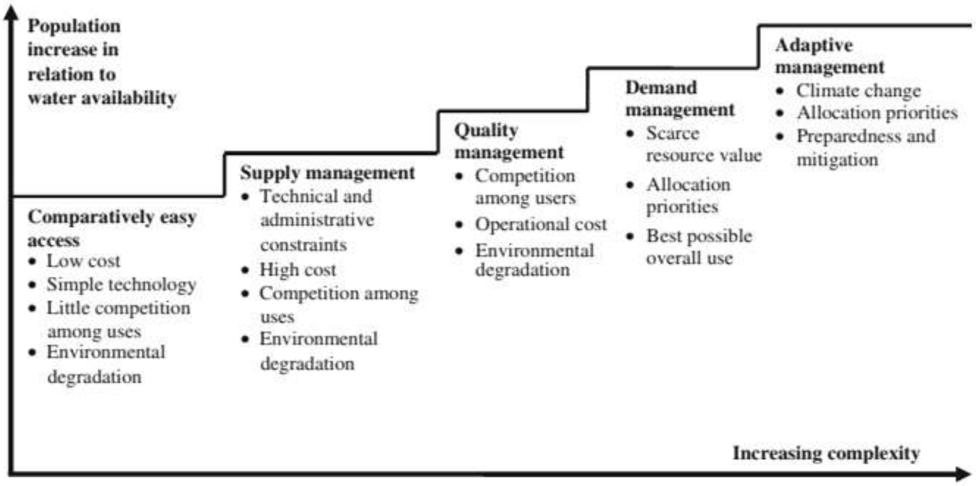


Figure 2-1: Paradigm Shifts in Water Management Levels
Source: (Kampragou, et al., 2011)

The systematic processes of continuously improving management policies and practices by learning from the outcomes of previously applied management strategies are known as *adaptive management* (Pahl-Wostl, 2007). Although neither the concept of adaptive management itself nor its implementation in natural resources management are new (Stankey, et al., 2005), but the current level of water adaptive management, globally, has definitely to upgrade in order to meet the recent and foreseeable challenges.

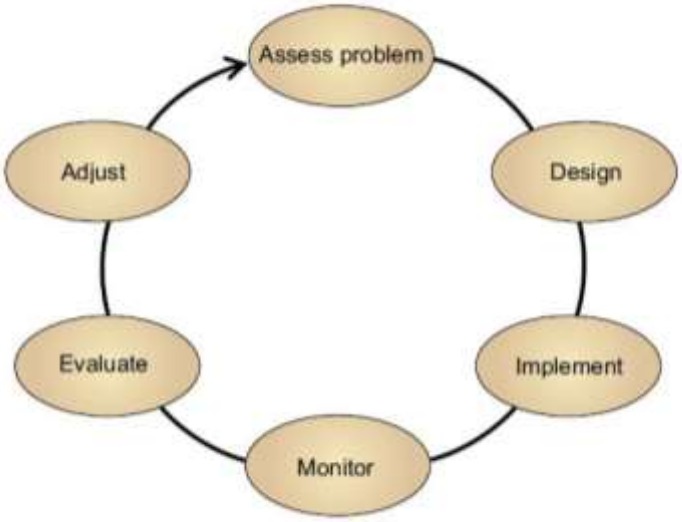


Figure 2-2: Adaptive Management Cycle
Source: (Williams, et al., 2012)

Such upgrade has to be based on a comprehensive shift towards participatory management and collaborative decision making. This necessarily means engagement of all related beneficiaries, decentralized management system (including open and shared information sources), higher attention towards the social aspects, consideration of the environmental issues as priorities, reliance on iterative learning cycles (figure 2-2) integrated with the overall management approach (Pahl-Wostl, et al., 2008).

2.2 Water (Re)allocation Policies

A researcher can find many literature about the impacts of water (re)allocation policies covering different aspects. For example, (Seung, et al., 1997) and (Seung, et al., 2000) analyzed the economic impacts of transferring surface water from irrigated agriculture to recreational use using basically the Computable General Equilibrium (CGE) model. Also, (Fang, et al., 2006), (Juana, et al., 2011), (Qtaishat, 2013) and (Qin, et al., 2013) analyzed the impact (negative and/or positive) of water reallocation from agriculture to other sectors (urban, industrial, etc...) on the economy and household income in different regions. Whereas, (Rosegrant, et al., 1999) investigated the potential impacts of water transfers from agricultural to urban and industrial areas on global food supply and demand. They found that comprehensive reforms are required to mitigate the potentially inconvenient impacts of water transfers for local communities and to sustain crop yield and output growth to meet increasing food demands at the global level.

In addition, (Bjornlund, et al., 2011) approached the same issue of reallocation irrigation water from another perspective. They investigated the acceptance of this matter and whether such acceptance differs between urban and rural residents. They concluded that urban inhabitants are more likely to prefer government intervention while rural inhabitants are more likely to support policies that aim to protect farmers' water rights. They also found that people, both in urban and rural areas, can be categorized into three categories depending on their attitudes towards water and the environment: 1) pro-environment; 2) pro-economic; and 3) undecided. In the same context, (Savenije , et al., 2009) argued from different perspective about water pricing which should primarily serve the purpose of financial sustainability through cost recovery in addition to necessarily adequate attention for equity considerations. On the other hand, (Fielding, et al., 2012) made huge effort to promote water conservation in the field experimentally. They reported an experimental study to test the long-term impact of three different interventions on household water consumption. Also, (Araral, et al., 2013) and (Tortajada, et al., 2013) focused on the important issue of public participation, where water conservation requires the engagement of the public and private sectors as well as of the society at large.

Regarding the environmental impacts of water (re)allocation policies, (Colby, et al., 1991) argued about the continuity of water reallocation to reflect environmental benefits alongside the traditional uses of water. They presented some examples from the American recent history about changes on water allocation, forced by law, to mitigate hazards threatening the nature. Also, (Howe, et al., 1986) discussed about the shortcomings of water users, especially related to quantity and quality return flow effects, confirming that they can be minimized through changes in the administrative framework of the water rights system. They proved that an efficient water allocation system must integrate quantity and quality management. Furthermore, (Weber, 2001) modeled a suggested optimal allocation of surface water and pollution rights along a river with water quality constraints in order to answer the question of whether it is possible to maintain water quality under a certain alternative mechanism for allocating surface water and pollution rights.

2.3 Water Use Efficiency

The approaches of water use efficiency estimation are varied. Starting from Classical Efficiency (CE), which is defined as the percentage of the water consumed to the total water abstracted. Pioneered publications that included this concept in irrigation were (Israelsen, 1932) and (Israelsen, 1950). In fact, CE in irrigation has been used worldwide for decades up to recently. Later, further publications went more in depth in this regard such as (Feddes, et al., 1978) in their book about which deal with the theory of field water use and of crop production, and more technically (French, et al., 1984) who investigated the relations between the crop of wheat yield and water use. Anyhow, it is worth mentioning here that (Burt, et al., 1997) presented a quite comprehensive definition and approach of CE in irrigation during their presentation and evaluation of irrigation performance indicators.

Moreover, the water use efficiency in irrigation gained most of the attention among authors recently, going more in depth technically from engineering perspectives. For instance, (Onta, et al., 1995) developed and applied an optimization model for an irrigation system for land and water allocation during the dry season in order to obtain optimum cropping patterns for different management strategies. Similarly, (Small, et al., 1996) evaluated under varying degrees of water shortage, using a simulation model, the irrigation performance implications of alternative water distribution rules for dry season. Within this context, (Howell, 2001) discussed the concept of enhanced CE in irrigation and its impacts on water conservation from different viewpoints. In order to approach enhanced water efficient use in irrigation, he recommended increasing the output per unit of water and reducing water losses to unusable sinks (engineering aspects), reducing water degradation (environmental aspects), and reallocate water to higher priority uses (societal aspects). One last example, (Gohar, et al., 2011) evaluated the potential economic benefits that can be supported by Egypt's irrigation water use by developing an integrated catchment scale framework.

However, considerable literature could be found discussing and proving the shortcomings and coverage inadequacy of CE, and others has been working on developing more comprehensive efficiency or performance indicators. (Jensen, et al., 1980) were among the firsts to highlight the misapplication of CE in resource development due to the absence of the irrigation water recovery. Furthermore, (Willardson, et al., 1994) and (Allen, et al., 2005) emphasized the necessity of improving the definition of water use efficiency for a better water management, where they discussed in their works terms such as evaporated, reusable, non-reusable and consumed fractions.

Hence, important contributions aiming toward a more comprehensive and complete understanding of water use efficiency and water system performance evaluation started taking place in the last two decades. An explicit example about this transition is Irrigation Sagacity (IS), which is defined as the ratio of irrigation water beneficially and reasonably used to the total irrigation water applied. This new efficiency term (IS) was presented in (Kruse, 1978) and very well organized and developed in (Solomon, et al., 1999). Nevertheless, (Keller, et al., 1995) introduced a thorough concept into the knowledge and understanding of water use efficiency in order to overcome the limitations of CE, which is Effective Efficiency (EE). They defined EE as the irrigation water consumed (evaporated) by crops divided by the effective use of water (the effective inflow minus the effective outflow).

The major step forward in (Keller, et al., 1995) definition and approach is the ability of its application on other uses of water and other measures of change in water quality or value, in other words, the inclusion of water quality dimension. This important inclusion, which came after solely quantitative approaches of water use efficiency, paved the road to other significant contributions in this regard. Later, (Haie, et al., 2008) developed EE models based on water quantity and quality, with the possibility of considering water reuse (recycling), for two scales (the first is called Project EE and the second is called Basin EE). They compared then between CE and EE results and found that CE values were less than EE due to water reuse absence in calculations. Hence, the real importance of their paper comes from their defense favoring EE versus CE, especially after the increased voices among researchers advocating the use of different concepts instead of efficiency concepts.

Finally, quite recently, (Haie, et al., 2012) made another major step forward by incorporating a third dimension to the definition of water use efficiency, which is the beneficence of water use. They employed the concept of water balance, based on conservation of mass, to develop three levels of composite efficiency indicators (macro, meso and micro levels). That was done through the definition of Usefulness Criterion, which they defined as the product of quality and beneficence weights assigned to the quality and the beneficial attributes of water use. The authors continued their efforts with another informative publication (Haie, et al., 2014) in order to better describe and, at the same time, examine the terminology associated with water use efficiency. Also, they proposed in their last paper integrated terminologies, starting from flow-path types in water balance and expanded into the three level efficiencies formulation.

3 METHODOLOGY

To achieve the predefined objectives of this work, a comprehensive methodological framework has to be set up. This will be conducted by dividing the work progress into five main parts as previously listed in the objectives. In order to better manage the work progress, each part will be completed through carrying out one or more clearly defined task(s). This chapter provides the detailed description of each part of this framework.

3.1 WS Alternatives

The water system (WS) in this work indicates a geographical area that has defined boundaries, water source(s), water users (beneficiaries) and inflow/outflow water paths. For the purpose of applying the methodological framework, choosing the WS at the beginning is vital in order to achieve the rest of the objectives. A selection process among three alternatives will be carried out based on the following criteria:

- Data availability and accessibility
- Water value
- Complexity of water issues

The three alternatives are: 1. Guadiana River Basin, Spain & Portugal; 2. Eastern Aquifer basin, West Bank, Palestine; and 3. Sacramento River Basin, California State, USA. Following is a brief description about each of them.

It is important to mention here that choosing any basin of the three listed here as WS does not necessarily mean considering the entire basin as the system. Only specific representative location within the geographic boundaries of that basin will be considered in order to have more reliable analysis and results.

Alternative 1: Guadiana River Basin

Located in the southernmost part of Europe (figure 3-1), the Guadiana River basin occupies an area of about $68{,}800\ km^2$ (83% in Spain and 17% in Portugal). The climate in its region is semiarid, with an average precipitation of about $450\ mm/year$, which is significantly less than the national mean annual precipitation (Aldaya, et al., 2008). The basin is one of the three main drainage units of the Iberian Peninsula (in addition to Duoro and Tejo). The source is in Spain, which has the largest storage capacity among the two countries, before flowing into Portugal (McEvoy, et al., 2008).

The Portuguese part of the Guadiana extends across the Alentejo and Algarve regions, which are significantly important regions for agriculture and tourism in Portugal. However, in that region, the primary water use sector is agriculture, with about 95% of total water demand in the entire basin. Relatedly, regarding the water economic productivity, (Aldaya, et al., 2008) concluded – in their analysis of the water footprint for the river basin – that urban and industrial water values are higher than the corresponding value in agriculture. Keeping in mind that the multifunctional value of agriculture has to be considered. Nevertheless, they also concluded that agricultural productivity (ton/ha) and total production ($ton/year$) of rainfed agriculture, however, are notably lower than that of irrigated agriculture. Hence, these facts give clear indications about the potentials of better manage and reallocate the Guadiana waters.

Figure 3-1: Location of Guadiana River
Source: (McEvoy, et al., 2008)

In fact, the continues changes in the natural hydrological system, in the form of dams, illegal dwells and increasing urbanization pressures within the Guadiana River basin in the last decades have caused growing problems with water scarcity along the Portuguese-Spanish border. Local stakeholders are beginning to realize that climate change may lead to opposing impacts on the human activities in the region. Portuguese governmental reports emphasize that Sado and Guadiana show up as the river basins with more vulnerability to climate change. In addition, global climate change models estimate a 60% potential decrease in annual runoff by 2100. Water shortages, summer drought and sand desertification are very likely to increase. Hence, the necessity of having adequate and comprehensive water management is of crucial importance for the future of water resources in that region (Cots, et al., 2007).

Alternative 2: Eastern Aquifer Basin

Groundwater is the water found underground in the cracks and spaces in soil, sand and rock. It is stored in and moves slowly through geologic formations of soil, sand and rocks called aquifers (The Groundwater Foundation, 2014). Groundwater is the primary source of water for Palestinians in the Occupied State of Palestine (OSP) (i.e. West Bank and Gaza Strip) and provides more than 90% of all water supplies. The main aquifer systems can be divided into four distinct units; the Western Aquifer Basin, the North-eastern Aquifer Basin and the Eastern Aquifer Basin for the West Bank, and the Coastal Aquifer for Gaza (PWA, 2012).

Figure 3-2: Palestinian Aquifers
Source: (UNEP, 2002)

The Eastern Aquifer is located on the eastern part of the West Bank as shown in figure 3-2. According to the Palestinian Water Authority (PWA), the area of the Eastern Aquifer is $2.9\ Km^2$, which is about 51.3% of the total area of the WB. The Eastern Aquifer basin is divided into three main sub-aquifers; namely the Mountainous Heights, Northeastern Tip and Jordan Valley. The annual yield of this basin varies from 145 to $185\ MCM/year$. However, the Palestinians utilized about $42\ MCM/year$ from groundwater wells and springs in 2011 (PWA, 2012).

Lack of access to adequate, safe, and clean water has been one of the most serious issues for the Palestinians since several decades. Related with the Israeli-Palestinian conflict, the Israeli water policies and practices, which are proven to be discriminating against the Palestinian, magnified the problem greatly (World Bank, 2009). In fact, Israel controls access to water resources by Palestinians. It restricts the amount of water available to Palestinians to a level which does not meet their minimum needs and does not constitute a fair and equitable share of the shared water resources (Amnesty International, 2009).

Hence, water is not only scarce in that part of the globe, it is also politically significant. Therefore, especially when the uncertainty incorporated with future scenarios regarding the potential changes of water resources is considered, water resources management there is a serious task indeed. The stability and welfare of the entire region is directly connected to the best possible water allocation between the two countries.

Alternative 3: Sacramento River Basin

California State, located in the southern part of the west coast of the United States of America is the most populous state with $38.3\ million$ population and $423{,}970\ km^2$ area (3rd largest) (U.S. Census Bureau, 2013). California's economy is strong enough to the level of competing the Great Eight (G8) countries. California, Italy and the Russian Federation were in a virtual tie in 2012 for eighth-tenth place in the world rankings with a gross domestic product (GDP) of $2.0\ trillion\ USD$ (CCSCE, 2013), which is 13.2% of the United States gross domestic product (GDP) (U.S. BEA, 2014).

In fact, CA has been the nation's top agricultural state in cash receipts every year since 1948 (Bervejillo, et al., 2002). To indicate its dominance in agriculture, it is enough said that more than $99\ percent$ of the following agricultural products in the US are provided by California: almonds, artichokes, dates, figs, raisins, kiwis, olives, pistachios, prunes, and walnuts. It is also the leading state in producing asparagus, broccoli, carrots, grapes, hay, lemons, lettuce, milk, peaches, strawberries, and processing tomatoes, among many others (Bervejillo, et al., 2002).

MULTI-YEAR DROUGHTS OF LARGE-SCALE EXTENT SINCE 1900

1918–1920
1923–1926
1928–1935
1947–1950
1959–1962
1976–1977
1987–1992
2000–2002
2007–2009

California's climate is highly variable both spatially (from temperate rain forest conditions on the North Coast to the extreme aridity of Death Valley) and temporally. Records for maximum annual precipitation range from more than $2280\ millimeters$ on the North Coast to a little over $50\ millimeters$ in Death Valley. Droughts and floods can occur in close proximity. For example, the flooding of 1986 was followed by six years of drought (1987-92) (California Department of Water Resources, 2014).

Drought played a role in shaping California's early history, as the so-called great Drought in 1863–64 contributed to the demise of the cattle rancho system, especially in Southern California. Subsequently, a notable period of extended dry conditions was experienced during most of the 1920s and well into the 1930s, with the latter time including the Dustbowl drought that gripped much of the United States. Three twentieth century droughts were of particular importance from a water supply standpoint – the droughts of 1928–35, 1976–77, and 1987–92 (California Department of Water Resources, 2012).

What makes the situation even worse is the fact that the water footprint of the average Californian is $5{,}678\ liters/day$ ($1{,}500\ gallons/day$), slightly less than the average American but considerably more than the average resident in other developed countries or in the rest of the world. More than 90% of California's water footprint is associated with agricultural products: meat and dairy products have especially large water footprints due to the water-intensive feed required to raise the animals (Pacific Institute, 2014).

The Sacramento River Basin occupies nearly $70{,}000\ Km^2$ in the north central part of California (figure 3-3). The river is the largest in California, with an average annual runoff of $27\ billion\ m^3$ (Domagalski, et al., 1998). Between 2005 and 2010, the region supported about $1.95\ million\ acres$ of irrigated agriculture on average. While the gross value of agricultural production in the Sacramento Valley for 2011 was about $4.1\ billion\ USD$ (California Department of Water Resources, 2014).

Figure 3-3: Sacramento River Basin
Source: (Domagalski, et al., 1998)

3.2 Characterizing the WS

As mentioned earlier, a water resources system has known boundaries, water source/s the system relies on (e.g. a river, lake, groundwater well), water users (beneficiaries) and inflow/outflow water paths (water paths' variables). A conventional WS might be a farm, a town, an entire river basin or even a subbasin. However, in order to characterize the WS, distinction has to be made between the different characteristics of water: quantity, quality and beneficence. Regardless the type of the system and regardless the numerical amount of the variables, each WS has to have these characteristics.

3.2.1 Water Quantity

The main component of characterizing the WS is to determine the amounts or quantities of water paths' variables flowing into or out of the WS under consideration. Typically, as illustrated in figure 3-4, the water abstracted from the source/s and precipitation form the main inflow paths, while the return flow, evapotranspiration and the nonreusable waters form the main outflow paths. Distinction between the flows of both directions has to be made due to the obvious differences regarding the calculation methods, quality and beneficence of each path.

- **Total Inflow:**
  - Precipitation (PP): the amount, usually expressed in millimeters or inches of liquid water depth, of the water substance that has fallen at a given point over a specified period of time (American Meteorological Society, 2012). PP amounts are calculated through using isohyetal maps (e.g. figure 3-5) for the area under consideration, which are maps of lines connecting points of equal precipitation depth (averages of known time period).

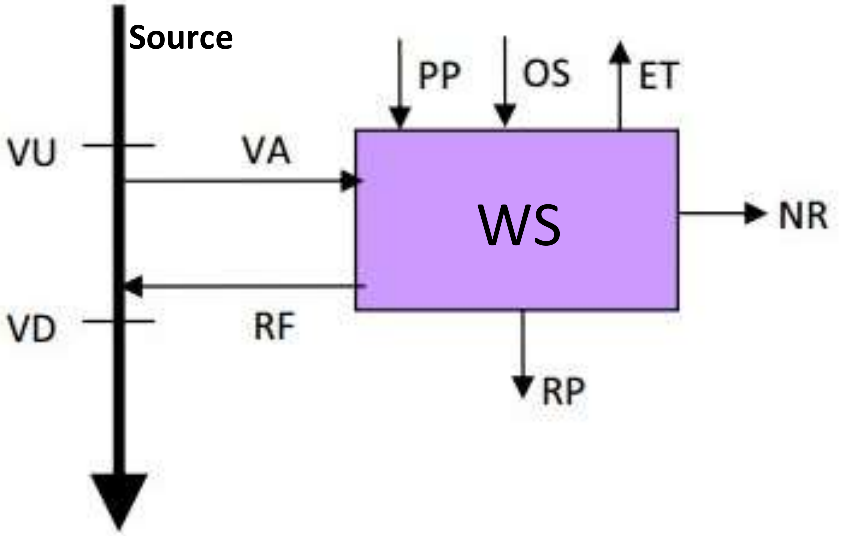


Figure 3-4: Water Flow Paths Diagram
Source: (Haie, et al., 2012)

Figure 3-5: Isohyetal Map Example

  - Abstracted Water (VA): the amount of water abstracted from the main water source/s of the system. Such amounts are usually known (measured) by water authorities. Alternately, the volume of water upstream before abstraction (VU) can replace VA, regardless the type of water source.
  - Other Sources (OS): any abstracted water from sources other than the main source.

- **Total Outflow:**
  - Evapotranspiration (ET): the combined processes through which water is transferred to the atmosphere from open water and ice surfaces, bare soil, and vegetation that make up the earth's surface (American Meteorological Society, 2012). ET estimation is of high complexity due to the variety of the included variables. However, Penman Method (PM), illustrated in FAO Irrigation and Drainage Paper 56 by (Allen, et al., 1998), will be used for ET estimation.

    To estimate the reference ET (ET_o), which is the evapotranspiration rate of a referenced crop (usually alfalfa) at standard meteorological conditions, the PM equation is:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad \text{Eq. (3.1)}$$

Where[*1]:

ET_o: Referenced evapotranspiration in $mm.day^{-1}$
R_n: Net radiation at the crop surface in $MJ.m^{-2}.day^{-1}$
G: Soil heat flux density in $MJ.m^{-2}.day^{-1}$
T: Mean daily air temperature at 2 m height in °C
u_2: Wind speed at 2 m height in $m.s^{-1}$
e_s: Saturation vapor pressure in kPa
e_a: Actual vapor pressure in kPa
$e_s - e_a$: Saturation vapor pressure deficit in kPa
Δ: Slope vapor pressure curve in $kPa.°C^{-1}$
γ: Psychrometric constant in $kPa.°C^{-1}$

Then, to convert ET_o to actual crop ET (ET_c), the crop coefficient approach is going to be used:

$$ET_c = K_c \times ET_o \qquad \text{Eq. (3.2)}$$

Where:

ET_c: crop evapotranspiration in mm.day^{-1}
K_c: crop coefficient (dimensionless)

The crop coefficient, K_c, is basically the ratio of the crop ET_c to the reference ET_o, and it represents an integration of the effects of four primary characteristics that distinguish the crop from reference grass. The crop coefficient integrates the effect of characteristics that distinguish a typical field crop from the grass reference, which has a constant appearance and a complete ground cover. Consequently, different crops will have different K_c coefficients. The changing characteristics of the crop over the growing season also affect the K_c coefficient. Finally, as evaporation is an integrated part of crop

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[*1] Further details about the equations to calculate other variables in the ET_o equation can be found in the source (Allen, et al., 1998).

evapotranspiration, conditions affecting soil evaporation will also have an effect on K_c (Allen, et al., 1998).

- Return Flow (RF): amount of water that returns to the main source. Such amount might be in the form of runoff, infiltration (to groundwater wells) or wastewater. Estimation the RF depends on the form of it, which by itself varies from a WS to another. Alternately, in case of using VU as a type of inflow, the volume of water downstream after the occurrence of the return flow (VD) can replace RF, regardless the type of water source.
- Potential Return (RP): similar to RF but returns to an outlet other than the main source.
- Nonreusables (NR): the amount of water that does not return nor evaporate, which is used to maintain the conservation of mass.

It is important to keep in mind the consistency of units for all variables. For example: volume, depth, percentage or fraction (Haie, et al., 2012).

3.2.2 Water Quality

Water quality variables are of high complexity due to the variety of conditions under consideration from physical to chemical and biological conditions. Moreover, the quality dimension is not only about the quality of water and the system that water flows through, but also the level of toleration for a design quality, which is a management decision (Haie, et al., 2012). Hence, it is highly important to simplify the method of dealing with quality using reliable classification methods.

Water quality is a qualitative characteristic that is usually indicated by a lot of field or lab tests and measurements. A quantification approach is needed to indicate it when measuring the performance of a WS. Hence, the water quality index (WQI) approach will be used. The WQI is a single number that expresses water quality by aggregating the measurements of water quality parameters (such as dissolved oxygen, pH, nitrate, phosphate, ammonia, chloride, hardness, metals etc.). Usually the higher score alludes to better water quality (excellent, good) and lower score to degraded quality (bad, poor). The index provides a simple and concise method for expressing the quality of water bodies for varied uses such as recreation, swimming, drinking, irrigation, or fish spawning, etc. The significance of the WQI can be easily appreciated as the water resources play a crucial role in the overall environment (Lumb, et al., 2011).

In fact, the Canadian water quality guidelines (CWQGs) of the Canadian Council of Ministers of the Environment (CCME) presented in 2001 an index called the Canadian Water Quality Index (CWQI) that is still used until nowadays (CCME, 2001). It has also been endorsed by United Nations Environmental Program (UNEP) in 2007 as a model for Global Drinking Water Quality Index (GDWQI) (Lumb, et al., 2011).

It is well documented and explained in the CCME 2001 guideline that conceptually CCME WQI comprises three factors as illustrated in figure 3-6. First, F_1 deals with the **scope** that assesses the extent of water quality guideline noncompliance over the time period of interest. Second, F_2 deals with **frequency** i.e. how many occasions the tested or observed value was off the acceptable limits (objective) or the yardsticks. The third factor, F_3 deals with the **amplitude** of deviation or, in other words, the number of tests by which the acceptable limits are exceeded (CCME, 2001). Following is a detailed explanation about the calculation process of the three factors (F_1, F_2 and F_3) and the final result of CCME WQI:

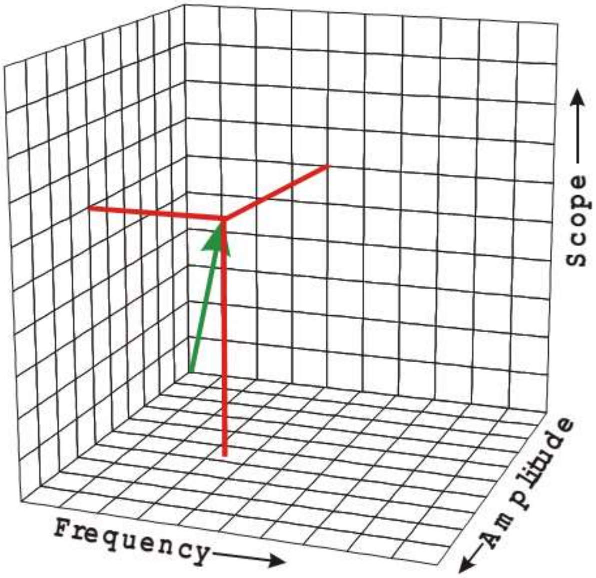


Figure 3-6: Conceptual Model of CCME WQI
Source: (CCME, 2001)

F_1 and F_2 are calculated according to their definition in the following equations:

$$F_1 = \left[\frac{No. of\ failed\ variables}{Total\ no. of\ variables}\right] \times 100 \quad \text{Eq. (3.3)}$$

$$F_2 = \left[\frac{No. of\ failed\ tests}{Total\ no. of\ tests}\right] \times 100 \quad \text{Eq. (3.4)}$$

F_3 is calculated in three steps. The first step is to calculate the number of excursions, which are the number of times by which an individual concentration is greater or less than the objective. For cases in which the test value must not exceed the objective:

$$excursion_i = \left[\frac{FailedTestValue_i}{Objective_j}\right] - 1 \quad \text{Eq. (3.5a)}$$

For cases in which the test value must not fall below the objective:

$$excursion_i = \left[\frac{Objective_j}{FailedTestValue_i}\right] - 1 \quad \text{Eq. (3.5b)}$$

The second step is to calculate the normalized summation of excursions as the following:

$$nse = \frac{\sum_{i=1}^{n} excursion_i}{No. of\ tests} \quad \text{Eq. (3.5c)}$$

Then, the third step is to calculate F_3 by an asymptotic function that scales the normalized summation of the excursions from objectives (nse) to yield a range between 0 and 100:

$$F_3 = \left[\frac{nse}{0.01 nse + 0.01}\right] \quad \text{Eq. (3.5d)}$$

Finally, after calculating the three factors, the CCME WQI can be calculated by the following equation:

$$CCME\ WQI = 100 - \left[\frac{\sqrt{{F_1}^2 + {F_2}^2 + {F_3}^2}}{1.732}\right] \qquad \text{Eq. (3.6)}$$

The constant of 1.732 has been introduced to scale the index from 0 to 100. Equation 3.6 produces a value of CCME WQI between 0 and 100 (which will be divided later by 100 to make it from 0 to 1 in order to match the requirements of this study). A zero (0) value signifies very poor water quality, whereas a value close to 100 signifies excellent water quality. The water quality is ranked in the following five categories: excellent: 95-100; good: 80-94; fair: 65-79; marginal: 45-64; poor: 0-44 (CCME, 2001) and (Lumb, et al., 2011).

3.2.3 Water Beneficence

Water beneficence in this work, similar to quality, is indicated by a value representing its level, or in other words, how much beneficial is water in that flow path. These values or weight are basically management decisions. They are defined by the managers, consultants, and decision makers and depend on the specific priorities of the WS inhabitants.

Within this context, extensive studies and researches are needed to cover several aspect, including: political, economic, environmental and social analysis of water needs; impact assessments; health requirements diagnoses; surveys of public participation; and others. The results of these studies and researches are supposed to direct the managerial decisions of defining water beneficence weights. In fact, the weights should reflect the significance of water use of each water flow paths' variables and, indeed, they must be directed towards meeting the human, local, regional and global requirements of welfare and wellbeing.

However, this area of research is beyond the scope of this work. Therefore, the author will rationally assume the beneficence weights of water flow paths' variables by mental logic.

3.3 WS Performance

The process of measuring the WS performance is based on the general framework that (Haie, et al., 2012) suggested in their paper "*Macro, Meso, and Micro-Efficiencies in Water Resources Management: A New Framework Using Water Balance*". They developed performance composite indicators in order to determine efficiency using water balance, considering two types of total flows: total inflow and total consumption (using the two binary indices (i, c) (with values 0 or 1, and $i + c = 1$).

As previously explained, the preliminary steps are the definition of the WS and the quantitative, qualitative and beneficence characteristics. These quantity characteristics (shown in figure 3-4) are classified into two parts: (1) $total\ inflow = VA + OS + PP$; and (2) $total\ outflow = ET + RP + RF + NR$. The total inflow and total outflow variables should satisfy the water balance principle, as such ($total\ inflow - total\ outflow = \Delta$), where Δ is the change in water storage of a WS. This principle is based on the universal mass conservation equation that is defined for a time period (e.g. one year) in which Δ is assumed 0:

$$(VA + OS + PP) - (ET + RP + RF + NR) = 0 \qquad \text{Eq. (3.7)}$$

Where:

VA: Volume of abstracted water (or source upstream volume)
OS: Volume of water from other sources
PP: Precipitation
ET: Evapotranspiration
RP: Potential return
RF: Return flow (or source downstream volume)
NR: Nonreusable water

Classical efficiency is defined as the percentage of abstracted water consumed beneficially (Haie, et al., 2012). The word "consumed" has to be questioned because consumptive use is only a portion of the total water use, while the non-consumptive use is the other. Any use of water that causes a physical removal of water from the system making it unavailable for reuse is classified as consumptive. The evapotranspiration (ET) incurred during crop irrigation, golf course irrigation and lawn watering are typical examples, while vegetative growth (irrigated and unirrigated) is by far the dominant consumptive use indeed (Frederiksen, 1992). This term (consumptive use) has a special significance in water resources and irrigation management (particularly in real-water saving), therefore, Haie, et al., 2012, considered this type of total flow in addition to the total inflow.

The total inflow type is considered when $(i, c) = (1, 0)$, while the total consumption type is considered when $(i, c) = (0, 1)$. $S_{efficiency}$ is going to be calculated considering each type of flow apart in order to highlight the differences between two types of conservation practices: (1) abstraction savings (S_A); and (2) consumptive savings (S_C). According to (Haie, et al., 2008), S_A is a reduction in water diversion (abstraction or withdrawal) from its source such as a river, while S_C is a reduction in the water permanently removed from the river basin. Reducing total inflow of water through S_C or S_A mechanisms is crucial in developing a sustainable system, while properly implementing both of these two types of saving (parallel to the two types of water total) will probably result many benefits for the WS.

Indeed, the classical efficiency definition, as many scholars proved, has to be upgraded to be more comprehensive. The distinct remark about this framework, which makes it favorite over the other efficiency estimation approaches, is the inclusion of water quality and beneficence dimensions. The quality value (W_{q_X}, X being any of the water paths) and the beneficence value (W_{b_X}) are expressed by weights (between 0 and 1 with 0 being its "worst" state). Having these dimensions defined, then the useful part of a variable, designated with a subscript ''s'' and called *Usefulness Criterion*, is the product of both dimensions, indicating the equally high significance attached to both of these aspects (Haie, et al., 2012). Hence:

$$s = W_{q_X} \times W_{b_X} \qquad \text{Eq. (3.8)}$$

And,

$$X_s = W_{q_X} \times W_{b_X} \times X \qquad \text{Eq. (3.9)}$$

Finally, using the equations derived, efficiency can be calculated at three different levels: Macro, Meso, and Micro-Efficiencies (3ME). Actually, Macro-Efficiency ($MacroE$) is used to indicate the impact of a WS on a basin, for example the major river where water was abstracted, while Meso-Efficiency ($MesoE$) is related to a situation between micro and macro levels indicating, for example, the impact of return flows generated by a WS. However, Micro-Efficiency ($MicroE$) is used to indicate the useful outflow generated by a WS for itself (Haie, et al., 2012).

Therefore[*2]:

$$\boldsymbol{MacroE} = \left[\frac{\boldsymbol{ET + NR + i(VD + RP)}}{\boldsymbol{VU + OS + PP - c(VD + RP)}}\right]_{\boldsymbol{s}} \qquad \text{Eq. (3.10)}$$

$$\boldsymbol{MesoE} = \left[\frac{\boldsymbol{ET + NR + i(RF + RP)}}{\boldsymbol{VA + OS + PP - c(RF + RP)}}\right]_{\boldsymbol{s}} \qquad \text{Eq. (3.11)}$$

$$\boldsymbol{MicroE} = \left[\frac{\boldsymbol{ET + NR}}{\boldsymbol{VA + OS + PP}}\right]_{\boldsymbol{s}} \qquad \text{Eq. (3.12)}$$

These equations will be applied on the defined water variables of the selected WS in order to determine the multi-level performance indicators of the system.

[*2] Derivation of the equations starting from the equation of water balance (3.7) can be found detailed in the source (Haie, et al., 2012)

3.4 (Re)allocation Policies

Allocation or reallocation policies of water resources are subjected to a prioritization or trade off process between three main competing sectors, which are: agriculture, urban/industry, and nature. Also, this process could be pursued between the different water flow paths' variables within one of those mentioned sectors. The objectives of the allocation or reallocation policies is to: 1. Satisfy all, or at least the most possible, of water sectors' demands; and 2. Achieve the highest possible water use efficiency and WS performance according to these policies.

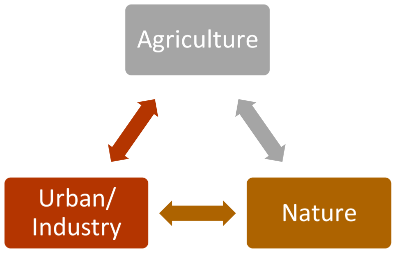


Figure 3-7: Priority Triangle

For example, as in most of the developed countries, the agricultural sector uses the most quantity of the available water. Serious questions should be addressed about the effectiveness of their use. The answers of such questions pave the roads to the discussions and research about the advancement of the irrigation adopted. However, in other countries, especially the developing ones, the allocation of water in agriculture at the expense of the residential demands should always be under evaluation. Moreover, the ecological concerns regarding water contaminating have to be always addressed due to their major effects.

Policies are set up and decided by stakeholders/leaders. In many cases, interests of water competitors intersect or conflict in a way that affects the performance of the WS. The major significance of the indicator presented in this work is the ability to represent and include these interests in the resulted indicator. Anyhow, in such a changing world, mostly by our own hands, water (re)allocation policies are demanded to be on the reliable level to meet all the human requirements of water use, and to face and mitigate any future potential threat.

4 APPLICATION

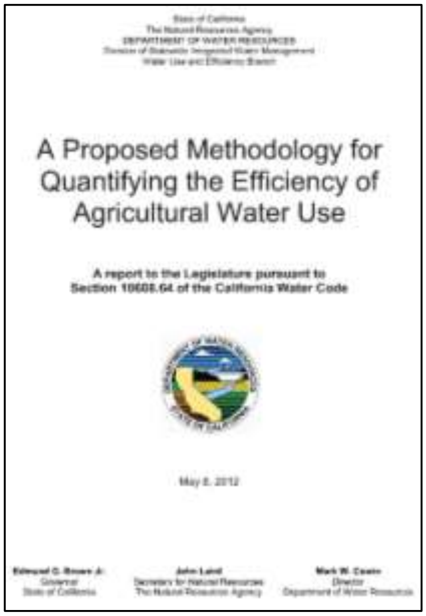
After setting up and illustrating the methodological framework of this study, this chapter will cover the application of it. This will be done by selecting a WS, as an initial step, in order to implement the remaining steps of the process. The progressive steps of the application chapter will follow the same order of the previous one (chapter 3: Methodology) in order to have a well-structured and comprehensive workflow.

4.1 WS Selection

As previously mentioned, the selection is based on data availability; water value; and complexity of the issue. It is important to remember here that choosing any basin of the three listed here as WS does not mean considering the entire basin as the system. Only specific representative portion of the basin will be considered in order to have more reliable analysis and results.

- Taking the first criterion (data availability) under evaluation, what is assumed to consider data as available is: accessibility (online, necessity to travel, etc…); understandability (in terms of language); and to be from an accredited source. Most of the accessible data found regarding the first alternative (Guadiana River basin) were written in either Spanish or Portuguese languages, at which the researcher faces difficulties dealing with. When it comes to the second alternative (Eastern Aquifer basin), online accredited data sources were very limited, which makes traveling necessary. In contrast, enormous amount of several types of data from accredited sources are accessible online covering the entire State of California (alternative 3).
- Regarding the second and third criteria, as briefly described about each alternative, the current and projected water values and the complexity of water issues in each area are crucially high. The significance of the agriculture in Guadiana River basin, the drought which this area is suffering, in addition to the climate change projections are all enough reasons to realize how much water is valuable and the situation is complex there. Similarly, Sacramento River basin area has the same reasons to consider, with even higher monetary values of the agricultural sector in that part of the world. The situation is somehow different in the Palestinian Eastern Aquifer basin area, where the value goes high enough to touch the human level. However, many political complex interventions play significant role in water issues there, which is an undesirable case for this type of researches to go through.

Hence, based on the evaluation of the three criteria, the researcher, with the assistance of his supervisor, has chosen the third alternative: **Sacramento River basin** area as a water system in order to implement the study and achieve the rest of the work's objectives.



A Proposed Methodology for
Quantifying the Efficiency of
Agricultural Water Use

A report to the Legislature pursuant to
Section 10608.64 of the California Water Code

May 8, 2012

Figure 4-1: WDR 2012 Report Cover Page

Although data acquisition for the basin as a system is possible in order to measure the $S_{efficiency}$ at the basin level, but to simplify the implementation process and to be closer to real cases scenario, this study would rather consider a smaller scale. Thus, the case presented in the Department of Water Resources (DWR) of California report (figure 4-1): "A Proposed Methodology for Quantifying the Efficiency of Agricultural Water Use. Appendix C: Calculation Examples of Water Use Efficiency Quantification" will be used for the quantitative characterization of the WS.

The report is prepared by DWR – in consultation with the California Agricultural Water Management Council, academic experts, and other stakeholders – after the direction of the Water Conservation Act of 2009 (Senate Bill X7-7). It proposes a methodology to evaluate current conditions and strategies for improving agricultural water management on the diverse array of agricultural irrigation systems and operations found throughout California (DWR, 2012). Importantly, the examples illustrated in that report consider data extracted from irrigated areas in Davis city, Yolo County, CA (figure 4-2).

Figure 4-2: Davis City and Yolo County

However, concerning the qualitative characterization of the WS, the DWR offers in its online water data library an enormous water quality data set. This set includes results records of experimental tests of water quality elements performed in many stations distributed all over the state of California. Data of some stations are recorded since several decades ago.

4.2 WS Characteristics

The characteristics of the selected WS are presented in this section according to the previous description in section 3.2. The agricultural nature of the system implies specific theme of its characteristics. For example, in this system, ET has major importance that will be represented in its high values (both quantity and beneficence). On the other hand, other variables, such as RP will not have as much importance as in other types of water systems.

As previously mentioned, the numbers presented here are extracted from the examples listed in appendix C in the DWR 2012 report. According to the report, these are not completely real-case numbers, but they are decent representative estimations of water paths' variables of a regular farmland area in central California (where Davis, Yolo County is). However, further explanation about this matter can be found in the following elaboration of the selected system's quantitative, qualitative and beneficence characteristics.

4.2.1 Quantitative Characteristics of the WS

The initial and primary step of characterizing the WS is to allocate the quantities of each water paths' variables. These variables, which are previously described in subsection 3.2.1, are complex to estimate and differ from a WS type to another. In the case of the selected WS, which is an irrigated tomato farms area, the major inflow is the water abstracted from the main source, Sacramento River, while the major outflow is the water consumed in the form of ET.

As expected, the raw data found in the DWR 2012 report are presented in a different structure than the one explained previously in this study, and in US customary units. However, these raw data will be restructured, edited and converted into metric units in order fit the used structure and equations of this study. Following is an elaboration of this process.

Raw Data Editing and Conversion:

The calculations of a seasonal crop water balance for a tomato crop grown at Davis, California is shown below. Most of the raw data are extracted from the DWR 2012 report, unless otherwise stated.

- First of all, the supplied water is diverted from Sacramento River at a section near the area of Sacramento Weir that leads to Yolo Bypass, which is considerably close to the area of interest as described in the DWR 2012 report. In fact, a DWR station for discharge gauging is located there, while all the recorded data (since long time ago) of the daily flow of Sacramento River Delta[*3] area could be found in the DWR online data library. However, after accessing the data of that station and accumulating the values for 2010 water year (the year of interest in the

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[*3] Yolo County is one of the five counties (Contra Costa, Sacramento, San Joaquin, Solano, and Yolo) encompassing the Sacramento-San Joaquin Delta, which have formed the Delta Counties Coalition (Sacramento River Delta, 2012).

presented case), **the resulted diverted flow rate from Sacramento River to Yolo County equals $\boldsymbol{579,181\ af\ per\ year}$ $(\boldsymbol{714.40\ MCM/year})$.**

Hence, based on these available data and the assumption that the area of interest in Davis city delivers its water from Yolo's share of Sacramento River, **the value of VU equals $\boldsymbol{714.40\ MCM/year}$.**

- Water supplies $45{,}000\ acres = 182.11\ Km^2$ of irrigated farmlands.
- Aggregate farm-gate deliveries $148{,}555\ af\ per\ year$ $(183.24\ MCM/year)$. This estimate is provided by water supplier in monthly measured billings.

  Hence, $\boldsymbol{VA = 183.24\ MCM/year}$
- Concerning evapotranspiration, a weighted mean K_c value of 0.82 for the periods of planting to harvest was used to represent tomato. For simplification, the values of K_c for the different periods within the growing season are represented as straight lines**. The cumulative $\boldsymbol{ET_o}$ value obtained from the CIMIS station at Davis for the cropping season is $\boldsymbol{2.92\ ft}$.**

  $ET_o = 2.92\ ft. = 890\ mm$

  $Weighted\ mean\ K_c = 0.82$

  $ET_c = ET_o \times weighted\ mean\ K_c$ (Equation 3.2)

  $= 2.92 \times 0.82 = 2.40\ ft. = 730\ mm$

  Therefore, the flow quantity of $ET = 2.40 ft \times 45{,}000\ acre = 108{,}000\ af\ per\ year$

  Hence, $\boldsymbol{ET = 133.22\ MCM/year}$
- $PP = 1.15\ ft. = 350.52\ mm$

  Therefore, the flow quantity of $PP = 1.15 ft \times 45{,}000 = 51{,}750\ af\ per\ year$

  Hence, $\boldsymbol{PP = 63.83\ MCM/year}$
- The agronomic use (AU) is defined by the report as the amount of applied irrigation water needed to meet leaching requirement of a tomato crop grown in Yolo County in 2010. Leaching requirements are determined by multiplying the volume of water that ET uses by the leaching factor (equation 4.1), which is defined as the ratio of the quantity of water draining past the root zone to that infiltrated into the soil's surface (WateReuse Foundation, 2007). Furthermore, an additional assumed amount of $2520\ af = 3.1\ MCM$ is considered for seedbed preparation.

$$LR = \frac{EC_i}{5(EC_e) - EC_i} \qquad \text{Eq. (4.1)}$$

Where:

LR: Leaching factor (dimensionless)

EC_i: Salinity of irrigation water in dS/m (deciSiemens per meter) = $1.10\ dS/m$ in Davis

EC_e: Soil salinity in dS/m. The EC_e for tomato at a 100% yield potential = $2.5\ dS/m$

Therefore:

$$LR = \frac{1.1}{5(2.5) - 1.1} = 0.10$$

And so,

$AU = (0.10 \times 2.40ft \times 45{,}000acre) + 2520 = 13{,}320\ af\ per\ year = 16.43\ MCM/year$

This quantity has the potential to percolate deep into the ground and replenish groundwater, which is not the main source. Hence, it will be considered as **RP** $= \mathbf{16.43}\ \boldsymbol{MCM/year}$

- Applying the water balance (equation 3.3), which is a primary condition, the remaining portion of the total delivered water:

  $(183.24 + 63.83) - (133.22 + 16.43) = 97.42\ MCM/year.$
- Based on the estimate of the acreage of non-cropped area, 20% is assumed to be used by non-crop plants that are not part of intentional environmental objectives. Therefore, $0.20 \times 97.42 = 19.48\ MCM/year$ are irrecoverable amount of water. Hence, **NR** $= \mathbf{19.48}\ \boldsymbol{MCM/year}$.

  Consequently, the portion remaining (80%) is considered returning as spills running off to the main source (the river). Therefore, **RF** $= \mathbf{0.80 \times 97.42 = 77.94}\ \boldsymbol{MCM/year}$.
- Finally, due to the unavailability of data about the water flow of the river at the section right after the area of interest (downstream), it would be impossible to estimate VD quantity based on actual measurements. Therefore, this quantity is theoretically estimated by subtracting the quantity of water abstracted (VA) from the quantity of river flow upstream (VU) and adding the quantity of the return flow (RF).

  Hence, $\boldsymbol{VD = VU - VA + RF = 609.10\ MCM/year}$.

Data Verification:

Both ET and PP are real data taken from accredited source (California Irrigation Management Information System (CIMIS)). Though, the DWR 2012 report clearly states: “None of the assumed quantities or percentages used in the examples necessarily represents acceptable default value”. The report writers mean by ‘the assumed quantities’ those amounts that has been estimated based on assumptions stimulated from a hypothesized scenario.

Indeed, it would be extremely difficult, within the scope of this work, to verify the validity of these assumptions. On the other hand, it is a fact that DWR, which is the primary official and governmental water management body in California, has hypothesized and used these assumption to explain their own proposed methodology for quantification the agricultural water use efficiency. Thus, this fact gives the author of this work enough confidence to rely on these assumptions.

Nevertheless, in order to somehow indicate the validity of the data presented in the report, the values provided for ET_o ($2.92\ ft.$) and PP ($1.15\ ft.$) will be verified. Starting with ET, CIMIS offers in its online data section enormous ET-calculation-related data. The data include measurements of all the variables that form PM equation for reference evapotranspiration (ET_o) calculation (presented in subsection 3.2.1). These measurements are recorded in many stations distributed all over the state of California since several years ago, while in some station, several decades ago. Davis city is where one of these stations locates, which is, obviously, the chosen station to extract data from. Davis station has: CIMIS ID = 6; region = Sacramento Valley; latitude = $38.535694°$; φ = $0.673\ rad$; and elevation = $18.3\ m$. Table 4-1 gives a sample of the raw data extracted from CIMIS online data section.

Date	Jul	**CIMIS ET$_o$ (mm)**	PP (mm)	Sol. Rad. (W/m^2)	Av. Vap. Pres. (kPa)	Max. Air T. (°C)	Min. Air T. (°C)	Av. Air T. (°C)	Max. Rel. Hum. (%)	Min. Rel. Hum. (%)	Av. Rel. Hum. (%)	Dew Pt. (°C)	Av. Wind Spd. (m/s)	Wind Run (km)	Av. Soil T. (C°)
7/1/2010	182	**6.45**	0	325	1.2	28.7	9.7	18.9	89	32	54	9.5	2.3	200.2	-
7/2/2010	183	**6.53**	0	333	1.2	30.7	11.4	20.6	79	29	51	10.2	2.1	179.3	-
7/3/2010	184	**9.05**	0	344	0.9	32.9	15.3	24.7	69	16	30	6.1	4	349.7	-
7/4/2010	185	**9.21**	0	347	1.1	35.2	16	25.7	67	14	32	7.7	3.7	323.7	19.9
7/5/2010	186	**7.24**	0	332	1.3	33.3	12.6	22.4	76	25	48	10.8	2.5	216.4	20.6
7/6/2010	187	**6.47**	0.1	331	1.3	28.4	12	19.3	81	41	60	11.4	2.6	228.5	20.8
7/7/2010	188	**6.47**	1.4	323	1.3	30.1	10.6	19.8	83	34	57	11	2.4	206.2	20.8
7/8/2010	189	**6.44**	0	317	1.4	30.8	12	20.2	79	38	58	11.6	2.5	216.3	20.9
7/9/2010	190	**6.53**	0	321	1.5	30.8	12.2	20.4	89	40	62	12.8	2.6	228.7	-
7/10/2010	191	**7.17**	0	331	1.5	36.7	12.6	23.1	85	18	53	12.9	2.4	206.6	20.1
7/11/2010	192	**6.83**	0	329	1.4	34.8	12.7	22.8	82	25	52	12.5	2	176.9	21.3
7/12/2010	193	**6.89**	0	323	1.4	30.7	13.6	21.1	80	34	55	11.8	3.3	284.9	21.6
7/13/2010	194	**6.12**	0	381	1.4	29.3	-	24.1	74	35	47	12.2	3	259.2	22.3
7/14/2010	195	**6.96**	0	343	1.2	33	13.6	23.2	75	18	43	10.1	1.9	165.2	22
7/15/2010	196	**7.38**	0	317	1.4	36.7	-	29.7	65	22	34	12.3	2.3	200.6	23.1

Table 4-1: Sample of CIMIS Raw Data
Source: (CIMIS, 2015)

These raw data need a lot of processing in order to achieve the variables that form equation 3.1 for calculating ET$_o$. The processing includes the calculation of $\Delta, R_n, \gamma, e_s, e_a, u_2$, and others, which is a massive task indeed. However, a Microsoft© Excel file is attached to this dissertation contains the detailed calculations of ET$_o$. Table 4-2 presents a sample of the final results after performing these calculations for the same period (1st to 15th of July, 2010).

Δ (kPa.°C^{-1})	**R$_n$** (MJ.m^{-2}.d^{-1})	**G**[*4] (MJ.m^{-2}.d^{-1})	**γ** (kPa.°C^{-1})	**T** (°C)	**(e$_s$-e$_a$)** (kPa)	**u$_2$** (m/s)	**ET$_o$** (mm)
0.14	15.81	0	0.07	18.9	1.38	2.3	6.01
0.15	15.98	0	0.07	20.6	1.64	2.1	6.36
0.19	15.41	0	0.07	24.7	2.43	4	9.12
0.20	15.88	0	0.07	25.7	2.70	3.7	9.47
0.16	15.96	0	0.07	22.4	1.99	2.5	7.24
0.14	16.15	0	0.07	19.3	1.29	2.6	6.05

[*4] G for one day = 0 (Allen, et al., 1998).

0.14	15.78	0	0.07	19.8	1.46	2.4	6.20
0.15	15.63	0	0.07	20.2	1.56	2.5	6.41
0.15	15.97	0	0.07	20.4	1.45	2.6	6.35
0.17	16.12	0	0.07	23.1	2.33	2.4	7.73
0.17	15.90	0	0.07	22.8	2.07	2	6.88
0.15	15.78	0	0.07	21.1	1.60	3.3	7.01
0.18	18.82	0	0.07	24.1	0.92	3	6.16
0.17	16.03	0	0.07	23.2	2.06	1.9	6.80
0.24	15.67	0	0.07	29.7	1.96	2.3	6.77

Table 4-2: Sample of ET_o Final Results

As noticed in the third column of table 4-1 (ET_o calculated by CIMIS) and the last column of table 4-2 (calculated ET_o), there is a slight difference in the results. The author would rather to refer to it as 'difference' instead of 'error'. This is because CIMIS ET_o values are also calculated values using one of the know ET_o estimation methods as there is no known method to measure precisely the actual field ET_o. This difference resulted from: the formula used to calculate ET_o; the computer software used; sources of computational errors including rounding; and others. Anyhow, in order to compare between the two results, the percentage of difference is calculated (using the same method to calculate error) and presented in table 4-3.

CIMIS ET_o (mm)	**Calculated ET_o** (mm)	**Difference** (%)
6.45	6.01	6.89
6.53	6.36	2.64
9.05	9.12	0.79
9.21	9.47	2.82
7.24	7.24	0.00
6.47	6.05	6.42
6.47	6.20	4.12
6.44	6.41	0.45
6.53	6.35	2.83
7.17	7.73	7.82
6.83	6.88	0.80
6.89	7.01	1.74
6.12	6.16	0.65
6.96	6.80	2.23
7.38	6.77	8.26

Table 4-3: Difference between CIMIS and Calculated ET_o

The highlighted four cells correspond to the occasions where the difference between the CIMIS and the calculated ET_o values is larger than 5%.

Now, in order to consider the period in which the required ET_o values of the presented WS data fall, cropping season of tomato must be defined. Cropping season of tomato each year starts from the beginning of June until the end of November. For year 2010, the cumulative CIMIS and calculated ET_o values were identical, where both equal $910\ mm$, which equal $2.98\ ft$. The given value from the DWR 2012 report for ET_o is $2.92\ ft$. Therefore, with 2% difference only, ET_o value is verified.

Moving to the verification of precipitation (PP), as mentioned previously in section 3.2.1, an isohyetal map will be used to estimate the amount of PP and compare it with the given DWR 2012 report value ($1.15\ ft. = 351\ mm$). The United States Geological Survey (USGS) provides an online data base for several fields, among which precipitation GIS map is one of them. Figure 4-3 shows the isohyetal map of Davis city. It is worth mentioning here that the isohyetal map indicates the average yearly precipitation based on the available historical data.

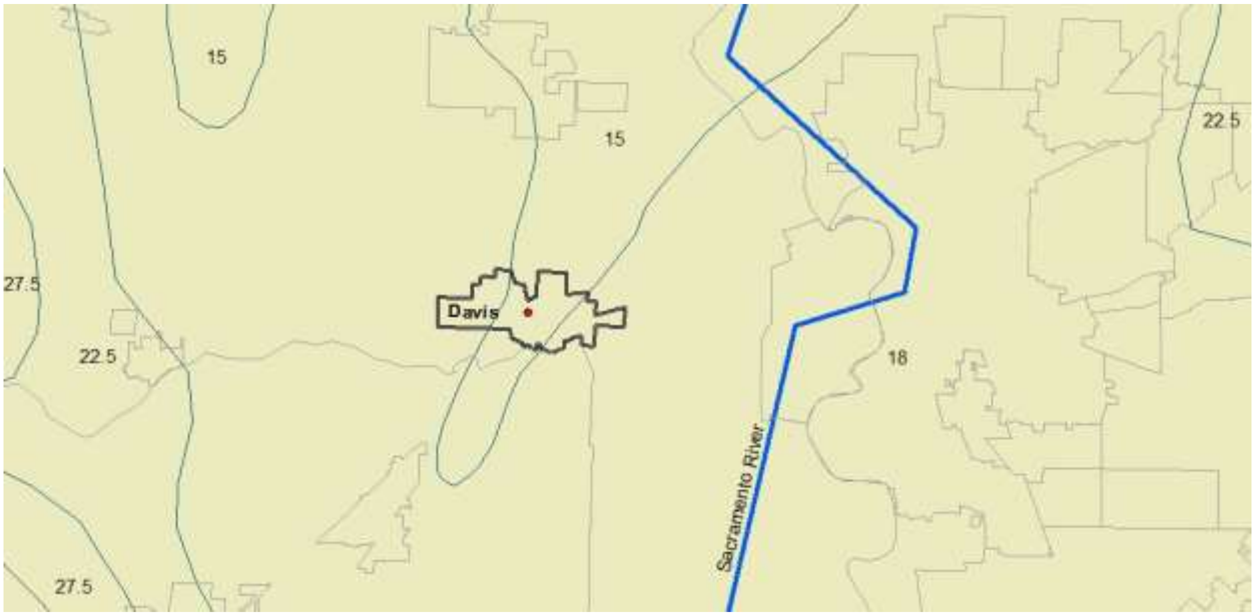

Figure 4-3: Isohyetal Map of Davis City

From the map, it can be found that Davis city locates inside the 15-inch-line, which equals $381\ mm$. Hence, the approx. annual precipitation of Davis city = $381\ mm$ (8% different than $351\ mm$). Although the difference seems quite acceptable considering the fact that it is compared here with the historical average of precipitation, but another verification will be carried out.

After investigating the data available on the DWR online data library, monthly precipitation records for a station located in Davis city were found. These records cover the period for a whole year from October 2011 to September 2012. The cumulative amount of precipitation for that year equals $12.83\ in.$, which equals $326\ mm$ (7% different). The second verification gives another indication that the given value of PP in the DWR 2012 report ($1.15\ ft.$) is quite acceptable, and therefore, it is verified.

Summary Table and WS Schematic:

The results of the extracted data editing and conversion process are summarized in table 4-4. These results are the quantitative characteristics of the chosen WS of tomato farms in Davis city, Yolo County, CA:

Variable (X)	Quantity (MCM/year)
VU	**714.40**
VD	**609.10**
VA	**183.24**
PP	**63.83**
ET	**133.22**
OS	**0**
RP	**16.43**
RF	**77.94**
NR	**19.48**

Table 4-4: Summary Table of WS Quantitative Characteristics

These numbers are presented in the hypothesized WS schematic in figure 4-4. The picture shown in the schematic is imaginary and is used only for presentation purposes.

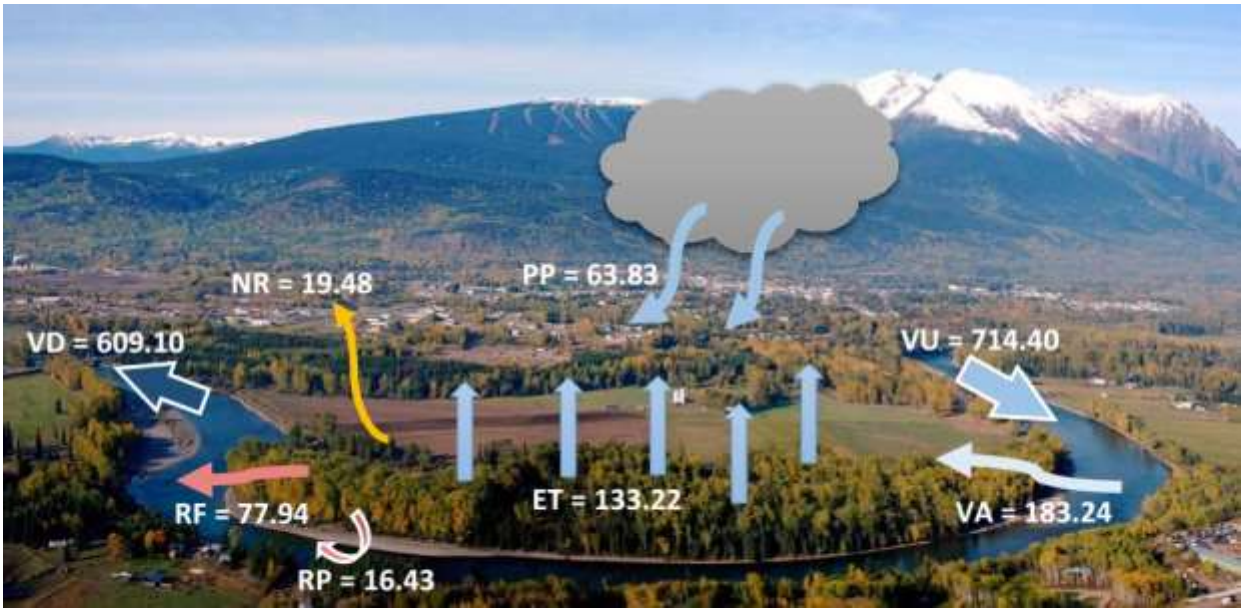

Figure 4-4: WS Schematic
Photo Credit: Spark Design

4.2.2 Qualitative Characteristics of the WS

As mentioned earlier, water quality is a qualitative characteristic that is usually indicated by many tests and measurements. Hence, and in order to meet the numerical requirements of the $S_{\text{efficiency}}$ indicators equations, a quantification approach of water quality that estimates the quality weights of water flow paths' variables (W_{q_X}) is crucial. This work has already chosen the water quality index (WQI) approach, and specifically, the WQI that the Canadian Council of Ministers of the Environment (CCME) presents (explained in details in subsection 3.2.2).

Distinguishing between the Variables:

When referring to quality, water paths' variables are very different due to the variety in their nature. First of all, the precipitation (PP), evapotranspiration (ET) and nonreusable water (NR) are flows of water in its best conditions. To elaborate, waters in the different forms of PP, i.e. rain, sleet and snow, are normally of a very high quality (to the level of being drinkable). Exceptional cases, e.g. acid rain, are excluded from consideration within the scope of this work. Also, the amounts of water evaporated or lost in the transpiration process are in the purest possible condition of water (pure H_2O). Similarly, the definition of nonreusable water implies inconvenience of considering water quality issues. Hence, water quality weight (as defined in subsection 3.2.2) should be assigned at its best (i.e. 1) for these three variables. Therefore,

$$W_{q_{PP}} = W_{q_{ET}} = W_{q_{NR}} = 1$$

On the other hand, obviously, it is quite significant to estimate the quality of water supplied to the WS, thus, quality of the volume of water abstracted (VA) has to be evaluated. It is important to mention here that VA quality is assumed to be equal to the quality of the volume of water upstream (VU). Furthermore, the return flow (RF), the potential return (RP) and the volume of water downstream (VD) variables are all laid open to water quality concerns. Actually, the water flowing out of the WS, in the case under study, is expected to have less quality then. This usually occurs due to the exposure of used water to physical, chemical and/or biological pollutants. Thus, water quality weight of RF, RP and VD should be evaluated, and it is highly expected to be less than 1.

In fact, the estimation of VA (or VU) water quality weight is a doable task (explained next) because water was abstracted from a real water body (Sacramento River) at an approximately located section (nearby Davis city). In contrast, the reliance on a hypothesized scenario to estimate the quantity of RF implies, consequently, the reliance also on hypothesized values for water quality weight of this water paths' variable. Therefore, it is assumed that, after water has been used (or even just flowed) through the WS, the quality of returned water is dropped by 15% than the quality of supplied water. Hence,

$$W_{q_{RF}} = 0.85 \times W_{q_{VA}} \qquad \text{Eq. (4.2)}$$

As previously defined, the potential return flow in the case under consideration is that quantity of water used for satisfying the leaching requirements and seedbed preparations. This fact necessarily implies that water quality will be affected according to the soil salinity. Therefore, it is assumed that the quality of water is reduced by the leaching factor (LR). Hence,

$$W_{q_{RP}} = W_{q_{VA}} - LR \tag{Eq. (4.3)}$$

Within the same context, VD (downstream) quantity was theoretically estimated in the previous subsection (4.2.1) by applying water paths' changes on the value of VU (upstream). That was done due to the unavailability of river flow data downstream, the case which also applies on quality data, and thus, an assumption for VD quality is needed. Rationally, the quality of VD would be the same as VU if the WS did not take $183.24\ MCM/year$ (VA quantity) and return the $77.94\ MCM/year$ (RF quantity). Based on that, the quality weight of VD should have been affected by the changes which incurred to the river by the WS. Therefore, by applying this logic mathematically, VD quality equals the drop in VU quality due to the abstraction (VA) plus the addition of RF. Hence,

$$W_{q_{VD}} = \left(\frac{VU - VA}{VU} \times W_{q_{VU}}\right) + \left(\frac{RF}{VU} \times W_{q_{RF}}\right) \tag{Eq. (4.4)}$$

As a result, although the variables of PP, ET and NR have clear water quality weights equal to 1, it is obviously noticed, on the other hand, that the calculation of RF, RP and VD quality weights are dependent on the estimation of VA (or VU). Indeed, such dependence makes it even more crucial to well and comprehensively estimate the quality weight of VA (or VU). This is where the previously discussed quantification approach of water quality characteristics, CCME WQI, will be utilized. Following is a detailed explanation.

WQI:

As discussed above, water quality evaluation is also needed for the volume of water abstracted (VA) (or the volume of water upstream (VU)), which is CCME WQI's job. However, in order to implement CCME WQI approach and apply its equations, wide range of water quality tests for the location of interest must be available. In this regard, the DWR online water data library offers the required type of data. The data are group of results of quality measuring field tests performed and recorded in many stations distributed all over the state of California since several years ago. The chosen station that is located within the area under study is named: Sacramento River at W. Sac Intake Structure. It has an ID = 114; latitude = 38.598056°; and longitude = 121.548333°. Table 4-5 presents a sample of raw water quality data provided by DWR for the chosen station during July, 2010. The presented sample includes, for a selected date (06-July-2010), the set of tests' results regarding certain water quality indicators (analytes), including total alkalinity, the concentration of several chemical elements, field pH, field conductance and others.

Date	Analyte	Result	Units	Depth
6-Jul-10	Total Alkalinity	50	mg/L as CaCO3	1 Meters
6-Jul-10	Dissolved Ammonia	0.01	mg/L as N	1 Meters
6-Jul-10	Dissolved Boron	< R.L.[*5]	mg/L	1 Meters
6-Jul-10	Dissolved Bromide	< R.L.	mg/L	1 Meters
6-Jul-10	Dissolved Calcium	10	mg/L	1 Meters
6-Jul-10	Dissolved Chloride	3	mg/L	1 Meters
6-Jul-10	Dissolved Hardness	46	mg/L as CaCO3	1 Meters
6-Jul-10	Dissolved Magnesium	5	mg/L	1 Meters
6-Jul-10	Dissolved Nitrate	0.2	mg/L	1 Meters
6-Jul-10	Dissolved Nitrate + Nitrite	0.03	mg/L as N	1 Meters
6-Jul-10	Total Organic Carbon	1.5	mg/L as C	1 Meters
6-Jul-10	Dissolved Organic Carbon	1.4	mg/L as C	1 Meters
6-Jul-10	Dissolved Ortho-phosphate	0.02	mg/L as P	1 Meters
6-Jul-10	Total Phosphorus	0.03	mg/L as P	1 Meters
6-Jul-10	Dissolved Potassium	1	mg/L	1 Meters
6-Jul-10	Dissolved Sodium	6	mg/L	1 Meters
6-Jul-10	Total Dissolved Solids	91	mg/L	1 Meters
6-Jul-10	Dissolved Sulfate	4	mg/L	1 Meters
6-Jul-10	Total Kjeldahl Nitrogen	0.2	mg/L as N	1 Meters
6-Jul-10	Turbidity	5	N.T.U.	1 Meters
6-Jul-10	UV Absorbance @254nm	0.034	absorbance/cm	1 Meters
6-Jul-10	Field Conductance (EC)	120.8	µS/cm	1 Meters
6-Jul-10	Field Dissolved Oxygen	7.4	mg/L	1 Meters
6-Jul-10	Field Water Temperature	21.7	°C	1 Meters
6-Jul-10	Field Turbidity	8.62	N.T.U.	1 Meters
6-Jul-10	Field pH	7.53	pH Units	1 Meters

Table 4-5: Sample of Water Quality DWR Data

Water quality data for Sacramento River at W. Sac Intake Structure station (similar to the data shown in table 4-5) covering the period from January 2008 to December 2013 were extracted to use them for CCME WQI estimation of $W_{q_{VA}}$. The CCME has well-developed a calculator (available on their official website) for calculating CCME WQI quickly and in a very well-organized process. The CCME calculator, which will be used in this work as the implementation tool of CCME WQI, is a Microsoft© Excel file that consist of several progressively arranged sheets as follows: Getting started; Instructions; Data; Tested Data, Guidelines; Output; Parameter Output; and Excursions. The user can easily follow the instructions detailed in the Instruction sheet in order to test the validity of the data inserted, then to calculate and present the output variables including F_1, F_2, F_3 (explained previously in subsection 3.2.2) and the final CCME WQI result.

[*5] (< R.L.) means: less than the Reporting Limit

Table 4-6 presents the resulted values of CCME WQI calculations for $W_{q_{VA}}$ after applying the raw water quality data in the calculator.

Index Period	F_1	F_2	F_3	CCME WQI
Winter, 2007/8	9.1	9.1	36.5	**77.7**
Spring, 2008	9.1	6.1	9.6	**91.6**
Summer, 2008	4.5	4.5	4.3	**95.5**
Fall, 2008	4.5	4.5	11.4	**92.4**
Winter, 2008/9	9.1	7.6	17.9	**87.6**
Spring, 2009	9.1	7.6	14.4	**89.2**
Summer, 2009	4.5	4.5	2.9	**95.9**
Fall, 2009	4.5	4.5	7.7	**94.2**
Winter, 2009/10	9.1	7.6	28.7	**82.1**
Spring, 2010	9.1	6.1	19.6	**87.1**
Summer, 2010	9.1	6.1	2.3	**93.6**
Fall, 2010	9.1	6.1	7.7	**92.3**
Winter, 2010/11	9.1	9.1	15.6	**88.3**
Spring, 2011	9.1	9.1	2.7	**92.4**
Summer, 2011	9.1	6.1	5.8	**92.9**
Fall, 2011	9.1	6.1	4.4	**93.2**
Winter, 2011/12	9.1	7.6	18.9	**87.1**
Spring, 2012	9.1	9.1	13.0	**89.5**
Summer, 2012	4.5	4.5	5.0	**95.3**
Fall, 2012	9.1	9.1	6.7	**91.6**
Winter, 2012/13	9.1	9.1	27.1	**82.7**
Spring, 2013	9.1	7.6	8.5	**91.6**
Summer, 2013	4.5	4.5	5.0	**95.3**
Fall, 2013	9.1	6.1	8.4	**92.0**
Winter, 2013/14	9.1	9.1	15.8	**88.3**

Table 4-6: CCME WQI Results for $W_{q_{VA}}$

Instead of taking the values that corresponds only with the cropping season of tomato in year 2010. The author would rather to take an average value for the entire period (five-year-span) to gain a more representative value of the quality of VA water. Hence,

$$W_{q_{VA}} = W_{q_{VU}} = \frac{Avg. of\ CCME\ WQI\ values}{100} = 0.90$$

And,

$$W_{q_{RF}} = 0.85 \times 0.90 = 0.77$$

And,

$$W_{q_{RP}} = 0.90 - 0.10 = 0.80$$

And,

$$W_{q_{VD}} = \left(\frac{714.40 - 183.24}{714.40} \times 0.90\right) + \left(\frac{77.94}{714.40} \times 0.77\right) = 0.75$$

Summary Table:

Water quality weights results are added to the previous summary table (4-4) to form the new summary table 4-7. The results shown in the table are the quantitative and qualitative characteristics of the WS under study:

Variable (X)	Quantity (MCM/year)	Quality Weight
VU	714.40	0.90
VD	609.10	0.75
VA	183.24	0.90
PP	63.83	1
ET	133.22	1
OS	0	0
RP	16.43	0.80
RF	77.94	0.77
NR	19.48	1

Table 4-7: Summary Table of WS Quantitative and Qualitative Characteristics

4.2.3 Beneficence Characteristics of the WS

Water beneficence, similar to quality, is a qualitative characteristic. Hence, it is also very important here, in order to meet the numerical requirements of the $S_{efficiency}$ indicators equations, to quantify approach of water beneficence. In other words, to calculate the beneficence weights of water flow paths' variables (W_{b_X}). However, and unlike quality this time, beneficence is not indicated by measurements.

As discussed in subsection 3.2.3, the area of research that directs the managerial decisions, which are responsible for defining water beneficence, is beyond the scope of this work. Therefore, it was also mentioned that the author will rationally assume the beneficence weights of water flow paths' variables by mental logic.

Based on that, logically, the beneficence of both VU and VD is nonnegotiable as they both represent the flow volumes of Sacramento River, which is the primary source of water not only for the area under consideration, but also for the entire surrounding region. Also, the values of VA and PP, which represent the main water supplies for the farmland of interest, are both highly beneficial and even crucial for the WS. In fact, in an arid region that experiences a drought period like California (previously discussed in section 3.1), any source of water is valuable. Therefore, the beneficence weights of VU, VA, VD and PP are set to be 1 (highest value).

In the same context, and due to similar reasons, the value of water after being used, regardless its quality, remains high. The returned flow to the main source (RF) is an important replenishment source to keep the river flow level downstream (VD) the same, which is highly significant for the following beneficiaries. Hence, the beneficence weight of RF is set to be also 1. In addition, RP water quantity are highly expected to replenish groundwater aquifers, which is a vital source of water in California State as well. Hence, the beneficence weight of RP is set to be 0.90. This value was not set to reach the maximum beneficence weight because the definition of RP implies some margin of uncertainty.

Indeed, agriculture in California is highly significant and valuable. The fact mentioned in section 3.1 that California provides more than 99% of many US crops was only one among many facts proving the dominance of this state's agriculture. Therefore, the beneficence weight of ET should be very high, but, not as high as the maximum (1) because it would be difficult to accept that 100% of the ET amounts of water are used by beneficial crop yields. Other non-beneficial consumers, including non-crop plants, might consume portion of these quantities. Hence, the beneficence weight of ET is assumed to be 0.95.

Finally, on the other hand, the only water flow path which is considered as the least beneficial is NR. Its definition implies that this amount of water just disappears for reasons such as being used by unwanted users (e.g. visiting animals or non-crop plants). Hence, the beneficence weight of NR is assumed to be as low as 0.35 to clearly express its definition.

<u>Final Summary Table:</u>

Water beneficence weights, which resulted from the discussion in this subsection (4.2.3), are added to the previous summary table (4-7) to form the final summary table 4-8. The results shown in this table are the complete characterization quantitative and qualitative) of the chosen WS of tomato farms in Davis city, Yolo County, CA:

Variable (X)	Quantity (MCM/year)	Quality Weight	Beneficence Weight
VU	714.40	0.90	1
VD	609.10	0.75	1
VA	183.24	0.90	1
PP	63.83	1	1
ET	133.22	1	0.95
OS	0	0	0
RP	16.43	0.80	0.90
RF	77.94	0.77	1
NR	19.48	1	0.35

Table 4-8: Summary Table of WS Characteristics

4.3 WS $S_{efficiency}$

As stated before, the main aim of this work is to highlight and achieve the fundamental objective of water management of promoting water efficient use. This will be approached through systemically measuring the performance of the previously characterized WS using sustainable efficiency ($S_{efficiency}$) as a tool. This tool, which was presented in section 3.3, is based on the general framework that (Haie, et al., 2012) suggested in their paper "*Macro, Meso, and Micro-Efficiencies in Water Resources Management: A New Framework Using Water Balance*". Following in this section is an illustration about the application of this tool reaching the intended conclusion about the WS performance.

First of all, a primary step is to verify the satisfaction of water balance (equation 3.7). This verification proves the assumption that the change in water storage of the WS under consideration is 0. This verification has a crucial significance regarding the application of $S_{efficiency}$ framework since water balance equation is the base equation for the derivation of the 3ME (Macro, Meso, and Micro-Efficiencies) equations.

$$(183.24 + 0 + 63.83) - (133.22 + 16.43 + 77.94 + 19.48) = 0$$

Then, having all of the qualitative and beneficence characteristics of the WS defined in the previous section (4.2), the usefulness criterion (s) (equation 3.8) is resulted for each variable as the following:

Variable (X)	Quality Weight	Beneficence Weight	Usefulness Criterion
VU	**0.90**	**1**	**0.90**
VD	**0.75**	**1**	**0.75**
VA	**0.90**	**1**	**0.90**
PP	**1**	**1**	**1**
ET	**1**	**0.95**	**0.95**
OS	**0**	**0**	**0**
RP	**0.80**	**0.90**	**0.72**
RF	**0.77**	**1**	**0.77**
NR	**1**	**0.35**	**0.35**

Table 4-9: Usefulness Criterion Results

Then, having the usefulness criterion defined for each variable, the useful value of each variable (X_s) (equation 3.9) can be calculated. The useful value is the one that will be used for the *Full Model $S_{efficiency}$* calculations. The full model is the model in which the usefulness criterion (i.e. qualitative and beneficence characteristics) is considered for each variable, while there are other models, such as the *Quantity Model*, in which different value for each variable is considers. The quantity model, which considers the beneficence characteristics and neglects the qualitative characteristics resulting the beneficial value (X_b), can be used for highlighting the effects of pollution on the WS when comparing its values with the full model's values and/or making comparisons with other efficiency estimation approaches. Finally, after applying equation 3.9, the useful values for all variables are summarized in the following table 4-10:

Variable (X)	Quantity (MCM/year)	Beneficence Weight	Beneficial Value (X_b)	Usefulness Criterion	Useful Value (X_s)
VU	**714.40**	**1**	**714.40**	**0.90**	**642.96**
VD	**609.10**	**1**	**609.10**	**0.75**	**456.83**
VA	**183.24**	**1**	**183.24**	**0.90**	**164.92**
PP	**63.83**	**1**	**63.83**	**1**	**63.83**
ET	**133.22**	**0.95**	**126.56**	**0.95**	**126.56**
OS	**0**	**0**	**0**	**0**	**0**
RP	**16.43**	**0.90**	**14.79**	**0.72**	**11.83**
RF	**77.94**	**1**	**77.94**	**0.77**	**60.01**
NR	**19.48**	**0.35**	**6.82**	**0.35**	**6.82**

Table 4-10: Summary of the WS Variables' Beneficial Values & Useful Values

It is important to remember here that $S_{efficiency}$ considers two types of total flows: total inflow and total consumption (using the two binary indices (i, c) (with values 0 or 1, and $i + c = 1$). As previously presented in section 3.3, the total inflow type is considered when $(i, c) = (1, 0)$, while the total consumption type is considered when $(i, c) = (0, 1)$. These types of flow are considered in order to conclude about the two types of conservation practices (abstraction savings (S_A) and consumptive savings (S_C)).

The final step of calculating the water performance indicator ($S_{efficiency}$) of the WS under consideration is ready to be conducted after having all of the variables of the 3M $S_{efficiency}$ equations (3.10-12) defined. The process includes calculating water use efficiency, according to the mentioned equations, for two types of models: the full model and the quantity model, considering two types of total flows: total inflow and total consumption. To make it more explicit, in other words, by the end of the calculation process, 12 efficiency indicators will be resulted: 6 considering total inflow, while the other 6 indicators considering total consumption. These indicators are:

- Considering total inflow $(i, c) = (1, 0)$:
  3ME regarding the full model ($iMacroE_s$, $iMesoE_s$ and $iMicroE_s$).
  3ME regarding the quantity model ($iMacroE_b$, $iMesoE_b$ and $iMicroE_b$).
- Considering total consumption $(i, c) = (0, 1)$:
  3ME regarding the full model ($cMacroE_s$, $cMesoE_s$ and $cMicroE_s$).
  3ME regarding the quantity model ($cMacroE_b$, $cMesoE_b$ and $cMicroE_b$).

Sample Calculation:

Since the number of calculations is quite large, it would be difficult to present all of the calculations in this document. Therefore, for illustration purposes, a sample calculation will be present here. The sample will show the method to apply 3ME equations for calculating the system's $MacroE_s$ considering total inflow and $MesoE_b$ considering total consumption.

- $\boldsymbol{MacroE_s}$ **considering total inflow (**$\boldsymbol{iMacroE_s}$**):**

Recalling equation 3.10 for $MacroE$ calculation and inserting the notation "s" will result the following:

$$MacroE_s = \left[\frac{ET + NR + i(VD + RP)}{VU + OS + PP - c(VD + RP)}\right]_s$$

Since the case here is considering the total inflow, then the term $c(VD + RP) = 0$, and the term $i(VD + RP) = VD + RP$. Therefore, the equation becomes:

$$MacroE_s = \left[\frac{ET + NR + VD + RP}{VU + OS + PP}\right]_s$$

After applying the useful value for each variable, the final value is resulted as the following:

$$MacroE_s = \left[\frac{126.56 + 6.82 + 456.83 + 11.83}{642.96 + 0 + 63.83}\right] = 0.852$$

Hence, $\boldsymbol{iMacroE_s = 85.2\%}$.

- $\boldsymbol{MesoE_b}$ **considering total consumption (**$\boldsymbol{cMesoE_b}$**):**

Recalling equation 3.11 for $MesoE$ calculation and inserting the notation "b" will result the following:

$$MesoE_b = \left[\frac{ET + NR + i(RF + RP)}{VA + OS + PP - c(RF + RP)}\right]_b$$

Since the case here is considering the total consumption, then the term $i(RF + RP) = 0$, and the term $c(RF + RP) = RF + RP$. Therefore, the equation becomes:

$$MesoE_b = \left[\frac{ET + NR}{VA + OS + PP - (RF + RP)}\right]_b$$

After applying the beneficial value for each variable, the final value is resulted as follows:

$$MesoE_b = \left[\frac{126.56 + 6.82}{183.24 + 0 + 63.83 - (77.94 + 14.79)}\right] = 0.864$$

Hence, $\boldsymbol{cMesoE_b = 86.4\%}$.

Final Results Summary:

The calculations presented here in the sample are conducted repeatedly to get the final results for all of the 12 water performance indicators ($S_{efficiency}$) of the WS under consideration. For that purpose, an excel sheet was used to organize all of the data and to execute the calculations faster.

Table 4-11 and figure 4-5 present the final results:

3ME			
Total Inflow $i = 1$ $c = 0$	**Full Models**	$MacroE_s$	**85.2%**
		$MesoE_s$	**89.7%**
		$MicroE_s$	**58.3%**
	Quantity Models	$MacroE_b$	**97.3%**
		$MesoE_b$	**91.5%**
		$MicroE_b$	**54.0%**
Total Consumption $i = 0$ $c = 1$	**Full Models**	$MacroE_s$	**56.0%**
		$MesoE_s$	**85.0%**
		$MicroE_s$	**58.3%**
	Quantity Models	$MacroE_b$	**86.4%**
		$MesoE_b$	**86.4%**
		$MicroE_b$	**54.0%**

Table 4-11: $S_{efficiency}$ Final Results

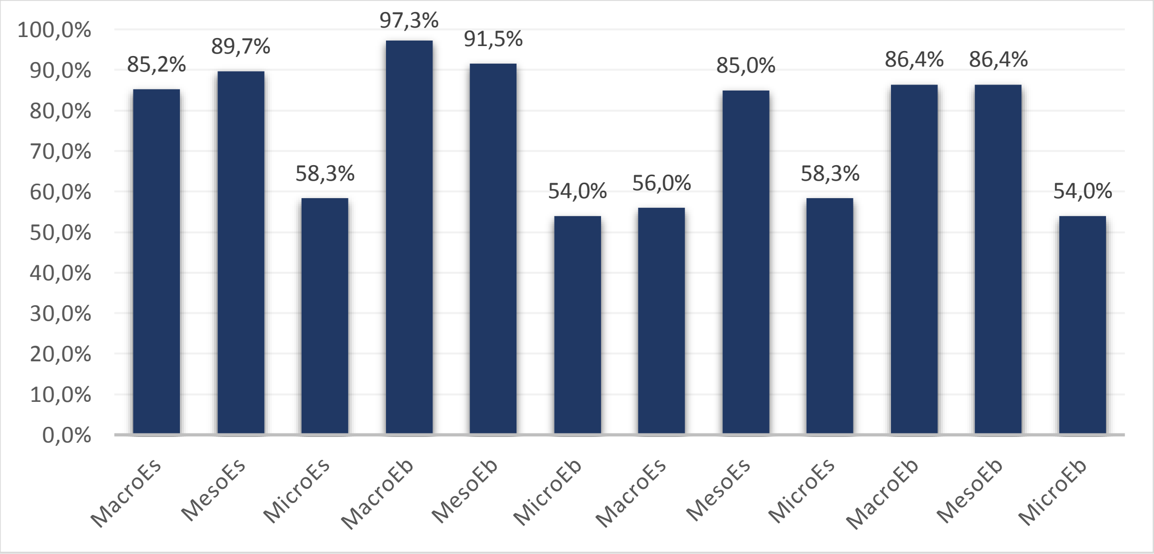

Figure 4-5: Sefficiency Final Results

4.4 Results Interpretation and Allocation Policies

All of what have been done in this work so far fall within the part which concerns the trials of understanding the WS with an arithmetic sense. This is important since numbers, if acquired correctly, cannot lie. The more important matter than numbers' acquisition is, nevertheless, the ability to understand and tell what those numbers indicate.

Efficiency, by far, is the most explicit and understandable indicator more than any other indicator used in the water sector. However, in order to well interpret the results achieved by this work, it is important here to recall what each of the resulted indicator among the 3ME stands for. As mentioned earlier in section 3.3, $MacroE$ is used to indicate the impact of the WS under consideration (tomato farms in Davis City, Yolo County, CA) on Sacramento River, while $MesoE$ is related to a situation between micro and macro levels indicating, for example, the impact of RF quantities generated by the WS. However, $MicroE$ is used to indicate the useful outflow generated by a WS for itself, in other words, local efficiency of the system.

In fact, according to (Haie, et al., 2012), the general relationships between the 3ME are validated if these cases are verified:

$cMacroE_b = cMesoE_b$ Verified
$MesoE \geq MicroE$ Verified
$iMicroE = cMicroE$ Verified

Hence, the general relationships between the 3ME are validated.

Results Interpretation:

From the first sight at the results listed in table 4-11, the WS under consideration seems to perform somehow well at the macro and meso levels (except $cMacroE_s$ for reasons detailed below), whereas the micro level performance of the system is obviously unsatisfactory. Also, it is clearly observed that the efficiencies in the full model are less than the quantity model, especially at the macro level. This is very expected because of the significant decrease in water quality values, for example, between the water volumes upstream ($W_{q_{VU}} = 0.90$) and downstream ($W_{q_{VD}} = 0.75$). This last observation highlights, indeed, the importance of water quality inclusion in efficiency estimation approaches.

In fact, the largest differences are found between the total consumption macro level values ($cMacroE_s$ and $cMacroE_b$) with 30.4% difference; and between the full model macro level values ($iMacroE_s$ and $cMacroE_s$) with 29.2% difference. The equation 3.10 tells explicitly that these two differences are symptoms of high impacts of pollution in increasing total water consumption of the system, which in turn decreases efficiencies. In the first difference (between $cMacroE_s$ and $cMacroE_b$), the consideration of water quality weights of both VD and RP (the consumption part) increases the denominator value of the equation in $cMacroE_s$ in comparison with $cMacroE_b$ (VD_s is 25% less than VD_b, RP_s is 20% less than RP_b and they are subtracted), resulting the apparent large efficiency decrease. Similarly, in the second difference (between $iMacroE_s$ and $cMacroE_s$), the consumption part of $cMacroE_s$ is much decreased by the low quality weights leading to a large increase in the total denominator value, and hence, resulting very low efficiency.

Looking at the results from another perspective, most of the values demonstrate that the different efficiencies have almost similar tendency and expose an idea, that is, the system at the higher levels (macro and meso) is functioning at good efficiency, though the local efficiencies ($MicroE$) are low. This clearly suggests that the farmers are not efficient in using their water resources, and necessarily requires the implementation of consumptive saving (S_C) rather than the abstraction type of saving (S_A). S_C savings are applied (for example through improving the irrigation techniques) in order to promote real water savings, which should in its turn result later a reduction in the abstracted water quantities as a part of a comprehensive and sustainable management plan.

Another remark could be observed from the results is that, unlike micro efficiencies, all meso efficiencies values are stable at high rates. This obviously indicates that the river replenishment is performing well, with no much return waters flowing away from the river. Nevertheless, meso efficiencies could have reached their peak if the percentage of the nonreusable water quantities, which have very low beneficial weights, are reduced to the advantage of ET or RF; in addition to improve RF quality characteristics (regarding full models efficiencies).

Allocation Policies

In case under consideration the only water use sector of interest is the agricultural sector. Other sectors, including the urban/industry and nature, are not considered in the systems' flow paths' variables. Most likely, the current water allocation from Sacramento River to the tomato farms in Davis affects other water systems in the surrounding environment. Moreover, as noticed in the 3ME results, the current distribution among the water flow path's variables shows some inefficient practices of water use, especially at the micro level.

Dealing with the consequential effects of the current allocation policies on the surrounding environment, especially the downstream systems, requires a larger scale of management and analysis, i.e. multi-WS water use efficiency analysis, which is beyond the scope of this work. These system might include other agricultural systems in addition to urban/industrial or environmental types of water systems. Having such scenarios implies, necessarily, a prioritization or trading off process in order to achieve the best possible allocation policies at which the highest potential 3M efficiencies are reached.

On the other hand, changing the current distribution among the water flow path's variables in order to promote a more efficient practices of water use, especially at the micro level, is recommended. Such change is directly connected with the implementation of water saving practices, such as the consumptive savings (S_C) and the abstraction savings (S_A). Furthermore, and as promoted in the core concept of $S_{efficiency}$ and the usefulness criterion, improving water qualitative and beneficence characteristics of water flow path's variable and/or decreasing the quantities of those variables which their usefulness criteria is impractical to be increased are actions of positive impact on the system's performance.

As mentioned before, all of these decisions regarding the allocation and reallocation practices are managerial decisions. Therefore, and as emphasized previously, $S_{efficiency}$ represents a very important tool for the decision makers, especially in areas that suffer water crisis such as California State, in order to promote more efficient water use practices reaching the end goal of making water an available resource for everyone.

5 CONCLUSION

After the completion the previous parts of this work regarding the illustration of the methodological framework of $S_{efficiency}$ and the application of it on the case study of interest, this final chapter will present and discuss some conclusive remarks and recommendations in addition to some potential future works in order to keep the doors opened for other researches to improve this framework.

5.1 Conclusive Remarks

The work progress went through many stages starting from introducing the seriousness of the global water issue and the significance of water management efforts in this regard, going later through a review of the literature related to the discussed issues, reaching finally to the comprehensive understanding of $S_{efficiency}$ and its application. Therefore, by the end of this work's progressive development, several remarks could be concluded and recommendations could be suggested as the following:

- In fact, all of the research and development efforts in the water sector indicate that humanity is experiencing recently serious water challenges that is highly expected to increase and become more serious in the future. A strong indication in this context is the prioritization upgrade that the UN carried out on the global water issue from being a target among a millennium development goal to be a complete sustainable development goal in their new agenda beyond 2015. Despite the cosmopolitan theme of the issue, but some areas are facing tougher challenges than others such as California State, where agriculture is a huge industry running billions of US dollars.
- Indeed, water is a limited resource that is constrained by the universal law of conservation of mass, i.e. cannot be created. Therefore, a sustainable solution for water shortage challenges would never be through seeking new sources, but it would be through well-manage the available resources. This is the core principle of water resources management modern approaches in which lies the promotion of more efficient water use. Based on that, water use efficiency indicators are key tools for wise management enhancement.
- Starting from Classical Efficiency several decades ago, the scientific understanding of water use efficiency has been evolving since then. Remarkable stages of this evolution include: Irrigation Sagacity (IS), Effective Efficiency (EE) and Sustainable Efficiency ($S_{efficiency}$). IS was a representation of the increased interest of irrigation efficiency, EE considered for the first time the quality dimension, while $S_{efficiency}$ introduced the usefulness criterion. The application of 3M $S_{efficiency}$ in this work shows the comprehensiveness and superiority of this approach over any other understanding of water use efficiency. This was obvious, for example, in the large differences between $cMacroE_s$ and $cMacroE_b$ and between $iMacroE_s$ and $cMacroE_s$

of the WS under consideration due to high impacts of pollution in increasing total water consumption of the system.

- $S_{efficiency}$ application requires a lot of data to characterize the WS, especially hydrologic and water quality related data. Tomato crop farmlands located in Davis City, Yolo County at the west bank of Sacramento River was chosen due to the availability and accessibility of a wide-range of accredited data; the enormous monetary values of the agricultural sector in that part of the world; and the seriousness of water issues there. Indeed, such selection made the data collection process easier and faster, also, increased the confidence level in the results.
- The results showed a noticeable difference between the full model and the quantity model efficiencies, especially at the macro level, due to the significant decrease in water quality values. In addition, they showed that the system's performance at the micro level is unsatisfactory, whereas unlike micro, all meso efficiencies values are stable at high rates. This obviously indicates that the river replenishment is performing well, with no much return waters flowing away from the river.
- There are no doubts about the fact that the WS under consideration has to improve its local efficiency ($MicroE$) in order to promote better performance for the entire system. Consequently, this improvement will be definitely reflected on the higher efficiency levels, especially through improving the macro level. In addition, and relatedly, the water quality issues are clearly serious in affecting the system's performance. Actually, the relationship between quality and micro efficiency low values can be noticed through highlighting the high quantity values of RF versus the low quality weight of this variable. Improving micro efficiency will result a decrease in RF quantity and, therefore, improve the quality of VD. This last remark, however, could result some decrease in meso efficiency values. The decision of which efficiency should be increased or invested in? A macro, meso, micro efficiency or a combination of the three? These are all clearly managerial decision that need a compromise between the conflicting stakeholders and decision makers.

5.2 Future Works

In order to improve this framework and to contribute toward better understanding of efficiency estimation using $S_{efficiency}$, successor researchers could perform one or more of the following potential future works:

- **To replace hypothesized and assumed data with real data.** This could be done either by selecting another location as a case study, where more actual data can be acquired; or by performing more investigation and research on the same location, including actually visiting the location and collecting the data insitu. Such improvement will absolutely make the 3ME results with more confidence, validity, and most importantly, make them more convincing for the decision makers.

- **To include other surrounding water systems and perform a multi-WS water use efficiency analysis.** These systems might be: downstream systems, urban/industrial, and/or natural systems. The idea here is that dealing with the consequential effects of the current allocation policies on the surrounding environment, especially the downstream systems, requires a larger scale of management and analysis. This improvement will make such comprehensive analysis possible.
- **Developing scenarios under uncertainty.** Projection of future scenarios incorporating relevant uncertainties is of crucial importance to achieve comprehensive water management approach. In fact, many recent evidences indicates that potential climate change effects has serious influence over significant meteorological variables, specially precipitation and temperature. Therefore, it would be very significant to consider future uncertainties, such as the potential changes on the system's quantitative characteristics due to climate change projections**.** After that, it is recommended **to perform sensitivity analysis** on 3ME results in order to evaluate the impacts of the different applied allocation or reallocation policies under those uncertainties in order to recommend the best future allocation policy, i.e. the policy with the highest 3ME values.

This approach and its applications are, indeed, at an early stage. Regardless the nature of the future work performed, there is one true fact, which is: this work is important as much as this precious source, water.

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