NANCIAL AND ECONOMIC APPRAISAL OF WATER SUPPLY DESALINATION TECHNOLOGIES AND REUSE INITIATIVES
Integrating Modern Portfolio Theory into Strategic Water Resource Allocation

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ABSTRACT

The study delves into the economic valuation of water supply projects, assessing not just traditional cost components but also the broader implications of non-market externalities. By employing contingent valuation, it gauges the public's willingness to pay for investment in the reliability and quality of water services. Furthermore, the approach includes a detailed examination of water supply variability, using statistical methods to model and predict the stability of different water sources. An application of the analytical framework is carried out for Morocco. In this study Modern Portfolio Theory (MPT) is applied to water resource management. It forges a nuanced balance between ensuring a reliable water supply and maintaining economic efficiency in water projects. At a time when water scarcity and climate uncertainty pose complex challenges, the use of the Simulation and Portfolio Optimization Tool (SPOT) developed in this study provides a sophisticated framework for the evaluation and selection of water source portfolios. SPOT equips policymakers with a robust tool for developing water management strategies that are both adaptable to changing environmental conditions and grounded in economic reality.

The insights provided by this research contribute to the strategic planning and economic efficiency in the design of water systems, highlighting the critical intersections of cost, reliability, and supply variability. It marks a pragmatic progression in resource management, aiming to align the stewardship of water resources with both environmental sustainability and economic efficiency.

Keywords: water supply projects, contingent valuation, willingness to pay, water service reliability, water service quality, water supply variability, Morocco, Modern Portfolio Theory, water resource management, economic efficiency, water source portfolios, policymaking, strategic planning, resource management, environmental sustainability.

Jel Classification: I38, Q25, Q38, Q55

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Abbreviations

ASR	Aquifer Storage and Recovery
CAPEX	Capital Expenditures
CSCFs or CFs	Commodity-Specific Conversion Factors or Conversion Factors
CVM	Contingent Valuation Method
EOCK	Economic Opportunity Cost of Capital
EOCL	Economic Opportunity Cost of Labor
LCOW	Levelized Cost of Water
MPT	Modern Portfolio Theory
MPTWSPT	Modern Portfolio Theory Water Supply Planning Tool
OPEX	Operating Expenditures
PV	Present Value
RMD	Robust Decision Making
SPOT	Simulation and Portfolio Optimization Tool
WEAP	Water Evaluation and Planning
WTP	Willingness to Pay

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The findings, interpretations, and conclusions expressed in this study are entirely those of the authors and should not be attributed in any manner to the World Bank, its affiliated organizations, or to members of its Board of Executive Directors or the countries they represent.

1 Introduction

Looking to the future, increasing pressures on water supplies are foreseen in many parts of the world. Population growth and rural-to-urban migration are increasing overall demand in many countries. Multiple studies project significant changes in climate across the Middle East and North Africa (MENA) region, with temperatures expected to increase while precipitation decreases. These elevated temperatures will result in higher evapotranspiration demands, which will, in combination with decreases in precipitation, severely stress the water resources in the region. These issues require water resources planners and water supply utilities to consider comprehensive risk reduction strategies and diversification of water supply portfolios to be able to meet their mandate of providing reliable and affordable water supply to communities.

Desalination and reclaimed water production might offer a solution to minimize overall water supply portfolio risk in any given country. Desalination removes salt, other minerals, or chemical compounds from impure water to produce fresh water suitable for human consumption and plant irrigation. Desalination technologies are mainly used for three types of water: seawater, brackish, and wastewater. Reverse Osmosis (RO) is a common desalination method used globally due to its low energy consumption compared to thermal distillation methods. In a RO desalination system, the higher the water's total dissolved solids (TDS) concentration, the higher the pump pressure required to drive water through the membranes and the higher the energy cost. Therefore, desalinating seawater often costs more than brackish and wastewater (Cooley et al., 2006; Madwar & Tarazi, 2003). Desalination is an energy-intensive process with a relatively high operating cost compared to traditional water supply projects. However, desalination technology requires moderate capital expenditure and provides a very reliable source of water with no correlation with precipitation.

When appraised using the least-cost approach, water desalination projects may appear relatively expensive due to high operating cost compared to traditional water supply augmentation projects based on conventional freshwater resources (surface, groundwater). However, the traditional least-cost appraisal method fails to account for the high reliability of water desalination projects compared to groundwater supply technologies. Modern portfolio theory[1] can be used to account for the water supply risk of each technology while seeking to determine the portfolio of water assets with the minimum risk given the budget constraints. Modern portfolio theory can accommodate different costs, yields, and risks when deciding optimum water resource portfolios.

These Guidelines are prepared to assist water system planners in low and middle-income countries that consider the introduction of seawater desalination and wastewater reuse in their water resources portfolios to increase the system's reliability.

The objective of the guidelines and the Excel tool that accompanies them is to determine the portfolio of water supply projects that provide a desired reliability level at the lowest cost to society. In this context, water supply reliability is defined as the frequency with which a given system fails to meet the demand. To do so in a practical manner, the authors limit the supply options to five:

1. Seawater and Brackish Water Desalination
2. Surface Water
3. Groundwater extraction (Aquifer Storage and Recovery)

[1] Markowitz, 1952; Sharpe, 1964

4. Surface Water Storage (Dam)
5. Wastewater Reclamation and Reuse

Modern Portfolio Theory (MPT) methodology is used to determine the most efficient portfolio of water supply interventions. Originally introduced by Harry Markowitz in 1952, MPT is an investment framework that aims to optimize the risk and return trade-off of a portfolio of assets. While it is most commonly applied to financial markets, its principles are increasingly being used in other fields, such as water resource management.

In the context of evaluating water projects like desalination and water reuse, Modern Portfolio Theory (MPT) can offer valuable insights for decision-makers. These types of projects often require substantial investments and carry varying degrees of financial, environmental, and social risks and returns. By applying the principles of MPT, one can build a more resilient and efficient portfolio of water projects that aligns with broader organizational or governmental objectives.

Just as with financial assets, different water projects come with their own risk-return profiles. Desalination projects may offer a high degree of water security but often come with higher costs and environmental risks, such as brine disposal. Water reuse projects, on the other hand, may be less expensive and have fewer environmental impacts but might face public perception challenges or regulatory hurdles. The key is to evaluate these projects not in isolation but in terms of how they interact within the larger portfolio.

Diversification plays a critical role here. Just like in financial portfolios, where the goal is to include a mix of assets that are not perfectly correlated, the aim in a water project portfolio would be to diversify across different types of projects to mitigate risks. For example, a portfolio might include a mix of desalination, water reuse, and traditional water supply projects to balance out the risks and returns. Statistical measures like correlation and covariance can be applied to understand how different projects' risks and benefits interact, aiding in the selection of a diversified portfolio that can withstand various challenges such as changing regulatory environments, fluctuating energy prices, or shifts in public opinion.

The quantitative approach of MPT is particularly useful when dealing with complex project variables. Key performance indicators (KPIs) specific to water projects, such as water yield, energy efficiency, cost per cubic meter, and environmental impact metrics, can be quantified and used to calculate expected returns and associated risks. Mathematical optimization techniques can then be employed to identify the most efficient set of projects to undertake, based on these quantified metrics.

Understanding the trade-offs between risk and return is crucial in any investment setting, including water projects. MPT provides the tools to make these trade-offs explicit, enabling decision-makers to quantify how much additional risk is associated with higher expected returns, and vice versa. This can inform not only the selection of individual projects but also the allocation of resources like funding, manpower, and time among multiple projects.

Customization is another benefit of applying MPT principles. Each community, organization, or governmental body has its own set of constraints, risk tolerances, and objectives. These can be incorporated into the mathematical models used for optimization, ensuring that the project portfolio is tailored to meet specific needs and goals.

Finally, the framework allows for the development of risk-adjusted performance metrics, similar to the Sharpe ratio in finance. These can help compare different portfolios of water projects in terms of their efficiency in delivering returns for a given level of risk, which can be an invaluable tool for stakeholders and decision-makers.

A comparison between the traditional method and MPT is made in Table 1. Table 2 presents the individual advantages and disadvantages of using MPT (Annex A presents the major limitations of MPT application). In applying MPT principles to the water supply systems, system planners can decide the preferred portfolio of water supply projects depending on the willingness of users to pay for the reliability, which is frequently measured by the direct/indirect cost of water shortages (coping cost approach).

Table 1: Advantages of the MPT compared to the least cost approach to water supply planning

Traditional approach	MPT approach
• Desalination and reuse projects are not considered part of a broader portfolio of water management solutions. • Focuses on the least cost way of closing the supply-demand balance without considering volatility and correlation of supply sources. • Does not explicitly trade off the cost of the portfolio of water supply projects with its reliability.	• Enables integration of desalination and reuse within a broader portfolio of water supply options. • Explicitly consider variability and correlation of supply sources. • Supports explicit risk-based investment planning, enabling planners to identify portfolios that are proportionate to the risks their water systems are facing.

Table 2: Individual advantages and disadvantages of using MPT

Advantages	Disadvantages
• Risk Optimization: MPT allows for the optimization of risk by diversifying the portfolio of water projects, reducing the impact of a failure in any single project. • Quantitative Analysis: MPT employs statistical and mathematical models, making it easier to quantify risks and returns associated with various water projects. • Resource Allocation: Through MPT, optimal resource allocation can be achieved, focusing on projects that offer the best return for the lowest risk. • Scalability: The theory is scalable and can be applied to portfolios containing multiple types of projects, such as water conservation, wastewater treatment, and infrastructure development. • Stakeholder Engagement: MPT can be a more transparent way to involve	• Data-Intensive: MPT relies on a lot of historical and projected data, which may not be readily available for all water projects. • Complexity: The mathematical models used are complex and require specialized knowledge, making it less accessible to some decision-makers. • Static Assumptions: MPT often relies on static assumptions about risk and return, which may not hold in the dynamically changing environment of water resource management. To adapt Modern Portfolio Theory (MPT) for water resource management, it's crucial to employ dynamic strategies like adjusting asset allocation based on changing conditions, evaluating investments through scenario analysis, and incorporating sustainability and impact investing. These approaches enhance resilience and align investments with long-term water security, moving beyond MPT's

stakeholders in the decision-making process, as it provides a rigorous methodology for selection and prioritization.	static assumptions to address the sector's dynamic challenges. • Cost: Implementing MPT can be expensive, particularly in the data collection and analysis phases. • Market Conditions: In financial markets, MPT assumes that markets are efficient. This assumption may not be valid in the context of water projects, which often involve regulatory and social considerations.

Subsequent chapters will elaborate upon the steps involved in applying MPT in order to obtain an optimal portfolio of water sources for any specific scenario.

2 Simulation and Portfolio Optimization Tool

The Simulation and Portfolio Optimization Tool (SPOT) utilizes modern portfolio theory to generate a series of portfolios containing various mixes of new projects that could potentially be implemented and operate alongside the base sources of water currently present within a given region.

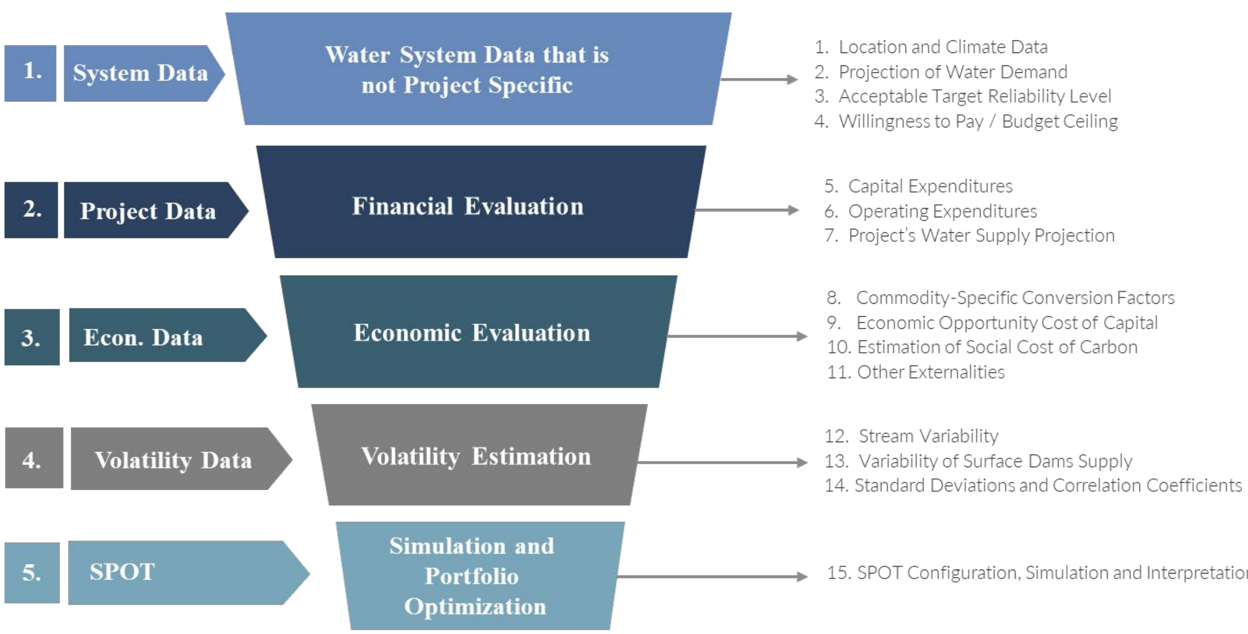


Figure 0: SPOT Analysis Framework

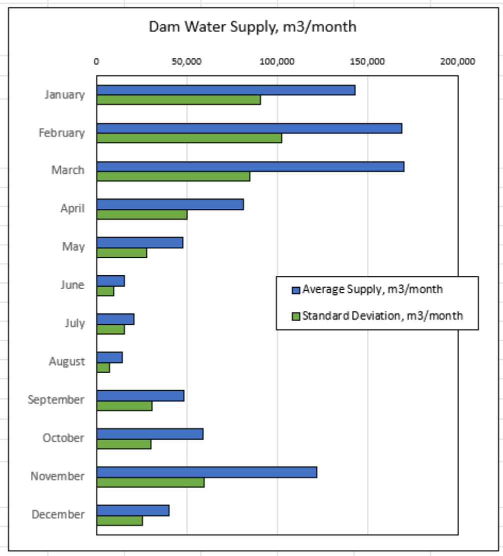
All portfolios are compared utilizing multiple metrics: The weighted average levelized cost of water and the standard deviation of the water supplied are unique to each portfolio. The tradeoff between reliability and weighted levelized cost of water is assessed according to specific user metrics, and an optimal portfolio is selected. The tool is comprised of 4 sheets. The following sections detail the structure of the tool. Factors affecting availability of water from various types of water supply fluctuates throughout the year with the summer months yielding the lowest amount of water on average. If an average amount of water supplied per month is utilized to select a portfolio of projects, the level of reliability shown of said portfolio may not actually reflect the actual level of reliability post portfolio implementation. To avoid this, the driest month of each project (the month with the lowest level of water supply) is utilized to represent a "worst case scenario" level of reliability which improves in other months. Planners can take this factor into account when selecting a desired level of reliability of the optimal portfolio generated by SPOT.

2.1 Sheets of Model

The following is a breakdown of each section/sheet within the tool. It will describe the contents and purpose of each sheet and how it interacts with the rest of the tool. Instructions on how to ultimately generate portfolios will be provided in the next section.

2.1.1 Water Sources Data

PROJECTED WATER SUPPLY FROM SURFACE WATER DAM - MOROCCO - 2050			
Peak Capacity = 300,000 m3/month			
MONTH IN 2050	Projected Supply, m3/month	Std Dev / Average*	Standard Deviation, m3/month
January	142,800	0.636	90,900
February	168,900	0.609	102,800
March	169,900	0.500	85,000
April	81,500	0.618	50,400
May	47,800	0.582	27,800
June	15,600	0.616	9,600
July	21,000	0.738	15,500
August	14,500	0.487	7,100
September	48,500	0.630	30,500
October	59,000	0.511	30,100
November	122,000	0.486	59,300
December	40,100	0.636	25,500
Minimum	14,500		7,100
25th Percentile	35,325		23,000
Median	53,750		30,300
75th Percentile	127,200		65,725
Maximum	169,900		102,800
* Interannual monthly standard deviation 2000-2020 / Average 2000-2020			



The water data sheet is a compilation of exogenous data of the projected supply of current water supply sources available within the region based on historical numbers. The example scenario present within the base form of the tool contains hidden separate sheets for each month of water supply data. This data is summarized in the manner shown above. One of the sheets containing the water supply data for January is not hidden for the user's viewing. The summarized projected water supplies per month for each source is linked and utilized in the optional LCOW Estimation sheet in order to provide an estimate of any particular project's LCOW.

2.1.2 LCOW Estimation

SPOT LCOW ESTIMATION

Generic Inputs		Unit
Discount rate	10%	%
Days	365	Days
Number of Projects	8	

Project Specific Inputs

BASE SOURCE - WATER SUPPLY PARAMETERS

Surface Dam

Capital Expenditure	100,000	$
OpEx - Fixed Comp	1,000.00	$/month
OpEx - Variable Comp	0.2	$/m3
Supply/month	14,500	m3/month
Supply/year	174,000	m3/year
Load Factor	1.00	#
Construction Period	1	Years
Operating Period	20	years
Liquidation Year	22	Year
Months in year	12	#

Year			1	2	3	4	5	6	7	8	9	10	11	12
Flag Construction	Year		1	-	-	-	-	-	-	-	-	-	-	
Operation flag	Flag		-	1	1	1	1	1	1	1	1	1	1	
Water Supply			-	174,000	174,000	14,500	14,500	14,500	14,500	14,500	14,500	14,500	14,500	14
Capital Expenditure		$100,000	100,000	-	-	-	-	-	-	-	-	-	-	
OpEx - Fixed Comp		$102,163	-	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12
OpEx - Variable Comp		$80,053	-	34,800	34,800	2,900	2,900	2,900	2,900	2,900	2,900	2,900	2,900	2
Net Cash Outflow			100,000	46,800	46,800	14,900	14,900	14,900	14,900	14,900	14,900	14,900	14,900	14

PV of Water Supply	400,265	m3
PV of Costs	$282,216	$
LCOW	$0.71	$/m3

The LCOW Estimation sheet is an optional section that utilizes exogenously provided data points such as capital expenditure, operating expending (fixed and variable), construction periods, etc. in order to provide an estimate of any particular projects LCOW. Blue cells (see guide in tool) are filled by the user and the premade formulas automatically calculates the rest.

2.1.3 Inputs

1. INPUT DATA

Unit	Input	Calculation	Output	Linked Cell

1. Location and Project Data

Parameter	Units	Base Value
Current Year	Year	2020
Target Year	Year	2050
Number of years	#	30
Current Population	#	60,000
Growth Rate of Population	% / year	2.04%
Current Potable Water Service Connections	#	20,000
Growth Rate of Connections	% / year	2.04%
Future Potable Water Service Connections	#	36,700
Increase of urban potable consumption / year	% / year	1.00%
Current Unit Water Consumption - Winter	m³/connection/month	8
Current Unit Water Consumption - Summer	m³/connection/month	12
Current Unit Water Consumption Cost/WTP - S	USD/m³	1.3

Parameter	Units	Base Value	
Current Cultivated Area - Winter	ha	800	
Current Cultivated Area - Summer	ha	400	
Growth Rate of Cultivated area	% / year	0.50%	
Growth of Cultivated area by target year	%	116%	
Growth Rate of agricultural water consumption / year	% / year	1.00%	
Growth of agricultural water consumption per month	%	135%	
Current Network Leakage: Liters / Connection /Day	L/C/D	375	*Based on an Average of 25 m pressure and LAMIC Performance Band C*
Cost Effective Leakage Reduction	%	50%	
Current Irrigation Distribution Efficiency	%	50%	
Future Irrigation Distribution Efficiency	%	80%	
Minimum Acceptable Reliability in Worst Month	%	95%	

2. Current and Future Water Demand (at water user)

Current Water Consumption

Current Urban Potable Water Consumption	Units	Base Value	J	F	M	A	M	J	J	A	S	O	N	D
Current Unit Water Consumption	m³/connection/month		8	8	8	12	12	12	12	12	12	8	8	8
Current Urban Potable Water Consumption	m³/Month		160,000	160,000	160,000	240,000	240,000	240,000	240,000	240,000	240,000	160,000	160,000	160,000

Current Agricultural Water Consumption	Units	Base Value	J	F	M	A	M	J	J	A	S	O	N	D
Current Cultivated Area	Ha		800	800	800	400	400	400	400	400	400	800	800	800
Crop Irrigation Requirement	m3/ha/month		0	0	0	200	400	600	600	400	200	0	0	0
Current Agricultural Water Consumption	m³/Month		0	0	0	80,000	160,000	240,000	240,000	160,000	80,000	0	0	0

Current Water Consumption	Units	Base Value	J	F	M	A	M	J	J	A	S	O	N	D
Total Current Water Consumption			160,000	160,000	160,000	320,000	400,000	480,000	480,000	400,000	320,000	160,000	160,000	160,000

Chart Area

The Input sheet is where the future water demand of both the urban and agricultural sectors in a specified target year are calculated given a set of inputs. The user will edit cells colored in blue and enter their own pieces of data. Some input cells can be left to their default values as they also function as general assumptions that are applicable to any situation (this way the user can decide how in depth they would like to go with custom data inputs). A description of each input is found in Table 13 below. The Input sheet also factors in inadequacies in infrastructure that lead to leakages and subsequently higher demands for water.

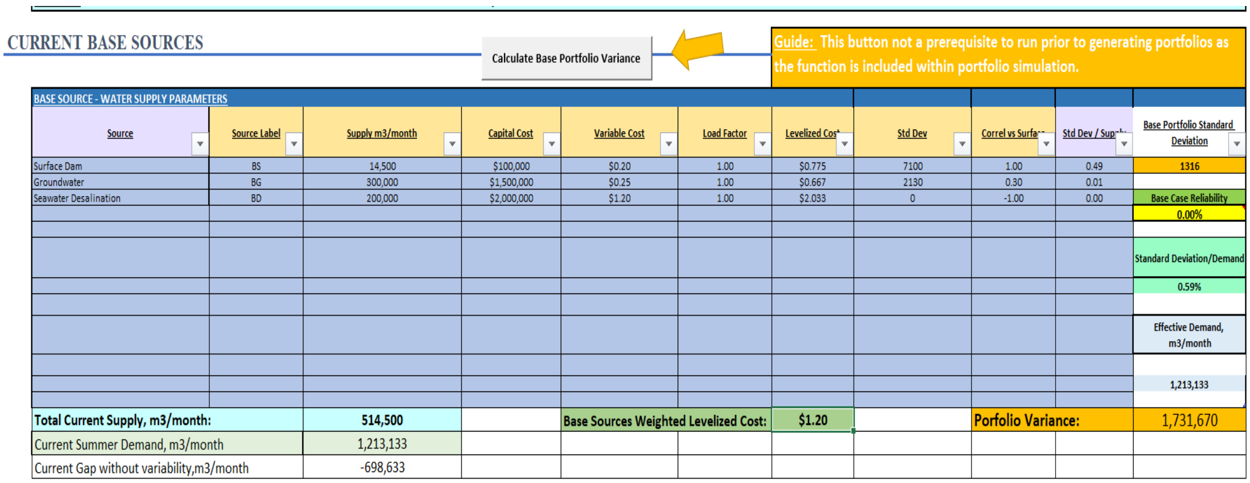
Table 3. Checklist of parameters needed to initialize SPOT.

Main Parameters	**Description**
Current Population	Current Population in area currently within area of service
Population to Connections Conversion	This value is the inverse of the average number of individuals utilizing one connection. (E.g., 3 people per connection = 0.3 PCC)
Current Unit Water Consumption	Quantity of water consumed in cubic meters per connection per month
Annual Population Growth Rate	Growth rate of the population serviced
Current Year	Year in which the analysis is taking place
Target Year	Future year at which the analysis ends
Current Network leakage	Quantity of water leaked per connection per day in liters
Future Water Consumption per Connection per Month in Target Year	Future quantity of water consumed per connection per month in cubic meters in the target year
Secondary Parameters	
Rate of increase of leakage per year	Rate of increase in leakages in litres per connection per day per year
Expected % Reduction in Leakages	The expected % reduction in leakages post implementation of leakage reduction measures
Leakage Reduction Project Commencement Year	The year in which the implementation of measures to reduce leakages is initiated.
Project Target Leakage Reduction Achievement Year	The target year in which leakage reduction measures are completed
Target Year of Future Demand	The future year of target demand utilized in the calculation of the number of leakages saved due to leakage reduction measures

2.1.4 GeneratePortfolioOne

Once all the initial input metrics are entered into the tool, the user will move on to the “GeneratePortfolioOne” sheet. This is where the user will enter data related to water sources currently in use (current/base sources) and new/potential water sources. It also contains the main results of the analysis post-simulation.

Base Sources:


CURRENT BASE SOURCES

Calculate Base Portfolio Variance

Guide: This button not a prerequisite to run prior to generating portfolios as the function is included within portfolio simulation.

BASE SOURCE - WATER SUPPLY PARAMETERS

Source	Source Label	Supply m3/month	Capital Cost	Variable Cost	Load Factor	Levelized Cost	Std Dev	Correl vs Surface	Std Dev / Supply	Base Portfolio Standard Deviation
Surface Dam	BS	14,500	$100,000	$0.20	1.00	$0.775	7100	1.00	0.49	1316
Groundwater	BG	300,000	$1,500,000	$0.25	1.00	$0.667	2130	0.30	0.01	
Seawater Desalination	BD	200,000	$2,000,000	$1.20	1.00	$2.033	0	-1.00	0.00	Base Case Reliability
										0.00%
										Standard Deviation/Demand
										0.59%
										Effective Demand, m3/month
										1,213,133
Total Current Supply, m3/month:		514,500		Base Sources Weighted Levelized Cost:		$1.20		Porfolio Variance:		1,731,670
Current Summer Demand, m3/month		1,213,133								
Current Gap without variability,m3/month		-698,633								

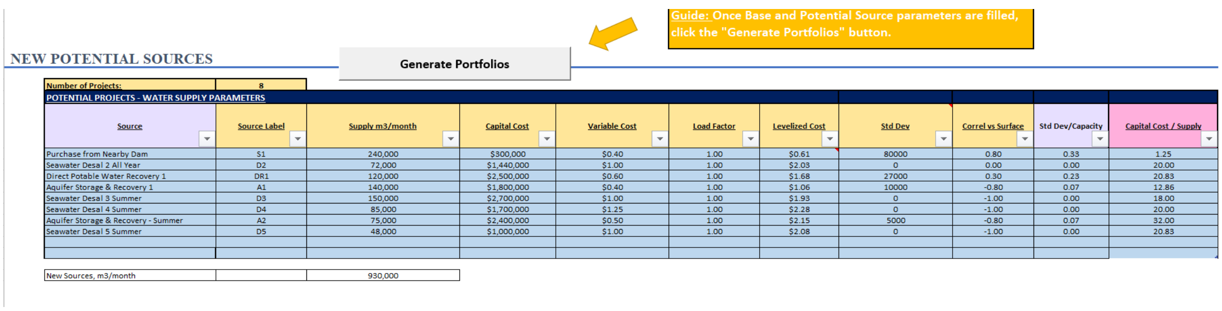
The first table the user will find is where the data related to the current water supply/supplies will be inputted. The first row of the table lists the title of each column and, hence, what type of data it will contain. Blue cells are those that must be filled by the user with the appropriate data type. Starting from the leftmost column, the following is a description of each data type:

Table 4

Source	Name of the water source (should include type of technology in name)
Source Label	A unique identifier attached to a particular project
Supply m3/month	Quantity of water supplied by source in m3/month
Capital Cost	Capital cost of source (see section 3.1 for background guidance on this estimate)
Variable Cost	Variable cost of source
Load Factor	The average level of output of the source in relation to its maximum level of output. By default, it should be entered as 1 for any particular potential project. This is done because each project’s monthly water supply is obtained from the worst month of the year (driest month of the year). In other words, projects utilizing technologies dependent on climate are already operating below maximum capacity and using a load factor of 1 in such a case is a reasonable assumption as all water generated by said projects will be utilized. The exception comes in the form of desalination plants where the load factor of 1 indeed indicates operating at maximum

	capacity as the technology's supply of water is not affected by climate. A load factor of 1 is applicable as the user in in complete control of the amount of water being produced at any point in time and can adjust output as needed.
Levelized Cost	Levelized cost of water of source
Std Dev	Standard deviation of supply of source
Correl vs Surface	Correlation of source with Surface dam Technology

New Project Supplies:



NEW POTENTIAL SOURCES

Generate Portfolios

Guide: Once Base and Potential Source parameters are filled, click the "Generate Portfolios" button.

Number of Projects: 8

POTENTIAL PROJECTS - WATER SUPPLY PARAMETERS

Source	Source Label	Supply m3/month	Capital Cost	Variable Cost	Load Factor	Levelized Cost	Std Dev	Correl vs Surface	Std Dev/Capacity	Capital Cost / Supply
Purchase from Nearby Dam	S1	240,000	$300,000	$0.40	1.00	$0.61	80000	0.80	0.33	1.25
Seawater Desal 2 All Year	D2	72,000	$1,440,000	$1.00	1.00	$2.03	0	0.00	0.00	20.00
Direct Potable Water Recovery 1	DR1	120,000	$2,500,000	$0.60	1.00	$1.68	27000	0.30	0.23	20.83
Aquifer Storage & Recovery 1	A1	140,000	$1,800,000	$0.40	1.00	$1.06	10000	-0.80	0.07	12.86
Seawater Desal 3 Summer	D3	150,000	$2,700,000	$1.00	1.00	$1.93	0	-1.00	0.00	18.00
Seawater Desal 4 Summer	D4	85,000	$1,700,000	$1.25	1.00	$2.28	0	-1.00	0.00	20.00
Aquifer Storage & Recovery - Summer	A2	75,000	$2,400,000	$0.50	1.00	$2.15	5000	-0.80	0.07	32.00
Seawater Desal 5 Summer	D5	48,000	$1,000,000	$1.00	1.00	$2.08	0	-1.00	0.00	20.83

New Sources, m3/month		930,000

The table directly underneath is where new project values are inputted. It is structured in the same fashion as the base sources table (Table 14). If all values are known and inputted, then the user can immediately move to portfolio generation by clicking the "Generate Portfolios" button and wait for the simulation to complete. (Please make sure to enable macros within the Excel sheet beforehand).

If the levelized cost of water for any particular source is unknown, then the user can utilize the "LCOW Estimation" Tab to calculate a rough estimate for any particular project.

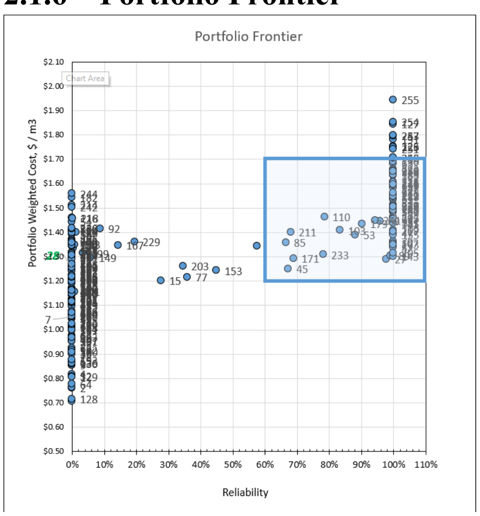
Note: Once the number of projects inserted into the model reaches 12 projects and beyond, the number of portfolio combinations will reach into the thousands/tens of thousands. This will cause Excel to "freeze" for approximately 2-20 minutes, depending on the number of projects within the upper limits that the model is capable of handling. The model is still fully functional despite its unresponsiveness, and given enough time, it will get through its processes. This issue can potentially be mitigated to a certain extent once some constraints are added to filter out obviously undesired portfolios.

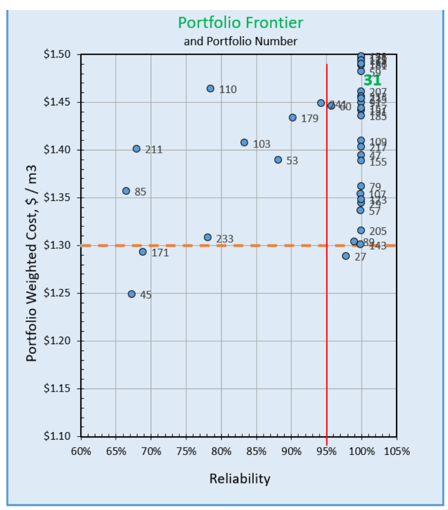
2.1.5 Optimal Portfolio Selector

Potential Optimal Portfolio of New Sources at around 100% Reliability - WORST MONTH							
Portfolio #:	27	Portfolio LCOW:	$1.29	Portfolio Reliability:	97.90%	Portfolio Supply (m3/month)	1,026,500
Source Label	Source	Supply - m3/month	LCOW	Correl w/ Surface Dam	Load Factor		
	All Base Sources	514,500	$1.20				
S1	Purchase from Nearby Dam	150,000	$0.61	0.8	1		
D2	Seawater Desal 2 All Year	72,000	$2.03	0	1		
DR1	Direct Potable Water Recovery 1	0	$0.00	0	0		
A1	Aquifer Storage & Recovery 1	140,000	$1.06	-0.8	1		
D3	Seawater Desal 3 Summer	150,000	$1.93	-1	1		
D4	Seawater Desal 4 Summer	0	$0.00	0	0		
A2	Aquifer Storage & Recovery - Summer	0	$0.00	0	0		
D5	Seawater Desal 5 Summer	0	$0.00	0	0		

After generating every possible portfolio, the optimal portfolio selector (found within the “GeneratePortfolioOne” tab) will show the portfolio that can achieve a reliability value above a user-defined minimum level of reliability at the least possible cost. In the above example, the min. level of reliability accepted is defined as 90%. Projects not included in the optimal portfolio have their supply defined as 0. To ensure proper operation of the portfolio selector

2.1.6 Portfolio Frontier





All portfolios generated are plotted on a portfolio frontier with weighted levelized cost on the Y axis and reliability on the X axis. On the blue graph, the user can compare portfolios above 60% reliability (or any min. user-defined level of reliability) and take into account other portfolios for a clearer picture of the tradeoff between LCOW and reliability. The orange horizontal line represents the WTP and adjusts according to the value inputted in prior tabs.

2.1.7 Annual Portfolio Assessment

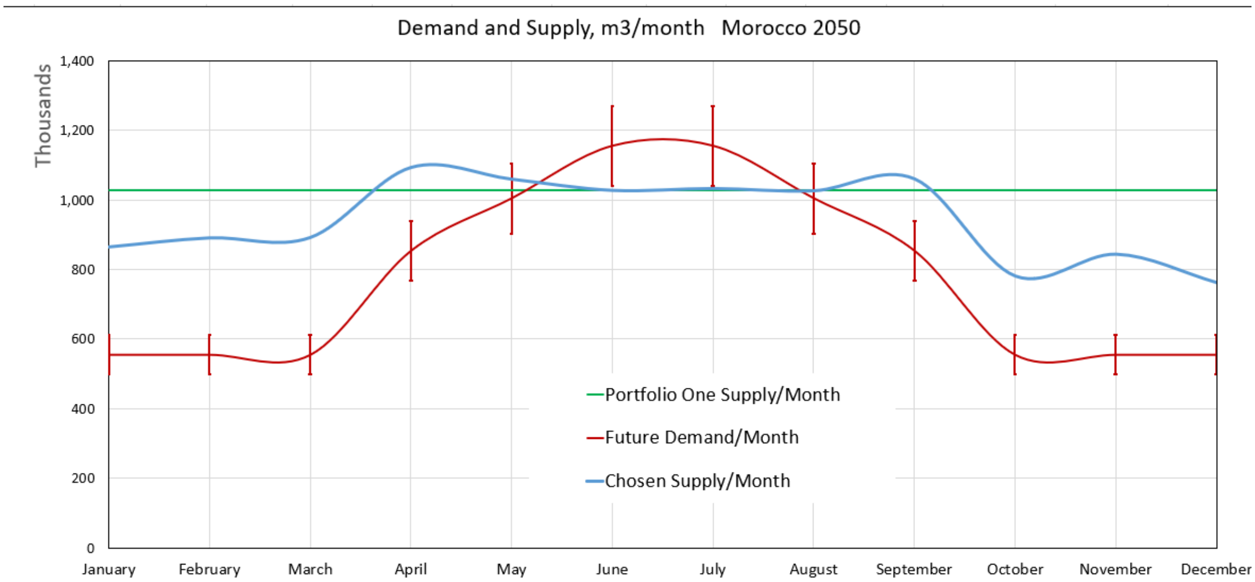
ANNUAL PORTFOLIO ASSESSMENT

COMPOSITE DATA FOR ALL WATER SOURCES				Scenario:	Urban Water and Agriculture Morocco #1		
Code	Water Supply Source	Technical Parameters			Financial Parameters		
		Potential Supply m3/year	Average Load Factor	Selected Annual Supply, m3/year	Unit Variable Cost, $ / m3	Annual Variable Cost, $ / Year	Capital Fixed Cost
BS	Surface Dam	931,600	1.00	931,600	$0.20	$186,320	$100,000
BG	Groundwater	3,600,000	1.00	3,600,000	$0.25	$900,000	$1,500,000
BD	Seawater Desalination	2,400,000	1.00	2,400,000	$2.03	$4,880,000	$2,000,000
S1	Purchase from Nearby Dam	1,800,000	1.00	1,800,000	$0.40	$720,000	$300,000
D2	Seawater Desal 2 All Year	864,000	1.00	864,000	$1.00	$864,000	$1,440,000
DR1	Direct Potable Water Recovery 1	1,440,000	0.00	0		$0	$0
A1	Aquifer Storage & Recovery 1	1,680,000	0.50	840,000	$0.40	$336,000	$1,800,000
D3	Seawater Desal 3 Summer	1,800,000	0.50	900,000	$1.00	$900,000	$2,700,000
D4	Seawater Desal 4 Summer	1,020,000	0.00	0		$0	$0
A2	Aquifer Storage & Recovery - Sum	900,000	0.00	0		$0	$0
D5	Seawater Desal 5 Summer	576,000	0.00	0		$0	$0
						Variable Cost	CAPEX
	TOTAL	**17,011,600**	0.67	**11,335,600**		**$8,786,320**	**$9,840,000**
	FUTURE DEMAND			**9,355,088**	Annual Reliability	Avg Unit Var Cost	CAPEX $/m3/month
					97.9%	$0.775	$13

Solver Zone		
	Load Factors from User	Load Factors from Solver
BS	1.00	
BG	1.00	
BD	1.00	
S1	1.00	1.00
D2	1.00	1.00
DR1	0.00	0.00
A1	1.00	1.00
D3	1.00	1.00
D4	0.00	0.00
A2	0.00	0.00
D5	0.00	0.00

The "Annual Portfolio Assessment" tab is an optional sheet where the user can delve into the optimal portfolio and slightly adjust the load factor of each project using Excel's "Solver" function to see if any micro adjustments in water supply within the portfolio can be done to further reduce costs with an acceptable sacrifice in reliability.

The graph below is present in the sheet to provide the user with a quick snapshot of how the water supply of the optimal portfolio compares with the target level of demand throughout the year.



2.2 SPOT

The SPOT sheet can also be called the engine the hood of the tool. It is programmed to dynamically adjust and account for every project listed when utilizing modern portfolio theory to construct portfolios. The SPOT sheet is where all constructed portfolios are displayed and data respective to each portfolio is listed. It does not require any interaction from the user but if inclined, the user can access the sheet for further inspection. The input tables to the left of the SPOT sheet are identical to those in the dashboard sheet and automatically populated from the values in the dashboard tables when portfolios are generated.

Portfolio #	Base Source Supply			New Project Supply								Total	Levelized Costs of Base Source			Levelized Costs of New Proje		
#	BS	BG	BD	S1	D2	DR1	A1	D3	D4	A2	D5	Total	CBS	CBG	CBD	S12	D22	DR12
1	14,500	300,000	200,000	150,000	0	0	0	0	0	0	0	664,500	$0.77	$0.67	$2.03	$0.61	$0.00	$0.00
2	14,500	300,000	200,000	0	72,000	0	0	0	0	0	0	586,500	$0.77	$0.67	$2.03	$0.00	$2.03	$0.00
3	14,500	300,000	200,000	150,000	72,000	0	0	0	0	0	0	736,500	$0.77	$0.67	$2.03	$0.61	$2.03	$0.00
4	14,500	300,000	200,000	0	0	120,000	0	0	0	0	0	634,500	$0.77	$0.67	$2.03	$0.00	$0.00	$1.68
5	14,500	300,000	200,000	150,000	0	120,000	0	0	0	0	0	784,500	$0.77	$0.67	$2.03	$0.61	$0.00	$1.68
6	14,500	300,000	200,000	0	72,000	120,000	0	0	0	0	0	706,500	$0.77	$0.67	$2.03	$0.00	$2.03	$1.68
7	14,500	300,000	200,000	150,000	72,000	120,000	0	0	0	0	0	856,500	$0.77	$0.67	$2.03	$0.61	$2.03	$1.68
8	14,500	300,000	200,000	0	0	0	140,000	0	0	0	0	654,500	$0.77	$0.67	$2.03	$0.00	$0.00	$0.00
9	14,500	300,000	200,000	150,000	0	0	140,000	0	0	0	0	804,500	$0.77	$0.67	$2.03	$0.61	$0.00	$0.00
10	14,500	300,000	200,000	0	72,000	0	140,000	0	0	0	0	726,500	$0.77	$0.67	$2.03	$0.00	$2.03	$0.00
11	14,500	300,000	200,000	150,000	72,000	0	140,000	0	0	0	0	876,500	$0.77	$0.67	$2.03	$0.61	$2.03	$0.00
12	14,500	300,000	200,000	0	0	120,000	140,000	0	0	0	0	774,500	$0.77	$0.67	$2.03	$0.00	$0.00	$1.68
13	14,500	300,000	200,000	150,000	0	120,000	140,000	0	0	0	0	924,500	$0.77	$0.67	$2.03	$0.61	$0.00	$1.68
14	14,500	300,000	200,000	0	72,000	120,000	140,000	0	0	0	0	846,500	$0.77	$0.67	$2.03	$0.00	$2.03	$1.68
15	14,500	300,000	200,000	150,000	72,000	120,000	140,000	0	0	0	0	996,500	$0.77	$0.67	$2.03	$0.61	$2.03	$1.68
16	14,500	300,000	200,000	0	0	0	0	150,000	0	0	0	664,500	$0.77	$0.67	$2.03	$0.00	$0.00	$0.00
17	14,500	300,000	200,000	150,000	0	0	0	150,000	0	0	0	814,500	$0.77	$0.67	$2.03	$0.61	$0.00	$0.00
18	14,500	300,000	200,000	0	72,000	0	0	150,000	0	0	0	736,500	$0.77	$0.67	$2.03	$0.00	$2.03	$0.00
19	14,500	300,000	200,000	150,000	72,000	0	0	150,000	0	0	0	886,500	$0.77	$0.67	$2.03	$0.61	$2.03	$0.00
20	14,500	300,000	200,000	0	0	120,000	0	150,000	0	0	0	784,500	$0.77	$0.67	$2.03	$0.00	$0.00	$1.68
21	14,500	300,000	200,000	150,000	0	120,000	0	150,000	0	0	0	934,500	$0.77	$0.67	$2.03	$0.61	$0.00	$1.68
22	14,500	300,000	200,000	0	72,000	120,000	0	150,000	0	0	0	856,500	$0.77	$0.67	$2.03	$0.00	$2.03	$1.68
23	14,500	300,000	200,000	150,000	72,000	120,000	0	150,000	0	0	0	1,006,500	$0.77	$0.67	$2.03	$0.61	$2.03	$1.68

Within the SPOT table, each row represents a portfolio. The first row contains titles of different sections that are comprised of columns grouped under a specific variable. The second row is filled with secondary identifiers for each project or base source within a group. E.g.) BS, BG and BD in the blue columns under Base Source Supply, each represents base surface dam supply, Base Groundwater Supply and Base Desalination Supply, respectively. The following is a brief explanation of various columns within the SPOT table.

Total: The total water supplied per day by each portfolio is obtained by summing up both base sources and new projects selected for a particular portfolio.

Weighted Levelized Cost of Water: In a similar fashion to the previous section on the supply of sources, the levelized costs of base sources and new projects are listed out in each portfolio. The column in green takes the levelized costs of the new projects within a portfolio multiplied by the percentage of total water supplied by each project and summed up to find the portfolio-weighted levelized cost of water.

Sig P: Standard deviation of the portfolio. It is found using the standard deviations of water sources, their covariance with each other, respective correlation with surface water and % of total water supplied from every source.

Standard Deviation / Demand: The standard deviation of water supply divided by the demand for water in cubic meters is a measure of the risk or variability associated with a portfolio of water sources. It can be seen as a measure of the deviation of the actual supply of water from the expected supply relative to the demand.

Reliability: Reliability is defined as the % that a portfolio services the target demand completely without any shortages over the planning period (% months over planning period without water shortages).

2.3 Instructions for Generation of Portfolios

1. **Guide Sheet:** Go through the "Guide" sheet for a quick overview of the general framework of SPOT

SPOT: SIMULATION AND PORTFOLIO OPTIMIZATION TOOL
Version 3.0

Guide: Please Enable Macros in Excel before utilizing the model!
This can be done by going to File --> Options --> Trust Center --> Trust Center Settings --> Macro Settings --> Enable Macros

Worksheet Guide	Description
Modern Portfolio Theory	Modern Portfolio Theory (MPT) is a financial theory that attempts to maximize portfolio expected return for a given amount of portfolio risk, or equivalently minimize risk for a give return, by carefully choosing the proportions of various assets. In the context of water source optimization, diversification would involve relying on multiple water sources such as su groundwater, desalinated water, and recycled water to reduce the risk of shortages. Risk could be defined as the likelihood of water shortage due to various factors, and return as the reliably supplied.
Levelized Cost of Water	The levelized cost of water (LCOW) is an economic measure that calculates the average cost per unit of water produced over the lifespan of a water supply project. It includes capital, operating, maintenance, financing, and regulatory compliance costs. LCOW helps assess the long-term affordability and sustainability of water supply systems.
S.P.O.T.	The SPOT utilizes modern portfolio theory to generate portfolios that consist of unique combinations of water sources provided by the user. Various metrics are then taken into consideration to find the optimal mix of water sources that maximizes reliability while minimizing levelized cost. Other metrics/perspectives are a consideration.
Model Framework	This document describes the application of the SPOT Model to two hypothetical case examples of a fictitious city located in central, coastal Morocco. In a country such as Morocco, with a wet winter season and very dry summer, urban water utilities often have a supply shortfall in the dry season, leading to water supply rationing. to determine which additional water sources, at what scale and cost should be developed as part of an expanded portfolio to improve security of water supply in the driest month (Ju 2050. In this document, the term Security is the simple ratio of the water supply from a portfolio divided by net demand. This measure differs from the term Reliability which has a s definition, which implies a normal distribution of supply and demand which is difficult to verify.

Modeling Flowchart

2. **Inputs:** Access the "Inputs" sheet and input data into the blue data cells. Many parameters in the right Parameters table can be left as their generic values as they serve as general default values that apply to almost all scenarios for the purpose of estimations. The final calculation is the future efficient water demand

1. INPUT DATA

Unit	Input	Calculation	Output	Linked Cell

1. Location and Project Data

Parameter	Units	Base Value
Current Year	Year	2020
Target Year	Year	2050
Number of years	#	30
Current Population	#	60,000
Growth Rate of Population	% / year	2.04%
Current Potable Water Service Connections	#	20,000
Growth Rate of Connections	% / year	2.04%
Future Potable Water Service Connections	#	36,700
Increase of urban potable consumption / year	% / year	1.00%
Current Unit Water Consumption - Winter	m³/connection/month	8
Current Unit Water Consumption - Summer	m³/connection/month	12
Current Unit Water Consumption Cost/WTP - Sun	USD/m³	1.3

Parameter	Units	Base Value	
Current Cultivated Area - Winter	ha	800	
Current Cultivated Area - Summer	ha	400	
Growth Rate of Cultivated area	% / year	0.50%	
Growth of Cultivated area by target year	%	116%	
Growth Rate of agricultural water consumption / year	% / year	1.00%	
Growth of agricultural water consumption per month	%	135%	
Current Network Leakage: Liters / Connection /Day	L/C/D	375	*Based on an Average of 25 m pressure and LAMIC Performance Band C*
Cost Effective Leakage Reduction	%	50%	
Current Irrigation Distribution Efficiency	%	50%	
Future Irrigation Distribution Efficiency	%	80%	
Minimum Acceptable Reliability in Worst Month	%	95%	

2. Current and Future Water Demand (at water user)

Current Water Consumption

Current Urban Potable Water Consumption	Units	Base Value	J	F	M	A	M	J	J	A	S	O	N	D
Current Unit Water Consumption	m³/connection/month		8	8	8	12	12	12	12	12	12	8	8	8
Current Urban Potable Water Consumption	m³/Month		160,000	160,000	160,000	240,000	240,000	240,000	240,000	240,000	240,000	160,000	160,000	160,000

Current Agricultural Water Consumption	Units	Base Value	J	F	M	A	M	J	J	A	S	O	N	D
Current Cultivated Area	Ha		800	800	800	400	400	400	400	400	400	800	800	800
Crop Irrigation Requirement	m3/ha/month		0	0	0	200	400	600	600	400	200	0	0	0
Current Agricultural Water Consumption	m³/Month		0	0	0	80,000	160,000	240,000	240,000	160,000	80,000	0	0	0

Current Water Consumption	Units	Base Value	J	F	M	A	M	J	J	A	S	O	N	D
Total Current Water Consumption			160,000	160,000	160,000	320,000	400,000	480,000	480,000	400,000	320,000	160,000	160,000	160,000

3. **LCOW Estimation (Optional):** If the levelized cost of water for any project is not available then the LCOW Estimation sheet can be utilized to calculate it by providing the required inputs in the blue cells. The sheet provides space for a certain number of projects. If the user wishes to add more projects to the LCOW Estimation sheet beyond what is already premade, simply create a copy of one instance a project already present and insert it in an empty area. The calculated LCOW for a particular project can either be manually linked to the corresponding LCOW of said project back in the "GeneratePortfolioOne" sheet or entered manually.

Generic Inputs			Unit									
Discount rate	10%	%										
Days	365	Days										
Number of Projects	8											
Project Specific Inputs												
BASE SOURCE - WATER SUPPLY PARAMETERS												
Surface Dam												
Capital Expenditure	100,000	$										
OpEx - Fixed Comp	1,000.00	$/month										
OpEx - Variable Comp	0.2	$/m3										
Supply/month	14,500	m3/month										
Supply/year	174,000	m3/year										
Load Factor	1.00	#										
Construction Period	1	Years										
Operating Period	20	years										
Liquidation Year	22	Year										
Months in year	12	#										
Year				1	2	3	4	5	6	7	8	9
Flag Construction		Year		1	-	-	-	-	-	-	-	-
Operation flag		Flag		-	1	1	1	1	1	1	1	1
Water Supply				-	174,000	174,000	14,500	14,500	14,500	14,500	14,500	14,500
Capital Expenditure			$100,000	100,000	-	-	-	-	-	-	-	-
OpEx - Fixed Comp			$102,163	-	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000
OpEx - Variable Comp			$80,053	-	34,800	34,800	2,900	2,900	2,900	2,900	2,900	2,900
Net Cash Outflow				100,000	46,800	46,800	14,900	14,900	14,900	14,900	14,900	14,900
PV of Water Supply	400,265	m3										
PV of Costs	$282,216	$										
LCOW	$0.71	$/m3										

4. **Generate PortfolioOne Sheet:** Enter the base sources currently available in the region along with their corresponding data points in the blue cells:

CURRENT BASE SOURCES

Calculate Base Portfolio Variance

Guide: This button not a prerequisite to run prior to generating portfolios as the function is included within portfolio simulation.

BASE SOURCE - WATER SUPPLY PARAMETERS										
Source	Source Label	Supply m3/month	Capital Cost	Variable Cost	Load Factor	Levelized Cost	Std Dev	Correl vs Surface	Std Dev / Supply	Base Portfolio Standard Deviation
Surface Dam	BS	14,500	$100,000	$0.20	1.00	$0.775	7100	1.00	0.49	1316
Groundwater	BG	300,000	$1,500,000	$0.25	1.00	$0.667	2130	0.30	0.01	
Seawater Desalination	BD	200,000	$2,000,000	$1.20	1.00	$2.033	0	-1.00	0.00	Base Case Reliability
										0.00%
										Standard Deviation/Demand
										0.59%
										Effective Demand, m3/month
										1,213,133
Total Current Supply, m3/month:		**514,500**		**Base Sources Weighted Levelized Cost:**		**$1.20**		**Porfolio Variance:**		1,731,670
Current Summer Demand, m3/month		1,213,133								
Current Gap without variability,m3/month		-698,633								

5. Populate the "Potential Projects" table with the list of projects and appropriate data under each column heading. A maximum of 20 projects can be added to the model. The data required for each project listing must include:

click the "Generate Portfolios" button.

NEW POTENTIAL SOURCES

Generate Portfolios

Number of Projects:	8

POTENTIAL PROJECTS - WATER SUPPLY PARAMETERS

Source	Source Label	Supply m3/month	Capital Cost	Variable Cost	Load Factor	Levelized Cost	Std Dev	Correl vs Surface	Std Dev/Capacity	Capital Cost / Supply
Purchase from Nearby Dam	S1	240,000	$300,000	$0.40	1.00	$0.61	80000	0.80	0.33	1.25
Seawater Desal 2 All Year	D2	72,000	$1,440,000	$1.00	1.00	$2.03	0	0.00	0.00	20.00
Direct Potable Water Recovery 1	DR1	120,000	$2,500,000	$0.60	1.00	$1.68	27000	0.30	0.23	20.83
Aquifer Storage & Recovery 1	A1	140,000	$1,800,000	$0.40	1.00	$1.06	10000	-0.80	0.07	12.86
Seawater Desal 3 Summer	D3	150,000	$2,700,000	$1.00	1.00	$1.93	0	-1.00	0.00	18.00
Seawater Desal 4 Summer	D4	85,000	$1,700,000	$1.25	1.00	$2.28	0	-1.00	0.00	20.00
Aquifer Storage & Recovery - Summer	A2	75,000	$2,400,000	$0.50	1.00	$2.15	5000	-0.80	0.07	32.00
Seawater Desal 5 Summer	D5	48,000	$1,000,000	$1.00	1.00	$2.08	0	-1.00	0.00	20.83

New Sources, m3/month		930,000

a. **Source:** The name of the water source/project. The name of the project is up to the user; however, it is recommended to at least include the name of the technology in the name of the project.

b. **Source label:** The source label is used to identify each project within the portfolio. Every project must have its own unique Source label. The recommended structure of the source label is the first letter of the technology utilized, followed by a number or a second letter. For example, "S1" or "S-Ho" for the Hoover Surface Water Dam.

c. **Supply m3/month:** Insert the capacity of water provided by the project in '000 m3/day.

d. **Capital Cost:** Insert the capital cost that is needed or used to build the project.

e. **Variable Cost:** The operating costs of the source per 1 cubic meter of water.

f. **Load Factor:** The load factor is a measure of the actual output of a source compared to its potential output if it were possible for it to operate at full capacity continuously over a specific period of time. See Table 14 for elaboration on the selection of an appropriate load factor.

g. **Levelized Cost:** The Levelized Cost of Water (LCOW) is a measure of the lifetime cost of water supply divided by the total volume of water delivered over that lifetime in present value terms.

h. **Std Dev:** Insert the standard deviation of water per cubic meter for the project.

i. **Correl vs Surface:** Insert the correlation of the water supply of water source with the supply of water from Surface Dams.

6. **Generate Portfolios:** Once all data points are inputted, click on the "Generate Portfolios" button within the "GeneratePortfolioOne" tab and wait for the simulation to complete.

7. **Optimal Portfolio:** After generating portfolios, the optimal portfolio that services the target future demand at a reliability level above the user specified minimum level of reliability at the relativity lowest cost will be selected. The contents of the selected portfolio will also be displayed. Projects with 0 supply shown are considered to not be included in the selected portfolio.

Potential Optimal Portfolio of New Sources at around 100% Reliability - WORST MONTH							
Portfolio #:	27	Portfolio LCOW:	$1.29	Portfolio Reliability:	97.90%	Portfolio Supply (m3/month)	1,026,500
Source Label	Source	Supply - m3/month	LCOW	Correl w/ Surface Dam	Load Factor		
	All Base Sources	514,500	$1.20				
S1	Purchase from Nearby Dam	150,000	$0.61	0.8	1		
D2	Seawater Desal 2 All Year	72,000	$2.03	0	1		
DR1	Direct Potable Water Recovery 1	0	$0.00	0	0		
A1	Aquifer Storage & Recovery 1	140,000	$1.06	-0.8	1		
D3	Seawater Desal 3 Summer	150,000	$1.93	-1	1		
D4	Seawater Desal 4 Summer	0	$0.00	0	0		
A2	Aquifer Storage & Recovery - Summer	0	$0.00	0	0		
D5	Seawater Desal 5 Summer	0	$0.00	0	0		

Simulation Results						
Portfolio Total Capacity m3/month	Portfolio Weighted Levelized Cost	Portfolio Standard Deviation	Portfolio Reliability	Min Reliability Figure	Capital Cost of Optimal Portfolio	Weighted Variable cost of portfolio
1,026,500	$1.29	11,104	97.90%	95.00%	$17,440,000	$0.679

8. **Annual Portfolio Assessment:** The Annual Portfolio Assessment sheet can be utilized to slightly adjust the optimal portfolio in order to reduce costs while sacrificing an acceptable level of reliability. It is comprised of the following sections:

   i. A table summarizing supply, cost and load factor of each water source:

COMPOSITE DATA FOR ALL WATER SOURCES				Scenario:	Urban Water and Agriculture Morocco #1		
Code	Water Supply Source	Technical Parameters			Financial Parameters		
		Potential Supply m3/year	Average Load Factor	Selected Annual Supply, m3/year	Unit Variable Cost, $ / m3	Annual Variable Cost, $ / Year	Capital Fixed Cost
BS	Surface Dam	931,600	1.00	931,600	$0.20	$186,320	$100,000
BG	Groundwater	3,600,000	1.00	3,600,000	$0.25	$900,000	$1,500,000
BD	Seawater Desalination	2,400,000	1.00	2,400,000	$2.03	$4,880,000	$2,000,000
S1	Purchase from Nearby Dam	1,800,000	1.00	1,800,000	$0.40	$720,000	$300,000
D2	Seawater Desal 2 All Year	864,000	1.00	864,000	$1.00	$864,000	$1,440,000
DR1	Direct Potable Water Recovery	1,440,000	0.00	0		$0	$0
A1	Aquifer Storage & Recovery 1	1,680,000	0.50	840,000	$0.40	$336,000	$1,800,000
D3	Seawater Desal 3 Summer	1,800,000	0.50	900,000	$1.00	$900,000	$2,700,000
D4	Seawater Desal 4 Summer	1,020,000	0.00	0		$0	$0
A2	Aquifer Storage & Recovery - S	900,000	0.00	0		$0	$0
D5	Seawater Desal 5 Summer	576,000	0.00	0		$0	$0
						Variable Cost	CAPEX
	TOTAL	17,011,600	0.67	11,335,600		$8,786,320	$9,840,000
	FUTURE DEMAND			9,355,088	Annual Reliability	Avg Unit Var Cost	CAPEX $/m3/month
					97.9%	$0.775	$13

ii. Solver zone is where the load factors of each project from the optimal portfolio are listed and will potentially be adjusted while keeping in mind the minimum acceptable level of reliability. The table to the right contains a summarization of the supply provided by each project within the portfolio at the selected load factors. This formulas within the table will need to be revised to include any additions beyond the premade structure of the sheet. This is easily done by simply linking cells into the formulas premade in the default table.

Solver Zone		
	Load Factors from User	Load Factors from Solver
BS	1.00	
BG	1.00	
BD	1.00	
S1	1.00	1.00
D2	1.00	1.00
DR1	0.00	0.00
A1	1.00	1.00
D3	1.00	1.00
D4	0.00	0.00
A2	0.00	0.00
D5	0.00	0.00

Min. Acceptable Reliablity in Worst Month			95%			
Month	Future Demand, m3/month	Chosen Supply Existing	Chosen Supply New Sources,	Total Chosen Supply,	Demand Met , m3/month	Portfolio One, m3/month
January	555,255	642,800	222,000	864,800	555,255	1,026,500
February	555,255	668,900	222,000	890,900	555,255	1,026,500
March	555,255	669,900	222,000	891,900	555,255	1,026,500
April	853,591	581,500	512,000	1,093,500	853,591	1,026,500
May	1,003,927	547,800	512,000	1,059,800	1,003,927	1,026,500
June	1,154,263	515,600	512,000	1,027,600	1,027,600	1,026,500
July	1,154,263	521,000	512,000	1,033,000	1,033,000	1,026,500
August	1,003,927	514,500	512,000	1,026,500	1,003,927	1,026,500
September	853,591	548,500	512,000	1,060,500	853,591	1,026,500
October	555,255	559,000	222,000	781,000	555,255	1,026,500
November	555,255	622,000	222,000	844,000	555,255	1,026,500
December	555,255	540,100	222,000	762,100	555,255	1,026,500
Series "Future Urban Potable Water" Point "F"						
TOTAL	9,359,088	6,931,600	4,404,000	11,335,600	9,107,163	12,318,000
RELIABILITY				Worst Month	97.9%	

iii. Separate tables for each project containing a breakdown of the potential supply throughout each month of the year along with their responsive chosen load factors, unit and monthly variable costs, standard deviations etc. The load factors present in each table are linked to the Solver Zone and automatically update with the solver solution.

BS	Surface Dam	Base Supply	Capacity =	300,000	CAPEX =	$100,000	1.00	
	Month	Potential Supply	Chosen Load Factor	Chosen Supply,m3/mont	Unit Variable Cost, $ /m3	Monthly Variable Cost	Standard Deviation	Weight in portfolio
	January	142,800	1.00	142,800	$0.20	$28,560	$55,983	16.51%
	February	168,900	1.00	168,900	$0.20	$33,780		18.96%
	March	169,900	1.00	169,900	$0.20	$33,980		19.05%
	April	81,500	1.00	81,500	$0.20	$16,300		7.45%
	May	47,800	1.00	47,800	$0.20	$9,560	Correl vs Surface	4.51%
	June	15,600	1.00	15,600	$0.20	$3,120		1.52%
	July	21,000	1.00	21,000	$0.20	$4,200		2.03%
	August	14,500	1.00	14,500	$0.20	$2,900	1.00	1.41%
	September	48,500	1.00	48,500	$0.20	$9,700		4.57%
	October	59,000	1.00	59,000	$0.20	$11,800		7.55%
	November	122,000	1.00	122,000	$0.20	$24,400		14.5%
	December	40,100	1.00	40,100	$0.20	$8,020		5.26%

BG	Groundwater	Base Supply	Capacity =	300,000	CAPEX =	$1,500,000	1.00	
	Month	Potential Supply	Chosen Load Factor	Chosen Supply,m3/mont	Unit Variable Cost, $ /m3	Monthly Variable Cost	Standard Deviation	Weight in portfolio
	January	300,000	1.00	300,000	$0.25	$75,000	$0	34.7%
	February	300,000	1.00	300,000	$0.25	$75,000		33.7%
	March	300,000	1.00	300,000	$0.25	$75,000		33.6%
	April	300,000	1.00	300,000	$0.25	$75,000		27.4%
	May	300,000	1.00	300,000	$0.25	$75,000	Correl vs Surface	28.3%
	June	300,000	1.00	300,000	$0.25	$75,000		29.2%
	July	300,000	1.00	300,000	$0.25	$75,000		29.0%
	August	300,000	1.00	300,000	$0.25	$75,000	0.30	29.2%
	September	300,000	1.00	300,000	$0.25	$75,000		28.3%
	October	300,000	1.00	300,000	$0.25	$75,000		38.4%
	November	300,000	1.00	300,000	$0.25	$75,000		35.5%
	December	300,000	1.00	300,000	$0.25	$75,000		39.4%

Some projects may be specified to operate only throughout specific months of the year. The load factor of months where the project is not operating may be set to zero.

D3	Seawater Desal 3 Summer	Capacity =	150,000	CAPEX =	$2,700,000	1.00	
	Mo Series "Future Urban Potable Water" Point "F"	Supply m3/month	sen Load Factor	Chosen Supply,m3/month	Unit Variable Cost, $ /m3	Monthly Variable Cost	Standard Deviation	Weight in portfolio
	January	150,000	0.00	0	$1.00	$0	0	0.0%
	February	150,000	0.00	0	$1.00	$0		0.0%
	March	150,000	0.00	0	$1.00	$0		0.0%
	April	150,000	1.00	150,000	$1.00	$150,000		13.7%
	May	150,000	1.00	150,000	$1.00	$150,000	Correl vs Surface	14.2%
	June	150,000	1.00	150,000	$1.00	$150,000		14.6%
	July	150,000	1.00	150,000	$1.00	$150,000		14.5%
	August	150,000	1.00	150,000	$1.00	$150,000	-1.00	14.6%
	September	150,000	1.00	150,000	$1.00	$150,000		14.1%
	October	150,000	0.00	0	$1.00	$0		0.0%
	November	150,000	0.00	0	$1.00	$0		0.0%
	December	150,000	0.00	0	$1.00	$0		0.0%

In a similar fashion to the LCOW Estimation sheet, if more tables are needed, copy and insert a premade table and follow the proper linkage of default tables to incorporate more projects.

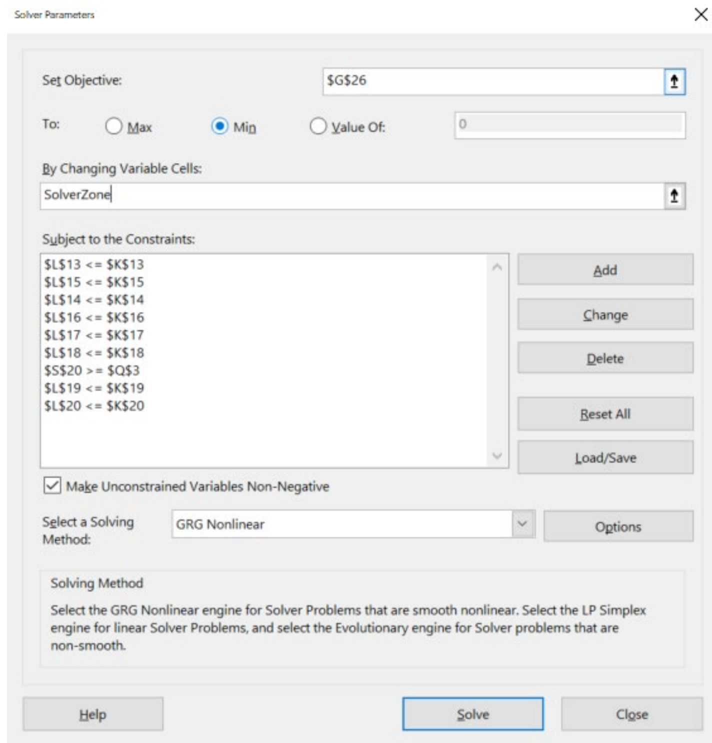
Solver Steps:

1) Ensure that the Solver Add in is enabled in Excel. To do so go to File > Options > Add-In > Solver > Enable
2) The Solver Zone is comprised of the load factors on the left that are directly grabbed from the Optimal portfolio selector. The load factors on the right are those that will be adjusted by solver. They are initially linked to the load factors on the left.

Solver Zone		
	Load Factors from User	Load Factors from Solver
BS	1.00	
BG	1.00	
BD	1.00	
S1	1.00	1.00
D2	1.00	1.00
DR1	0.00	0.00
A1	1.00	1.00
D3	1.00	1.00
D4	0.00	0.00
A2	0.00	0.00
D5	0.00	0.00

3) Make sure you are on the “Annual Portfolio Assessment” Sheet then go to the Data Tab, in the “Analyze” Section and click “Solver”

4) The following window will open:

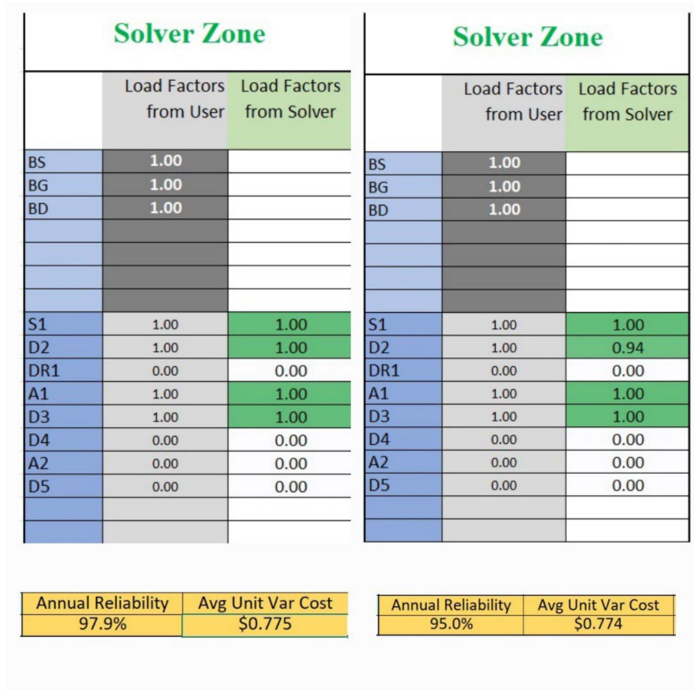


i. In the "By Changing Variable Cells:" area, enter the text "SolverZone". This will direct Solver to the Solver Zone in the sheet where load factors will be adjusted.

ii. In the "Subject to the Constraints" Section" ensure that there is a constraint for each cell (load factor from solver) on the right side of the Solver Zone to be equal to or less than the corresponding cell (load factor from user) in the same row on the left side of the Solver zone. This prevents solver from creating load factors that exceed that created by the optimal portfolio. Previously excluded projects will stay excluded and included projects do not receive a load factor above 1 (in many cases solver will not provide such irregular load factors however given the complexity of items involved the constraints ensure that such a chance is completely omitted). The objective cell is already set to minimize the Average Unit variable cost.

iii. Once the Solver Zone is specified and constraints are made click "Solve". (Note: In order to repeat the solver solution please save the produced result as a separate worksheet and open a new one as solver changes links which potentially break subsequent solver runs.)

5) If possible, the load factors will be adjusted with a resulting decrease in the Average unit Variable cost and decrease in reliability.



Solver Zone

	Load Factors from User	Load Factors from Solver
BS	1.00	
BG	1.00	
BD	1.00	
S1	1.00	1.00
D2	1.00	1.00
DR1	0.00	0.00
A1	1.00	1.00
D3	1.00	1.00
D4	0.00	0.00
A2	0.00	0.00
D5	0.00	0.00

Annual Reliability	Avg Unit Var Cost
97.9%	$0.775

Solver Zone

	Load Factors from User	Load Factors from Solver
BS	1.00	
BG	1.00	
BD	1.00	
S1	1.00	1.00
D2	1.00	0.94
DR1	0.00	0.00
A1	1.00	1.00
D3	1.00	1.00
D4	0.00	0.00
A2	0.00	0.00
D5	0.00	0.00

Annual Reliability	Avg Unit Var Cost
95.0%	$0.774

Note: In order to conduct a sensitivity analysis, create a template of SPOT tool with the initial input data and save it. Slightly adjust values as needed (usually load factors) and generate portfolios. The complexity of the model does not allow for sensitivity analysis to be conducted directly within the same open excel book without overwriting previous results.

3 Financial and Economic Cost of Water Supply Projects

The traditional analysis of water supply projects is often carried out using a cost-effectiveness approach, whereby the option capable of closing the water-supply demand gap at the lowest cost is selected. MPT takes an additional step in recognizing the variability of the volatility of water supply available from different sources and the correlation of different water supply projects in the portfolio of water resources. This, however, implies that the first step to apply MPT, is estimating the economic levelized cost of water (LCOW). LCOW is defined as the cost per unit volume of water produced by a given water supply source. The process of calculating the LCOW involves three steps (Figure 1). The first step requires estimating the financial cost of identified water supply technologies (i.e., financial capital, operating and maintenance expenditures). The second step involves deriving economic conversion factors to adjust for market distortions in the financial cost. The final step comprises estimating the economic cost and incorporating external costs that are not captured in the financial costs (e.g., emissions pollution).

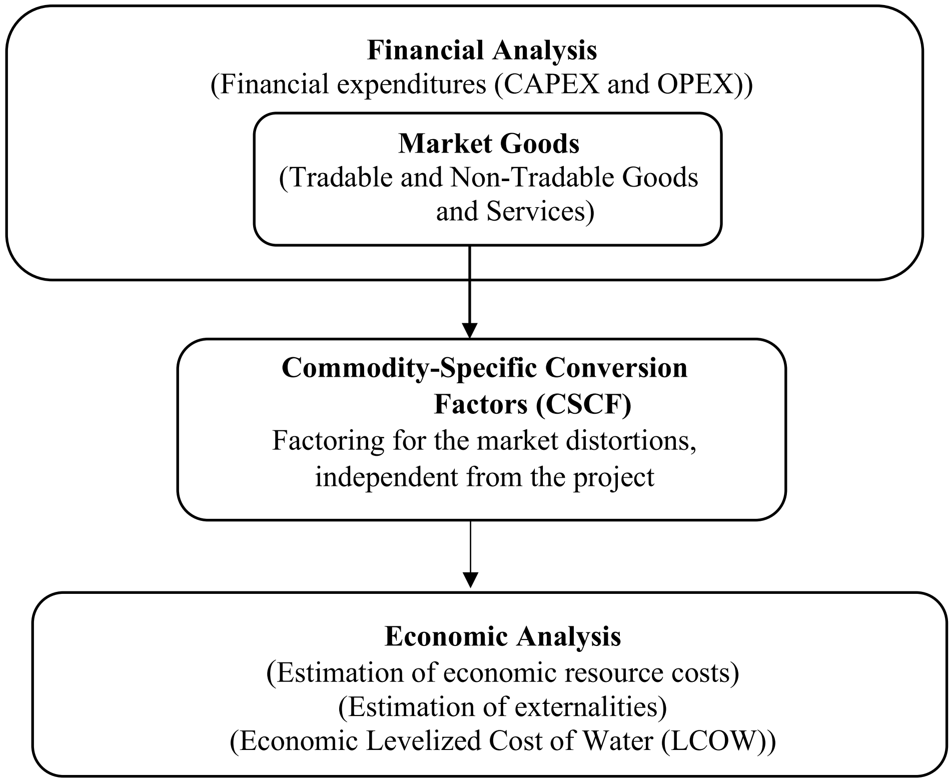


Figure 1: Economic Levelized Cost of Water: A Methodology Framework

3.1 Water Supply Options - Cost Components

Typical water supply infrastructure expenditures are categorized into capital, operating, and maintenance costs. Capital cost is often referred to as 'CAPEX' and is categorized into direct and indirect CAPEX. Direct CAPEX refers to expenses directly related to the physical construction and installation of water supply technologies. Examples of direct CAPEX include the cost of materials, equipment, labor, construction of reservoirs, pipelines, treatment facilities, etc. On the other hand, indirect capital costs are not directly associated with the project construction but with the implementation activities of the water supply project's completion. These include financing fees, environmental monitoring and mitigation, permits, legal and consulting fees, and other indirect capital costs.

Operating and maintenance costs, commonly referred to as OPEX, are ongoing expenses incurred to run and maintain a given water supply project. In the context of water supply technologies, the OPEX varies depending on the technology employed; these costs include energy, chemical labor, equipment replacement cost, repairs, and maintenance.

Seawater Desalination

The desalination process usually takes place in two different ways on large-scale levels: either as a thermal process such as Multi-Effect Distillation (MED) and Multi-Stage Flash (MSF) or through membrane technologies such as Reverse Osmosis (RO) (Saleh & Mezher, 2021). RO membrane-based technology is a common desalination method many countries use due to its energy efficiency compared to thermal desalination. Thus, the guideline focuses on RO seawater desalination plants.

The CAPEX components for a seawater RO plant comprise direct costs such as equipment (e.g., membrane equipment, pumps, filters, etc.), site development, building, pipelines, and other structures (e.g., intakes/outfall structures, storage tanks, etc.). At the same time, indirect CAPEX includes financing fees, engineering, legal, administrative, and contingencies. The direct capital cost components range from 50%-85% of the total CAPEX, while the remaining accounts for indirect costs (Ghaffour et al., 2012). The OPEX for desalination is divided into fixed and variable OPEX. The primary variable OPEX includes energy and chemicals (pre- and post-treatment chemicals). Costs of labor, maintenance, and insurance cost are usually included in the fixed OPEX. Energy is the most significant variable cost for desalination plants, accounting for 30-50% of the total variable cost of producing water.

CAPEX				OPEX
Direct Capital Costs				**Fixed OPEX**
Installed membrane equipment				Labor
Additional process items				Maintenance
Building & structures				Equipment and Membrane Replacement
Electric utilities & switchgear	Water treatment plant construction cost			**Variable OPEX**
Finished water storage				Power
High service pumping		Total project construction cost		Chemicals
Site development				Other costs (such as cartridge filters)
Miscelleneous plant items				
Supply intake/wells			Total Capital cost	
Raw water pipelines				
Finished water pipelines				
Waste concentrate/residual disposal				
Land				
Indirect Capital Costs				
Legal, administrative				
Interest				
Contingency				

Figure 1: Key factors for CAPEX and OPEX of a membrane desalination facility (Bergman, 2012)

Aquifer Storage and Recovery (ASR)

Construction, engineering, legal, and other construction-industry overhead are all included in the ASR CAPEX. The water supply option facilities consist of the following: the construction of one or more ASR wells and monitor wells; the installation of pumps, motors, wellhead piping, and valves; the construction of a small structure to house electrical, control, and disinfection facilities, and in some cases, the wellhead piping; the installation of well-field piping; the disinfection of water recovered from ASR storage; instrumentation and control systems; and, in some cases, the installation of standby emergency power generation (Pyne, 2014).

The OPEX components of ASR include energy, chemicals, disposal of residuals from any treatment processes, well maintenance and periodic rehabilitation, pump and motor maintenance and repairs, periodic backflushing to prevent well clogging, operation, and maintenance of controls, instrumentation systems, and disinfection, and a reasonable allocation of associated labor and overhead expenses (Pyne, 2014).

Wastewater Reclamation and Reuse

Recycled water is typically used for non-potable purposes, such as agriculture, landscape irrigation, industrial processes, and non-potable urban uses (such as toilet flushing, street washing, and fire protection).

While most water recycling projects were developed to meet non-potable water demands, several projects indirectly use recycled water for potable purposes. These initiatives include recharging groundwater aquifers and adding recycled water to surface water reservoirs.

The capital cost structure for wastewater reclamation and reuse may vary depending on the type of technology used. Some common wastewater treatment technologies include membrane technologies (reverse osmosis, membrane bioreactor, ultrafiltration) and disinfection technologies (ultraviolet radiation, chlorine dioxide, ozone, and peracetic acid). Membrane methods are critical for advanced wastewater reclamation and reuse schemes (Qin et al., 2006; Wintgens et al., 2005).

The CAPEX for RO membrane technology for wastewater reuse plants components includes site preparation, equipment (pumps, membrane, filters, cartridges and other equipment), construction (building, materials, labor), installation cost, design and engineering cost, permitting and legal fees, interest fees, and contingency. Civil CAPEX amounts to 60% of the total CAPEX for a typical water treatment and reclamation plant, while electrical and mechanical CAPEX amounts to 15% and 25 %, respectively (Swartz et al. 2014).

The OPEX components include human resources (personnel), maintenance and repairs (maintenance engineer, equipment replacement and infrastructures), insurance, raw water cost, energy, and chemicals (Swartz et al., 2014; Iglesias et al., 2017).

Surface Dam (Storage)

Typical capital cost for storage dams varies depending on several factors such as location, capacity and size. The CAPEX includes land acquisition and potential resettlement costs, engineering and design, construction materials and equipment, labor, permitting and legal fees, interest fees, and contingency.

The OPEX includes repair and maintenance costs and the annual operating cost. This may vary depending on the location and the specific project. These cost components include electricity, water testing, labor, and insurance cost.

3.1.1 Literature Review on Financial Cost of Water Supply Options

An ex-post evaluation study was carried out for several seawater reverse osmosis (SWRO) desalination plants in different regions across the globe[2] (Miklyaev et al., 2022). The analysis estimated and compared CAPEX and OPEX for different desalination plants with varying capacities. The average CAPEX per cubic meter of desalination plants with production capacity ranges from 100K-150K m^3/day equals 1,341 USD/m^3. Due to the economies of scale, the CAPEX for higher-capacity production ranges from 200K-250K m^3/day and 385K-625K m^3/day is estimated to be 1,149 USD/m^3 and 792 USD/m^3, respectively. The average OPEX across the different capacity groups ranges from 0.43USD/m^3 to 0.22 USD/m^3. The OPEX for desalination plants with production capacities range from 100K – 150K m^3/day is twice as much in comparison to desalination plant capacities ranging from 385K - 625K m^3/day (Table 5).

[2] Desal Plants in the Mediterranean Sea, Desal Plants in the Persian Gulf, Desal Plants in the Yellow Sea, Desal Plants in Algeria, Desal Plants in the Arabian Sea, Desal Plants in the Red Sea, Desal Plants in the North Sea, Desal Plants in the South China, Desal Plants in the Caribbean Sea, Desal Plants in the Gulf of Oman, Desal Plants in the North Pacific Ocean

Table 5: SWRO Desalination Plants Financial CAPEX and OPEX for Different Capacities (2008 Prices)

	Capacity (m^3/day)	CAPEX USD/m^3	Average CAPEX USD/m^3	OPEX USD/m^3	Average OPEX USD/m^3
1	100K - 150K	876 - 2,608[3]	1,341	0.26 - 0.77[4]	0.43
2	200K - 250K	739 - 2,117[5]	1,149	0.12 - 0.47[6]	0.28
3	385K - 625K	673 - 1,005[7]	792	0.22[8]	0.22

Source: Miklyaev et al., 2022

Bhojwani et al. (2018) found that the unit product cost[9] (UPC) for SWRO plants with capacities of 1 MGD[10], 2 MGD, 10 MGD, and 50 MGD equals \$1.401/m^3, \$0.893/m^3, \$0.82/m^3, and \$0.716/m^3, respectively. Cooley et al. (2019) estimated that the cost of large seawater desalination plants (> 20 million m^3) ranges from \$1.53/m^3 to \$1.93/m^3. While the cost of smaller seawater desalination facilities ($\leq$ 20 million m^3) ranges from \$2.10/m^3 to \$3.31/m^3 , with a median cost of \$2.13/m^3.

In general, operation and maintenance costs for seawater RO desalination (SWRO) are the most critical factors. A desalination plant's main variable cost is energy, ranging from one-third to more than half the cost of generated water (Chaudhry 2003). The average variable OPEX for desalination water supply is significantly higher (due to the high cost of energy) in comparison to the average fixed cost arising from its initial capital cost, unlike other conventional water supply technologies, such as dams, which typically have high capital fixed costs but relatively low operating and maintenance costs.

Aquifer Storage and Recovery (ASR) average unit capital costs are generally relatively lower compared to desalination (Pyne, 2014). The South Florida Water Management District (SFWMD, 2007) reported that the ASR average unit capital cost is \$1.24 million per million gallons per day (MGD) of recovery capacity. At the same time, the average annual operating and maintenance cost of four sites equals \$106,000 per MGD of recovery capacity (SFWMD, 2007). Tran et al. (2022) conducted a study of alternative water supply capital costs across a group of Water Management Districts in Florida, which showed a range of unit capital costs of \$0.50 to 2.00 million per million gallons per day (MGD). The results of Tran et al. (2022) are reviewed in more detail below. Vanderzalm et al. (2022) estimated that the levelized capital cost for an ASR small scheme of 1 Mm^3/y capacity to large scheme of 5 Mm^3/y capacity equals \$0.16/m^3 and \$0.05/m^3, respectively. While the levelized operating cost for 1 Mm^3/y capacity to 5 Mm^3/y capacity equals 0.09 to 0.05, respectively. With a five-fold increase in scale, the total levelized cost was reduced from \$0.25/m^3 for 1 Mm^3/y to \$0.10/m^3 for 5 Mm^3/y.

[3] Sample size of 25 desalination plants
[4] Sample size of 10 desalination plants
[5] Sample size of 17 desalination plants
[6] Sample size of 11 desalination plants
[7] Sample size of 4 desalination plants
[8] Sample size of 2 desalination plants
[9] The unit product cost is the sum of the CAPEX depreciated over the plant's life and its OPEX per m^3 of water treated.
[10] Million Gallons per Day

While wastewater reuse is more energy-efficient compared to seawater desalination[11], reuse incurs additional treatment costs, typically using advanced and complex techniques, unlike seawater desalination. Crutchik et al. (2021) study demonstrated that when municipal wastewater is processed in a standard wastewater treatment plant, and water flow demand exceeds 1500 m3/d, reuse of municipal wastewater is considered a cost-competitive alternative to seawater desalination. Chamaki et al. (2023) study showed the financial levelized for the RO treated wastewater plant at 50%, 75%, and 100% operation capacity levels equals $0.81/m^3, $0.73/m^3 and $0.68/m^3, respectively.

In terms of non-potable reuse cost, Cooley et al. (2019) found that small non-potable reuse facilities (with a capacity of less than 12 million cubic meters) have a median cost of $0.48/m^{3}with the range from $0.44/m^3 to $0.93/m^3. On the other hand, small indirect potable reuse projects have a median cost of $1.50/m^3, ranging from $1.21/m^3 to $1.80/m^3. While larger indirect potable reuse projects, due to economies of scale, have a cost range of $0.91–$1.28/m3, with a median cost of $1.06/m3 (Cooley et al., 2019). The cost of non-potable reuse is generally lower than that of potable reuse due to the reduced treatment requirements.

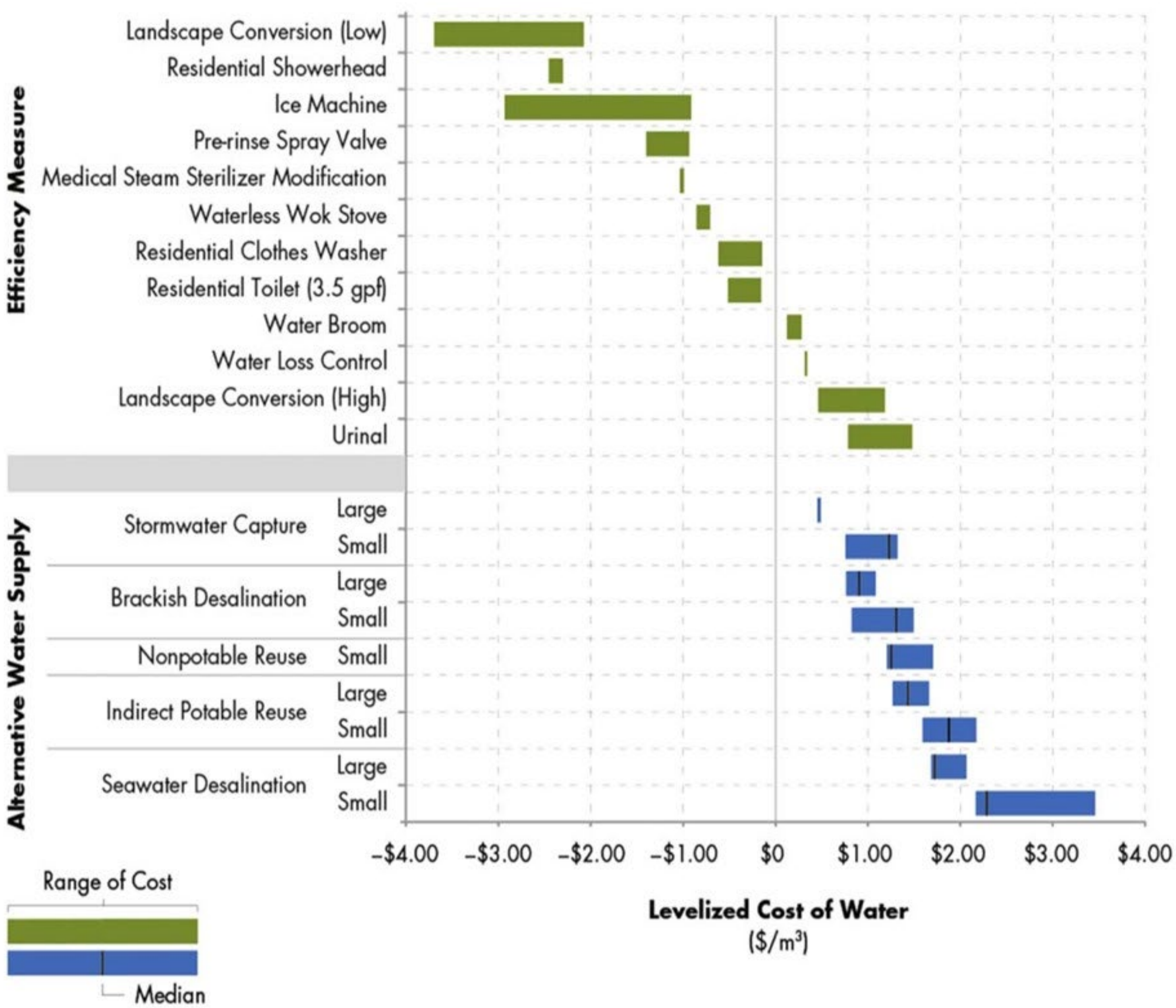
3.1.2 Comparison of Financial Costs of Various Demand Management Measures and Alternative Water Sources

Various studies have made comparisons of different alternative water supply systems/sources within a given geographical area. Because they are based on local capital and operating costs, results in one location cannot be used directly in another location with different technical and economic characteristics. Nonetheless, a review of a variety of such comparisons does show some commonalities – such as the very low levelized cost of urban or agricultural water efficiency measures. Beyond the specific results, these types of comparisons are useful for gaining a general understanding of cost levels when preparing and conducting a portfolio modelling analysis.

Cooley et al. (2019) compared the levelized cost of a variety of efficiency measures and new sources of supply for the case of California. The results, shown in Figure 3, show a very wide range of levelized costs from 2015 US $ -4.00[12] / m3 to 2015 US $4.00 / m3. For most of the Alternative Water Supplies, cost data are provided at small and large scale – with higher levelized costs at small scale.

[11] The concentration of total dissolved solids (TDS) in saltwater is often above 35 g/L, but the concentration of TDS in municipal wastewater is about 0.1-1 g/L. The higher TDS, the more energy is needed to generate enough pressure to flush them out. When compared to recycled water, the feed pressure requires for seawater desalination is four times higher (Dreizin, 2006).

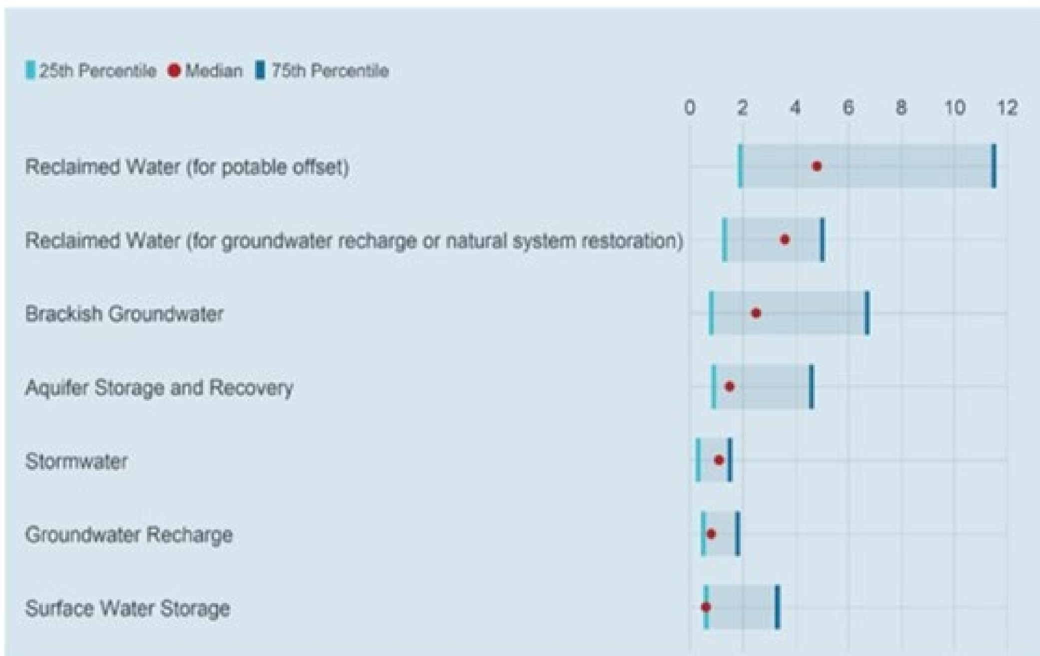
[12] A negative levelized cost indicates that, over its lifetime, a project or technology generates more economic value or financial returns than the costs associated with its development, operation, and maintenance.



Levelized cost of alternative water supplies and water conservation and efficiency measures, in 2015 dollars per cubic meter. Notes: All values are rounded to two significant figures. Costs for water supplies are based on full-system cost, which includes the cost to integrate the supply into a water distribution system. Ranges for water supplies are based on 25th and 75th percentile of project costs, except for large stormwater projects, which include the full cost range of the two projects. Conservation and efficiency measures shown in this figure represent only a subset of the measures examined in this study due to space limitations. Cost ranges for water conservation and efficiency measures are based on varying assumptions about the incremental cost and/or water savings associated with a measure. A rough estimate for the cost of new traditional storage systems in California is between $0.40 and $0.80 per cubic meter, excluding additional required costs of treatment, distribution, and use.

Figure 2: Levelized Cost of Water for Alternative Water Supply. Source: Cooley et al. (2019).

Tran et al. (2022) conducted a Modern Portfolio Theory analysis of water demands (both urban and agricultural) and potential supplies for various regions in the State of Florida, USA. The study analyzed costs and water supply for over 1800 projects in the State, mainly focused on alternative water supply sources and water demand management and conservation projects. Figure 4 provides a range of capital costs in Million US$ per Million m3/year. The costs of alternative supply options are highly variable within the same region, leading to a broad range of CAPEX. Groundwater recharge projects are among the least expensive alternative water supplies. The most expensive alternative water supply is reclaimed water, but it is also the most widely used one because of the potentially broad availability of reclaimed water in growing urban areas. Seawater desalination was not considered in the study.



Estimated Project Expenditures per Annual Unit of Capacity for Alternative Water Supply Projects (million USD 2021 per MCM). Data source: 2020 Annual Status Report on Regional Water Supply Planning, Florida Department of Environmental Protection (DEP)

Figure 3

In 2009, the Water Resources Group published a comprehensive study (WRG 2009) of the unit costs and available supply of a very broad range of water efficiency measures and new, alternative water supplies in India, China, Brazil and South Africa. Figure 5 below shows the framework for the presentation of the results, with unit costs on a vertical scale and water availability on a horizontal scale. The diagram, like Cooley (2019), shows measures with a negative cost (representing a net financial gain) and measures with a positive cost (representing a net financial cost). The scope of measures included activities and projects in the following sectors – Agriculture, Industry, Municipal and domestic and multi-purpose Supply.

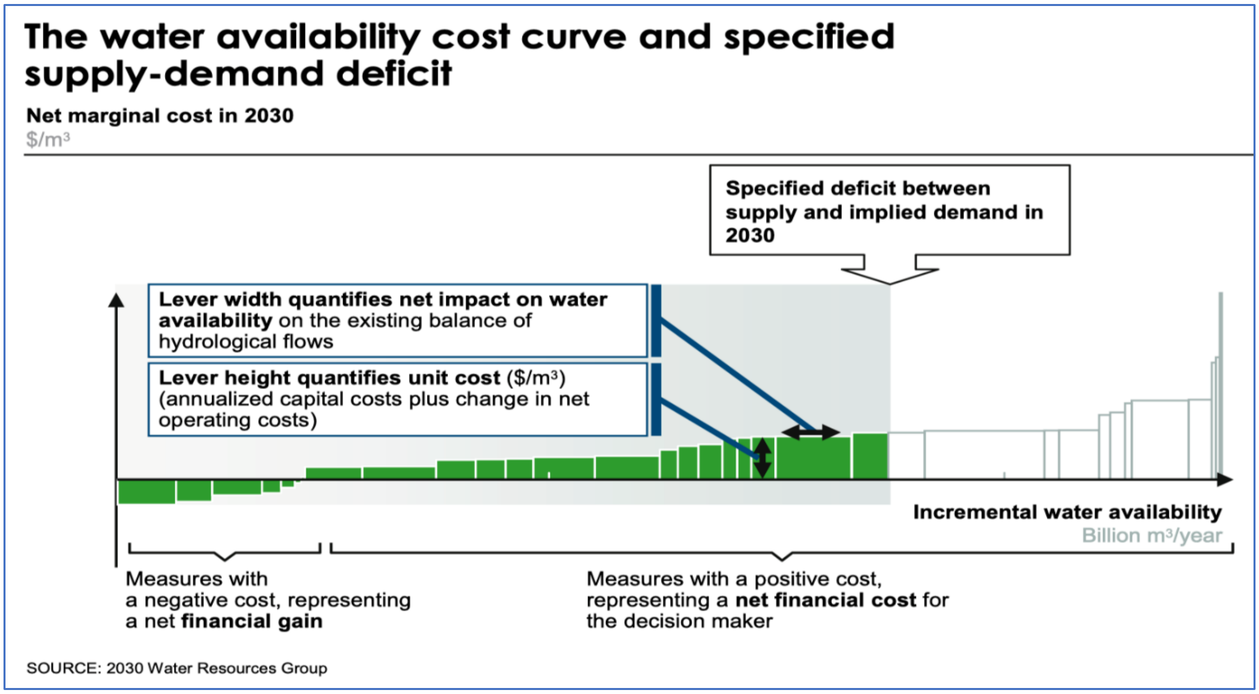


Figure 4

Figures 6 and 7 show the Water Availability Cost Curves for India and South Africa, including such measures as artificial recharge, wastewater reuse, on-farm canal lining, leakage reduction, and desalination, to name a few. These curves provide a unique perspective on the alternatives for closing the gap between supply and demand. WRG (2011) provides a similar analysis for Jordan.

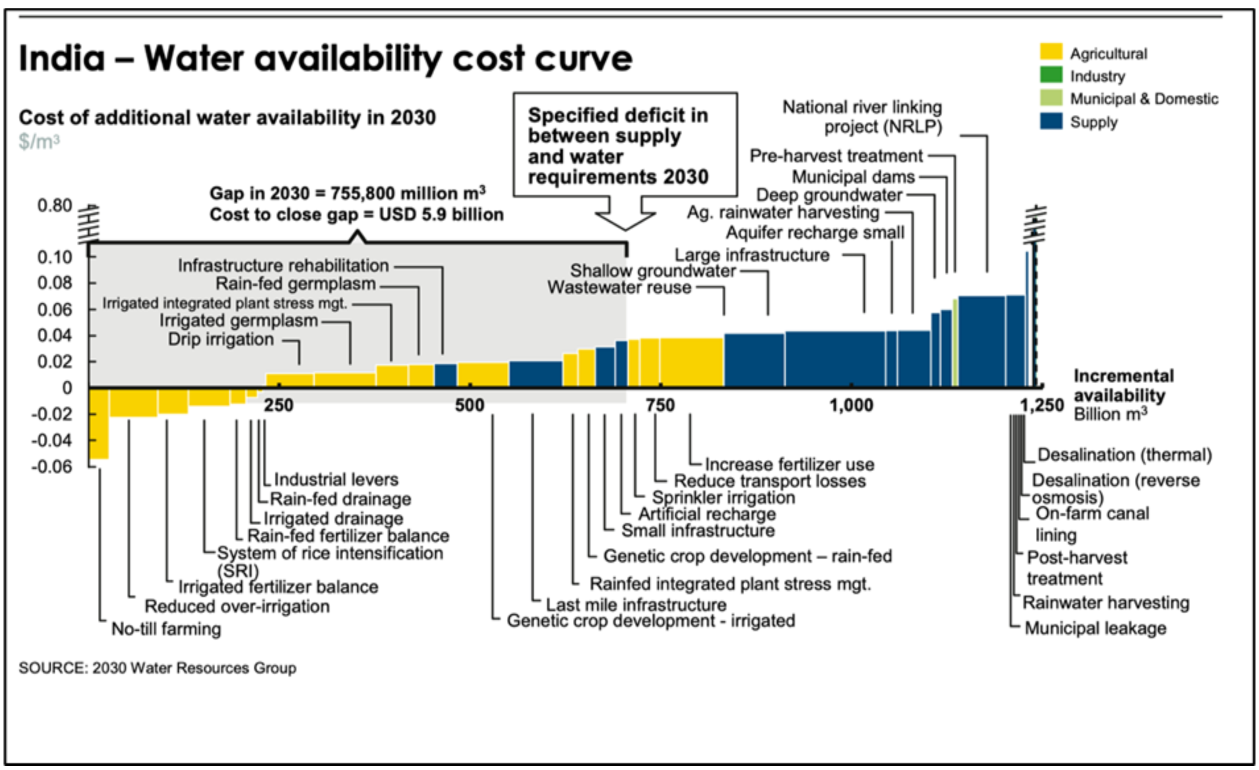


Figure 5

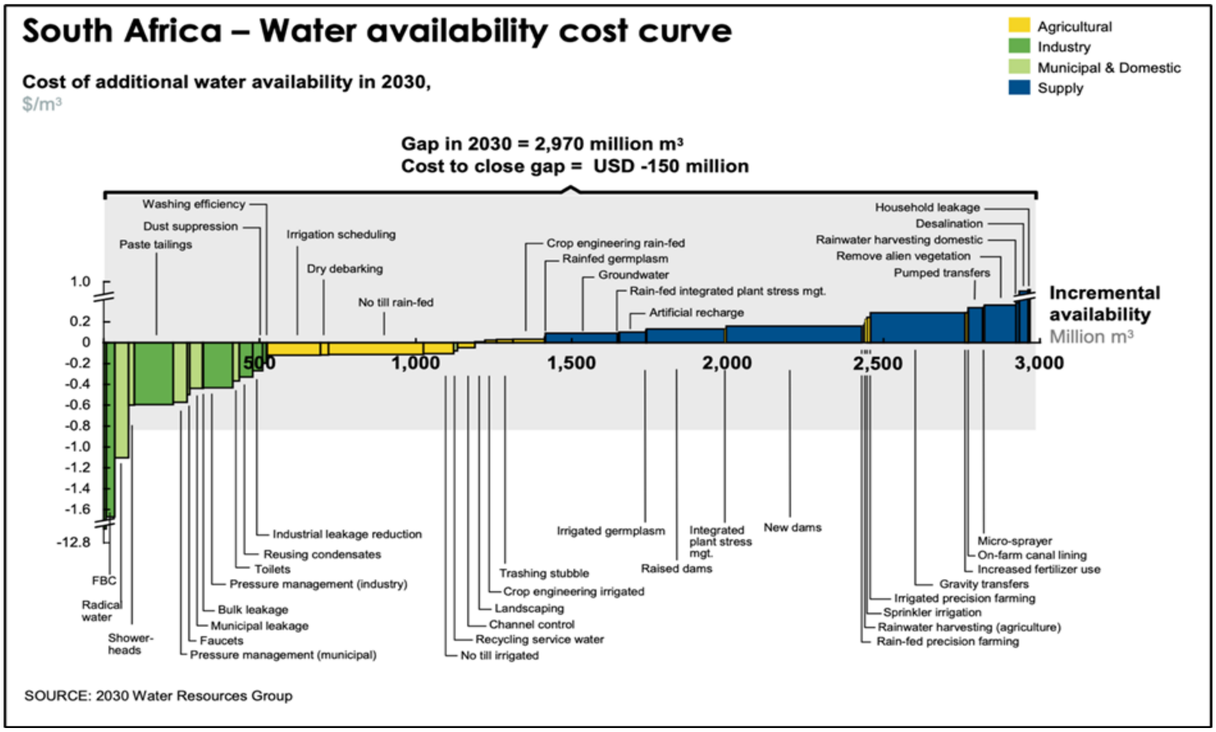


Figure 6

3.2 Importance of Economies of Scale

In general, understanding the economies of scale is important for the proper sizing of a water supply facility/project. If possible, larger facilities will be advantageous because of a lower unit cost, but larger facilities may not be possible or practical in many settings. Conventional engineering studies show that different water supply technologies have different economies of scale. For example, surface water dams have high economies of scale, whereas well fields have considerably lower economies of scale.

A capital cost function cost for well fields in Texas is provided in Figure 8 below (TWDB 2020) - which is a power function with a coefficient and an exponent. The higher the exponent, the closer the curve is to a linear function, indicating low economies of scale. A similar curve for surface water dams would be influenced by local factors but generally have an exponent of about 0.5 – 0.6.

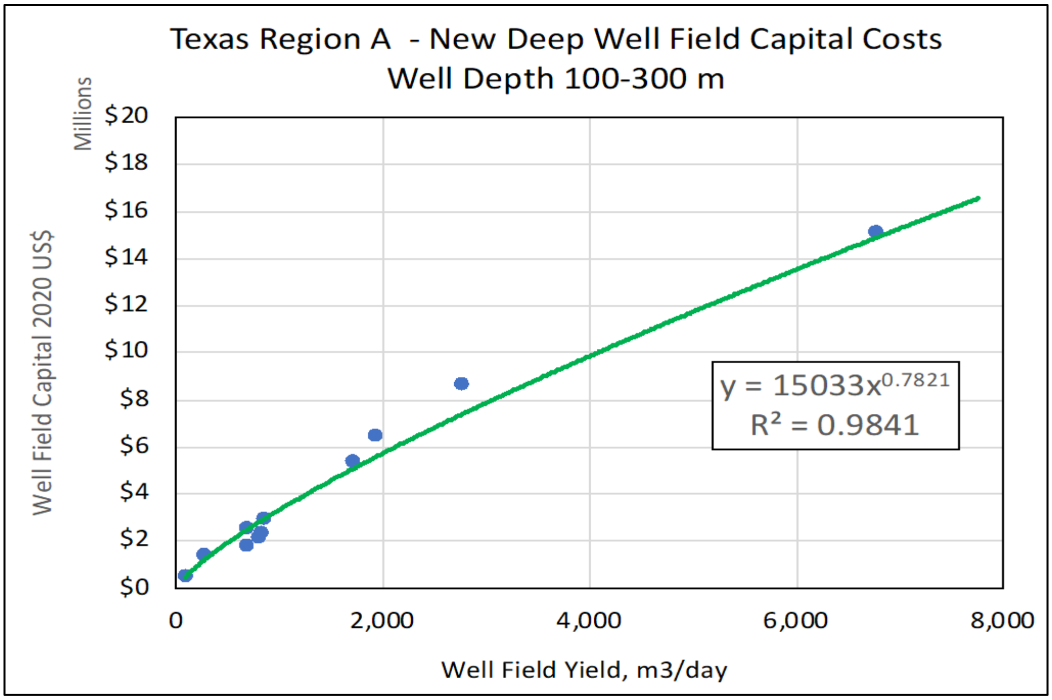


Figure 7

Ross and Hanain (2018) provides a graph of unit-levelized costs in 2016 US$/m^3 for a variety of types of managed aquifer storage projects in Australia, Netherlands, New Zealand and the USA. Figure 9 shows rapidly declining unit costs as scale increases – showing very large economies of scale.

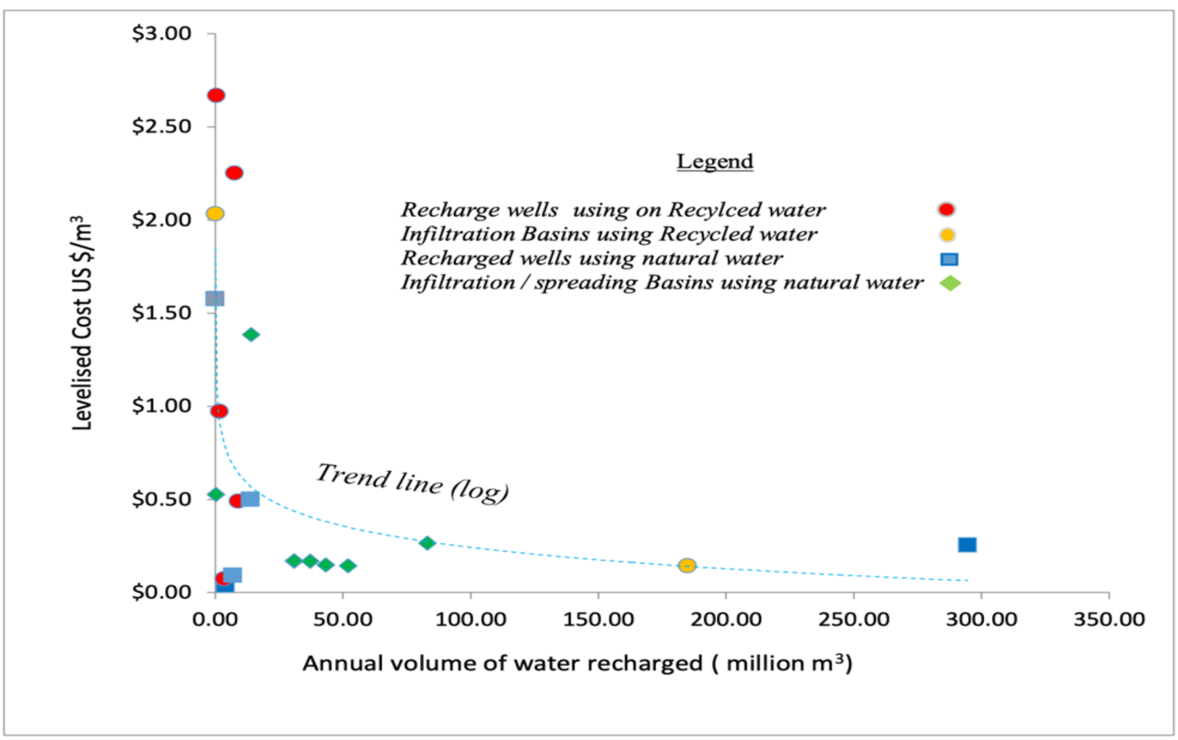


Figure 8

Wyatt (2022) provides the combined CAPEX and operational costs of 48 five-year NRW reduction projects in 19 countries. The total costs exhibit an economies of scale factor (exponent) of about 0.87, indicating that even small projects can be financially attractive.

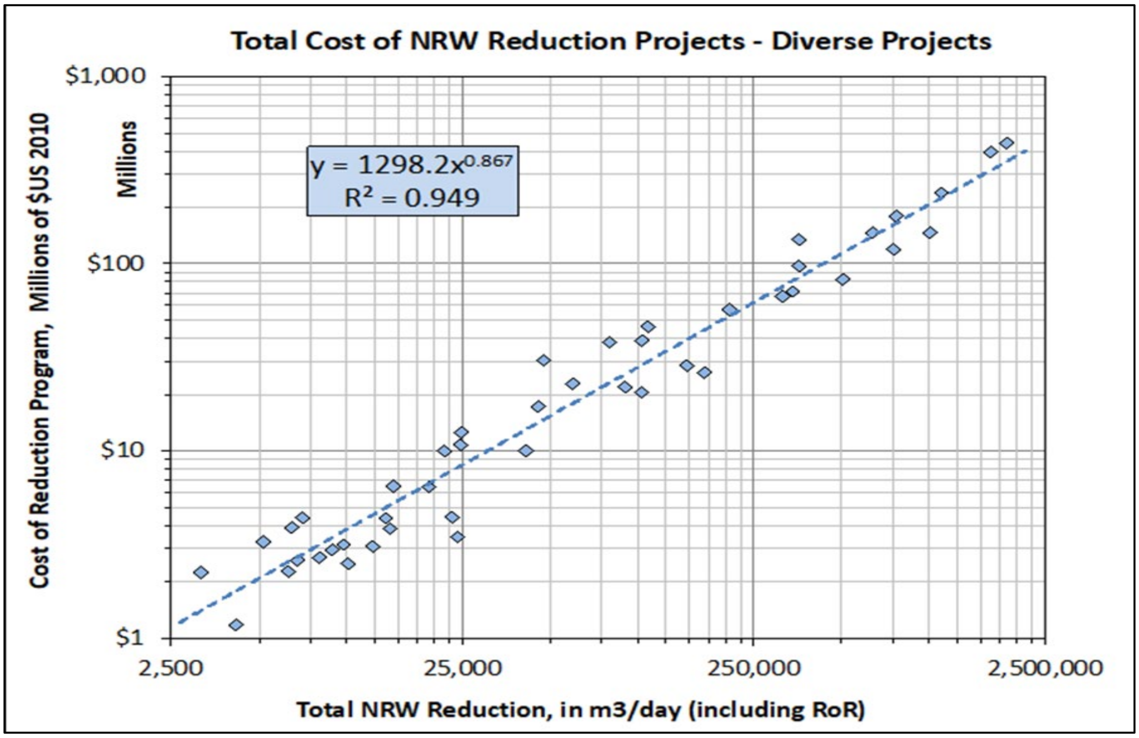


Figure 9

The economies of scale of water supply facilities are particularly important in the context of portfolio development and analysis using MPT. To capture economies of scale, a planner may include a large new water supply facility. However, a single large facility may end up dominating the selected portfolio in terms of water supply (m^3/month). If so, the tradeoffs between different possible facilities/sources will be diminished. In other words, the portfolio will be “lumpy”. Ideally, portfolio optimization would include many small projects of different types of facilities – each with its own variance and correlation with other new and existing supplies. A lumpy portfolio dominated by a large facility will result in an uneven, erratic portfolio frontier, which may not result in full optimality. So, there is a tradeoff between “capturing” economies of scale and “capturing” the most optimal portfolio.

3.3 Importance of Financial Fixed and Variable Cost Differentiation

The financial water supply project expenditures include capital, operating, and maintenance costs. The application of MPT also requires an analyst to break down these costs into fixed and variable costs. In the context of water supply projects, the fixed cost consists of two cost components: the investment (i.e., actual construction) and the fixed operating and maintenance (O&M) cost (e.g., labor, administration, general cost). The variable cost is categorized into two sections: electricity cost and variable O&M cost (e.g., chemicals, repairs, auxiliaries).

Box 1. Disaggregation of Project Costs - Fixed and Variable Costs

Suppose the current demand for water per month is 100 m^3, and the current supply is 90 m^3 (surface water), resulting in a shortage of 10 m^3. The traditional approach would select the most cost-effective water supply project to provide the 10 m^3 ignoring the reliability factor. On the other hand, the MPT approach first recognizes the project's standard deviation and the correlation of the standard deviation with the existing water supply source or alternative water supply projects. For example, suppose a desalination plant is to cover the deficit of 10m^3, in this case, this desalination has no correlation coefficient or correlation coefficient with the existing surface water is zero. Alternately, if a groundwater project is selected, there is a positive correlation of one with the existing surface water supply.

In estimating portfolio reliability, portfolio reliability requires analysis of the load factors of individual projects. Addition of a water desalination plant to a portfolio of water supply projects in order to meet prevailing deficit or growth in water demand over time would imply that the project will have a load factor equal (or close) to 1. The correlation coefficient with groundwater resources will in this case be zero. In turn, one can achieve reliability improvements by adding desalination project to an existing portfolio of assets as a "reserve plant", in this case the load factor will be less than 1 as the plant will only operate in situations where there is a water shortage, however, a more desired correlation coefficient of -1 (or close to it) can be achieved. Disaggregation of project costs into fixed and variable costs is therefore essential to correctly capture total cost of the "reserve plant" operations.

3.4 Constant-Reliability-Benefit Unit Costs

Suppose water supply planners ignore the reliability factor; in that case, decision-making would be based on the lowest LCOW options. However, if water supply planners fail to consider reliability, they may incorrectly conclude which alternatives are the most cost-effective. In addition, they may mistakenly conclude that several solutions have similar costs when, in fact, they differ significantly when the reliability benefits of the options are compared. For instance, surface water, desalinated seawater, or recycled wastewater have significantly diverse yield structures. Therefore, the unit cost of water supply options requires further adjustment. Constant-reliability-benefit unit cost provides a fairer comparison between water supply options with different uncertainty characteristics (Wolf and Kasower 2006).

Box 2. Constant-Reliability-Benefit Unit Costs - Sample Illustration

For illustration purposes, suppose that desalination, a new surface water supply, and outdoor conservation all have an average cost of 1 US$/$m^3$. Ignoring the reliability effects, there is no significant difference in cost between these options. However, using a constant-reliability-benefit cost approach changes the outcome of the cost when the reliability impact is factored in.

Let's assume that the estimated amount of water required to satisfy the growth in critical (drought) year demand (S_N) for an existing run-of-the-river water supply equals 600 m^3. The planner chooses a 95% level of reliability (implying a 1.65 standard deviation). If a supply option were to provide exactly this amount every year, the planner should invest in S_N of new supply. The question then is how much water should the new supply option (A(N)) provide in order to achieve the S_N ?

Water Supply Option	Coefficient of Variance V(N)	Coefficient of Supply Options (Rho (E, N))	A(N)	Average Unit Cost	Constant-Reliability Benefit Unit Cost
Surface Water	20%	1.0	896 m^3	1 US$/$m^3$	1.49 US$/$m^3$
Desalination	0%	0.0	600 m^3	1 US$/$m^3$	1.00 US$/$m^3$
Outdoor Water Conservation	10%	-1.0	515 m^3	1 US$/$m^3$	0.86 US$/$m^3$

In this case, we assume that the desalination remains constant across different years and is not correlated with the existing water source. Therefore, a plant built to produce 600 m^3per year will meet demand growth in all years. When averaging the critical and non-critical years, the unit cost remains constant.

On the other hand, the new surface water supply is perfectly correlated with the existing surface water supply (having the same pattern of wet and dry years), but more variable. If the coefficient of variation of the new surface water supply is 20%, then the water planner will need to acquire 896 m^3 in a typical year in order to guarantee 600 m^3 in the 95% reliability design year (896 - 1.65 x 0.2 x 896 = 600). This means that each unit of water during drought will cost 1.49 US$/$m^3$ on a constant-reliability benefit basis (US$1.00/ (1 – 1.65 x 0.2)).

If an outdoor water conservation solution saved more water during dry weather, its constant-reliability unit cost would be less than the assumed average 1 US$/$m^3$. If it were perfectly counter-correlated with the existing surface water source, and had a coefficient of variation of 10%, its constant-reliability unit cost would be $0.86 US$/m^3 ($1.00/(1+1.65 x 0.1)). Outdoor conservation measures sized to deliver only 515 m^3 per year on average would be needed to guarantee 600 $m^3$of water in the critical year.

Source: (Wolff 2006)

3.5 Estimation of Economic Cost

The economic cost estimation for water supply projects is carried out in two stages. Firstly, the water supply project's financial expenditures must be converted into economic resource costs using the economic conversion factors. In this stage, the financial costs are adjusted for market and fiscal distortions (e.g., taxes and subsidies). Secondly, the economic appraisal further incorporates the external costs associated with a given water supply technology that is usually not captured in the financial costs (e.g., pollution emission costs).

Box 3. Difference Between Financial and Economic Cost of Water Supply

Financial	Economic
• Includes market and fiscal distortions (e.g., taxes, subsidies). • Does not take into account other external costs other than that incurred by the project. • Financial levelized cost of water is an essential parameter input in estimating the cost recovery of end-user tariffs.	• No market distortions. • Takes into account broader external effects such as environmental cost (i.e., pollution). • Economic levelized cost of water is a decision-making metric used in comparing different alternative water supply projects.

3.5.1 Commodity-Specific Conversion Factors (CSCFs)

Financial prices are the market prices of commodities and services that include the impacts of government intervention and distortions in the market structure, such as taxes and subsidies. Taxes and subsidies are considered transfers from one group of the society to another. Thus, the financial expenditures of the given water supply project (CAPEX and OPEX) must be adjusted for any distortions by using the economic conversion factors (CFs) to convert the financial costs into economic costs.

A conversion factor (CF) is the ratio of a commodity's economic value to its financial value. Market distortions (externalities), such as taxes, subsidies, market imperfections, foreign currency premium (FEP) impact, and labor market distortions, are captured in conversion factors (Jenkins et al., 2019).

The inputs used by projects are generally divided into internationally tradable[13] and non-tradable[14] (domestic market) goods. The approach for estimating the conversion factors for these two categories of goods is different (Jenkins et al., 2019).

[13] Internationally traded goods are classified into importable and exportable goods. The domestic price of these commodities remains unchanged in response to a change in demand or supply by a country, but there will be an impact on the foreign exchange market that will affect the demand or supply of foreign exchange.

[14] A good or service is considered non-tradable when its domestic price is determined by local demand and supply.

In estimating the conversion factor for a tradable good, suppose that a project uses an imported input, e.g., membrane equipment or steel; the economic opportunity cost is the cost-plus insurance and freight (CIF) adjusted for the foreign exchange premium (FEP) and excluding any customs duties or taxes that are reflected on the financial cost of such importable good.

Box 4. Illustrative Example of the Estimation of Conversion Factors

Estimation of the Conversion Factor for Membrane Equipment (An Importable Input used in the Construction of a Desalination Plant Water Project)

Financial Cost of Membrane Equipment		***Economic Cost of Membrane Equipment***	
CIF Price	\$60,000	CIF Price	\$60,000
		FEP (6.5% of CIF)	\$3,900
Import Tariff (12% of CIF)	\$7,200	Import Tariff (12% of CIF)	-
Freight	\$1,500	Freight (75% of the financial cost of freight)	\$1,125
VAT (10% of CIF + Tariff)	\$6,720	VAT (10% of CIF + Tariff)	-
TOTAL	**\$75,420**	***TOTAL***	**\$65,025**

$$\text{Conversion Factor} = \frac{Economic\ Value}{Financial\ Value} = \frac{65{,}025}{75{,}420}$$

CF = 0.86 (The economic value of membrane, in this case, is 86% of its financial value)

The conversion factors estimation for non-tradable goods and services, such as electricity, construction services, etc., are more complex in comparison to tradable goods. The CFs for non-tradable goods and services take into account all repercussions of the project in the economy by capturing all distortions in direct product and indirect input markets of the non-tradable (Jenkins et al., 2019).

Furthermore, as one of the major input costs for each water supply option is labor, it is critical to incorporate all the relevant distortions to accurately estimate the economic opportunity cost of labor (EOCL). These distortions arise from income taxes, social security contributions, employment insurance, labor union monopoly power, enforced minimum wage laws or any other type of tax or subsidy in the project's labor markets (Jenkins et al.,2019). Hence, the CF for labor is the ratio of the EOCL to the financial project wage.

Once the conversion factors for each cost component for a given water supply option have been estimated, the economic CAPEX and OPEX will be derived by multiplying financial CAPEX and OPEX by their corresponding conversion factors (**Error! Reference source not found.**).

Table 6: Application of Conversion Factors to Project Inputs - Illustrative Example

		Financial Cost (Mil USD)	Conversion Factor	Economic Cost (Mil USD)
A. CAPEX				
	Membrane Equipment	33.5	0.84	28.1
	Pressure Pumps	24.5	0.85	20.8
B. OPEX				
	Labor	28.5	0.82	23.4
	Chemical	39.4	0.88	34.7
	Electricity	95.7	1.21*	115.80

*The conversion factor is greater than one due to energy subsidies. Hence, the financial input cost of the electricity is less than the actual economic cost. In the case of desalination water supply, whereby energy cost is a significant portion of the total cost of water supplied, this would result in a significant fiscal impact.

3.5.2 Economic Valuation of Non-Market Externalities

Another aspect of the economic appraisal is the valuation of the external costs associated with a given water supply project. There are several examples of these kinds of externalities, but in general, they are not accounted for in the financial cost but in the economic cost. The environmental impact is a typical example of a non-market externality. Such externalities that can be monetized are evaluated in economic analysis to internalize their costs.

Air pollution and greenhouse gas (GHG) emissions are prominent environmental externalities of the identified water supply options. The social cost of pollution generated by the electricity used during the construction and operating period of the water supply project must be incorporated into the economic cost. Emissions components may be broken down into two categories. First, certain emissions have an effect on the health and physical assets of the local communities, such as sulfur dioxide (SO_x), particulate matter (2.5 μm and less in size) and non-methane volatile organic compounds (NMVOCs). Second, there are greenhouse gases that have a global impact. These include the global emissions of carbon dioxide (CO_2), methane (CH_4) and Nitrous oxide (N_2O).

Box 5. Illustrative Example of Economic Valuation of Externality Cost (Emission)

Due to the large amounts of energy required for operation, air pollution and greenhouse gas (GHG) emissions are significant environmental externalities resulting from the water supply through desalination technologies. Thus, these external costs are quantified and included in the economic cost of desalinated water supply.

The economic evaluation of emission costs is derived following the steps below;

i. Calculate the annual electricity consumption by the desalination plant
ii. Estimate the total MMBtu (million British thermal units) fuel required to generate this electricity
iii. Estimate the quantities of pollutants emitted per MMBtu through generating this quantity of electricity when using the types of plants that are employed in a given country
iv. Estimating the monetary value of this cost using an economic price such as the social cost of GHG emissions by applying the simplified formula below:

$$\text{Cost of GHG emission} = C_{GHG} * V_{CHG}$$

Where:

- V_{CHG} is the volume of the greenhouse gas emissions generated by the undertaking the project, expressed in CO_2 equivalents
- C_{GHG} is the social cost of CO_2, expressed in constant prices of the year in which the analysis is conducted

Annual data of calculated emissions factors of a country's electricity grid can be extracted from internationally recognized databases such as the Institute for Global Environmental Strategies (IGES), National and European Emission Factors for Electricity Consumption (NEEFE), International Energy Agency (IEA), the United States Environmental Protection Agency (EPA). Annex B presents the estimated default grid emissions factors for MENA countries (IFI TWG, 2022).

Various organizations and governments use different calculation methodologies and discount rates to estimate the social cost of greenhouse gases. Table 5 presents the interim estimates of the social cost of carbon, methane, and nitrous oxide produced by the Interagency Working Group (2021).

Table 7: Social Cost of Greenhouse Gases (in 2020 USDs, @2.5% discount rate)

Social cost of GHG (USD per metric tonne)	Year		
	2020	2025	2030
Social cost of carbon (CO_2)	76	83	89
Social cost of methane (CH_4)	2,000	2,200	2,500
Social cost of nitrous oxide (N_2O)	27,000	30,000	33,000

Source: Interagency Working Group-United States Government (2021)

The estimated external emissions costs are incorporated into the economic cost, which directly fits into the portfolio model through the economic levelized cost of water.

There are additional externalities that are challenging to monetize but are essential to identify the effects in physical terms for a qualitative evaluation to provide decision-makers with further information when considering multiple alternative water supply options. The classifications of these externalities are in terms of water quality, ecosystem and biodiversity, as listed in **Error! Reference source not found.**.

Table 8: Non-Monetary Environmental Externalities for Water Supply Options

Water Supply Option	Environmental Externalities
Desalination	• Highly concentrated brine discharge, which also contains other chemical contaminants - These discharges have the potential to degrade coastal water quality and harm marine life by increasing salinity, water turbidity and temperature • Impingement and entrainment of marine species due to seawater intakes
Dam	• Water quality deterioration • Impact on aquatic ecology: obstacles in fish migration, extinction, and death of marine species, etc. • Changes in stream flow, sedimentation and flooding • Alterations in aquatic and wetland ecosystems
Aquifer Storage and Recovery	• Water quality impacts • Ecological disruption • Aquifer contamination

Source: Miller et al. (2015), Frank et al. (2019), Kress (2019), Petersen et al. (2019), Omerspahic et al. (2022), Haddad et al. (2018), Alla and Lui (2021), Overacre et al. (2006), Min L. et al. (2021)

Qualitative and Quasi-Quantitative Methodologies

In the case of externalities that are challenging to monetize, evaluators of desalination and water reuse projects generally resort to qualitative and quasi-quantitative approaches. These methods allow for analyzing and evaluating intangible ecological impacts.

Environmental Impact Assessment (EIA) is one of the methods for evaluating a project's prospective environmental impacts. It seeks to recognize, foresee, and assess potential environmental effects, including those that may not have direct monetary value. Hoepner (1999) study detailed a minimal guideline for EIA-proposed procedures for seawater desalination plants. The proposed strategies consist of five steps: (i) analysis of the source of impacts, (ii) analysis of the impacted ecosystem, (iii) definition of the links between source and targets, (iv) recommendation of mitigation measures, and (v) sustainability of the environmental protection measures. EIAs often incorporate qualitative evaluations of numerous ecological elements that might help understand water supply projects' overall externalities. These considerations can include biodiversity loss, habitat degradation, and changes in water quality. Many analyses have been performed to evaluate the EIAs for desalination and water reuse projects. Studies by Lattemann & Höpner (2008), Saleem (2010), and Soliman et al. (2021) are among the significant contributions to this field. It should be noted that there are other externalities that cannot be factored into portfolio simulation, as well as other forms of quantitative appraisal.

An alternative approach involves performing qualitative experiments, such as interviews and surveys. These methods aim to collect data on how stakeholders perceive the situation and address community concerns regarding the consequences of the water supply option. Kerman (2016) study evaluated the environmental externalities of excessive groundwater extraction using the choice experiment (CE) method and conditional logit model to extract the residents' willingness to pay to improve the non-monetary environmental attributes. Han et al. (2008) study assessed multiple environmental impacts caused by large dam construction using the CE approach to measure economic values for individual attributes of environmental impacts caused by large dam construction.

3.5.3 Estimation of Economic Levelized Cost of Water

The main output of the economic analysis of the water supply project is the levelized cost of water (LCOW). To compare water supply options of different scales of operations or other relevant factors, this LCOW takes into consideration the total economic CAPEX, OPEX and external cost of each potential option throughout the project's useful life.

When estimating the Levelized Cost of Water (LCOW) for desalination and water reuse projects, a specific issue to be particularly cognizant of is the accurate assessment and inclusion of external costs. These projects often have significant environmental and social externalities that are not fully captured by traditional capital and operational cost analyses. For desalination, external costs might include the environmental impact of brine disposal on marine ecosystems, energy consumption and its associated carbon footprint, and potential impacts on local communities and marine life. For water reuse projects, externalities could encompass the costs associated with public health risks if the treated water is not adequately purified, as well as the societal implications of changing public perceptions and acceptance of recycled water.

The LCOW may be used to construct the least-cost plan by rating the alternatives based on their cost-effectiveness in reaching the desired objective, given the variety of options that may be proposed to address future water demands. LCOW is defined as the ratio of the present value[15] of the total cost of a water supply project to the present value of the water produced by that project over its operating life, as expressed in the formula below:

$$\text{LCOW} = \frac{\text{PV CAPEX} + \text{PV OPEX} + \text{PV Ext.Cost}}{\text{PV } \text{Q}^{\text{W}}}$$

where:

- PV CAPEX is the present value of the economic capital expenditure over the life of the project at a given economic discount rate
- PV OPEX is the present value of the economic operation and maintenance expenditure over the life of the project option at a given economic discount rate
- PV Ext.Cost is the present value of externality cost, e.g. pollution emission cost over the life of the project at a given economic discount rate. Calculating the present value of externality costs for desalination and water reuse projects involves identifying environmental impacts, energy consumption, and social implications, then quantifying and monetizing these impacts. Environmental costs might include the effects of brine discharge on marine ecosystems or the carbon emissions from energy use, while social costs could consider public health impacts or changes in water usage patterns. These costs are then discounted to their present value using an economic discount rate and incorporated into the Levelized Cost of Water (LCOW) calculation.

[15] There is a need to account for what is commonly referred to as "the time value of money" when evaluating the monetary outcome of undertaking a project over a long period of time. Thus, all future expenditures are brought back to the present and summed in order to have comparable costs. This process is called discounting. The economic opportunity cost of capital (EOCK) is an appropriate discount rate to use in calculating the present value of the economic expenditures of the alternative water supply options.

- $PV\ Q^W$ is the present value of the quantity (volume) of water produced over the life of the project at a given economic discount rate

4 Willingness to Pay for a Reliable Water Supply

Improved planning is necessary to ensure the long-term viability and repeatability of water projects. This planning could involve surveying households to determine the relative importance of different service levels. The concept of "willingness to pay" (WTP) is fundamental to any such refined approach to planning.

The WTP concept generally refers to the economic value of a good/service to an individual (or household) under specified conditions (Gunatilake, 2007). In the context of water supply projects, the WTP is the maximum amount an individual is willing to pay for an improved water supply service, quality, or reliability. The information provided by WTP values is essential for water planners at all levels (national, provincial, municipal, and rural), including analyzing the economic viability of a project, developing socially fair subsidies, establishing reasonable tariffs, evaluating policy options, and assessing financial sustainability (Gunatilake et al., 2006; Perez-Pineda & Quintanilla-Armijo, 2013). Estimating the difference between the consumer's maximum WTP and the actual cost may assess the net economic benefits of an improved water supply service, quality, or reliability [16] (Figure 11).

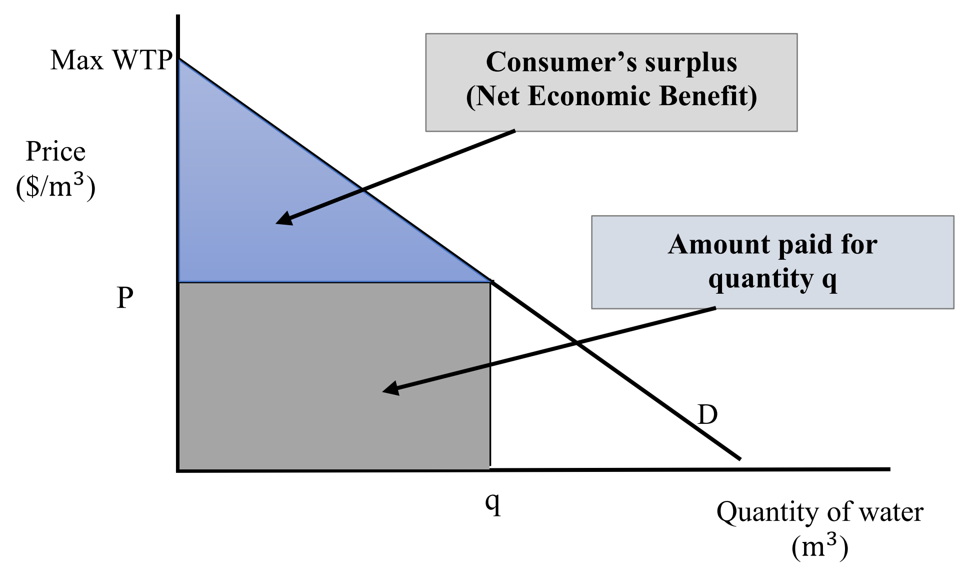


Figure 10: Demand Curve, Consumer Surplus, Willingness to Pay

Estimates of households' WTP are often made using one of two primary theoretical approaches: stated preference techniques or revealed preference methods. The study of environmental economics and public policy often uses these methods to assess the monetary value people assign to a variety of goods and services. The stated preference method is a survey-based approach used to determine an individual's WTP for an improvement in the quality or quantity of specific goods or services (Bateman et al., 2006). These methods are especially helpful when there are no existing market transactions for a given good or service. The foremost widely used types of stated preference approaches are contingent valuation and choice experiments. Contingent valuation, also known as the 'direct' approach, involves people responding to

[16] For a more in-depth analysis of this subject, see Jenkins et al., 2019.

hypothetical scenarios in which they are directly about their preferences and willingness to pay for publicly provided goods and services (Carson & Louviere, 2011; Johnston et al., 2017). On the other hand, Choice experiments divide the description of the environmental good into physical attributes, with varying levels for each attribute, and ask respondents to choose between two or more multi-attribute alternatives (Johnston et al., 2017).

The revealed preference approach entails determining an individual's implicit value of a specific environmental good based on actual behavior (Wittink, 2011). The method involves the study of people's preferences as indicated by market activities, which are significantly related to the value of the given environmental good or service. The travel cost and hedonic pricing methods are examples of revealed preference methodologies used to estimate WTP for publicly supplied goods and services.

Box 1. Direct and Indirect Approach in Estimating Willingness to Pay for Improved Water Supply Services

There are two main theoretical techniques that can be used to accurately estimate households' willingness to pay for improved water supply services.

The first, the "indirect" approach, uses data on observed water use behavior (such as quantities used, travel times to collection points, and perceptions of water quality) to assess the response of consumers to different characteristics of an improved water system. Possible models in this context include those with changing demand parameters, hedonic property value, and hedonic travel cost.

The second, "direct" approach, is simply to ask an individual how much he or she would be willing to pay for the improved water service, for instance, a public stand post or yard tap. This survey approach is termed the "contingent valuation method" because the interviewer poses questions within the context of a hypothetical market.

Source: Whittington et al. 1990

4.1 Literature Review on Contingent Valuation Method in Assessing Willingness to Pay for Improved Water Supply

The contingent valuation method (CVM) is one of the most common methods economists, policymakers, and water utility providers use in estimating WTP to improve water supply. To determine the demand for water and sanitation services in both rural and urban areas, the World Bank has been the primary user of the CVM in testing and promoting the usage of the approach (Parry-Jones, 1999).

While CVM surveys might be the most informative method for estimating WTP, a number of biases are associated with CVM, which is one of its disadvantages. There are four main biases: hypothetical bias, strategic bias, information bias, and starting point bias. Strategic bias arises when respondents do not disclose their true WTP because environmental commodities are non-excludable (free-riding). Therefore, respondents assume their valuation will not impact the provision of goods and services because others will pay for them. Hypothetical bias may arise because WTP valuations are hypothetical and not based on the actual market value. Informational bias can occur if the respondent lacks sufficient knowledge or experience about the environmental good or service being evaluated. The starting point bias may arise if the interviewer's initial suggested bid affects the respondent's final WTP. Nevertheless, all these biases can be reduced to acceptable levels by designing the CV survey appropriately (Perman et al., 2003).

Several studies have employed contingent valuation methods in estimating the WTP for improved water supply service, quality and reliability. **Error! Reference source not found.** reported literature studies on households' willingness to pay for improved water supply, quality, and reliability improvements.

Table 9: Household's WTP Summary Literature Using Contingent Valuation Method

	Author(s)	Findings
Improved Water Supply	Casey et al., 2006	The WTP for improved water service in Manaus amounts to US$6.12/month/household. The annual WTP approximately equals 2.5% of a household's yearly income.
	Tussupova et al., 2015	The study on WTP for improved water supply services in Pavlodar Region, Kazakhstan, revealed that households' WTP on average equals 10.6 USD per month.
	Aslam et al., 2018	The study estimated the WTP for improved water services in the mining region in Pakistan. The study found that households were willing to pay 11.8% (for risk-averting services) and 16.6% (for domestic pipelines and more decentralized water systems) more than their existing water expenditure.
	Odwori, 2020	The study found that, on average, households were willing to pay about US$5 monthly for improved water supply services in the Nzoia River Basin, Kenya.
	Eridadi et al., 2021	The study reported that households were willing to pay for improved water supply services, on average, 20 ETB/month on top of their 161 ETB monthly water cost. The mean increased WTP of 20 ETB/month equals 0.41% of the mean family income.
	Bui et al., 2022	The study investigated the WTP of households in Hanoi, Vietnam, for an improved urban domestic water supply system and found that the average WTP equals 12.2 USD/household, or 1.4% of the average family income.
	Islam et al., 2022	The study investigated the demand for improved water supply in coastal urban settings in Khulna, Bangladesh and revealed that households were willing to pay US$5.05/month on average.
Water Quality Improvement	Mmopelwa et al., 2005	The study reported that the maximum household WTP for water quality improvement equals 10 USD per month in Maun.
	Rodríguez-Tapia et al., 2017	The study estimated that the average WTP surcharge for improved potable water quality is $3.1, or 4.7% of the bimonthly water bill, which is equivalent to 0.22% of the average family income in Mexico City.
	Makwinja et al., 2019	The study result showed that the monthly individual aggregate WTP for water quality improvement varied from US$0.95 to US$ 111.38, averaging US$10.73 in Chia Lagoon, Malawi.
	Thapa & Thapa, 2020	The study reported that households' WTP to improve the water quality is just over 2.5 times the typical monthly water tariff in Kathmandu Valley in Nepal.
Water Reliability Improvement	Dutta & Tiwari, 2005	Established the willingness to pay for a reliable urban water supply in Delhi, India. The study found that consumers are willing to pay US$6.78 for a high-quality two-way collection and US$4.35 for a single-quality reliable supply.

	Mmopelwa et al., 2005	The study found that the maximum household's WTP improved water supply reliability equals 14 USD monthly.
	Fujita et al., 2005	The study reported that Iquitos residents would pay almost twice the current average payment level to ensure the long-term viability of their city's water delivery system.
	Genius et al., 2008	Evaluated the Rethymno residents' WTP as a percentage of their water bill for future water projects the Municipal plans to implement to avoid shortages and improve tap water quality. The result showed that the mean WTP for these future projects was estimated to be €10.64, equivalent to 17.67% of their average water bill.
	Vásquez et al., 2009	Residents in Parral, Mexico, are willing to pay from 1.8% to 7.55% of their income above their current water bill for safe and reliable drinking water services.
	Amoah & Moffatt, 2021	Estimated the WTP for water reliability improvement and found out that households were willing to pay about 15.25 USD per month, with equals about 7.5% of household monthly income.

4.2 Factors Affecting Household's Willingness to Pay for Water Supply, Quality and Reliability Improvement

Generally, household income levels are positively related to WTP; the level of household income plays a significant role in determining WTP for improved water supply (Akhtar et al., 2018), quality and reliability improvement (Moffat et al., 2011; Singh, 2020). Empirical studies have shown that household' WTP depends not only on income but also on household size, gender, distance, education, occupation, marital status, existing and improved supplies, and water qualities, among others. **Error! Reference source not found.** presents a summary of works of literature on factors determining the household's WTP for improved water supply, quality, and reliability improvement.

Table 10: Summary Literature on Factors Affecting Household's WTP

	Author(s)	Findings
Improved Water Supply	Akhtar et al., 2018	Reported that income was the most significant determinant of WTP for enhanced water supply.
	Anteneh et al., 2019	Found that WTP for improved water supply is significantly influenced by water price, service quality, levels of income, education, and public awareness of healthy living
	Akeju et al., 2018; Burt et al., 2017; Chatterjee et al., 2017	Gender, water consumption volume, education level, income, household size, water quality, and water installation costs determine WTP for improved water supply services.
	Dey et al., 2019; Jessoe, 2013; Thapa & Thapa, 2020	Current volume of water consumption, income and perceived waterborne diseases are strong positive determinants of willingness to pay for improved water supply.
Water Quality Improvement	Moffat et al., 2011	Found that WTP for improved water quality and reliability is significantly influenced by income and age
	Cooper et al., 2004; Jørgensen et al., 2013	Age, education, gender, marital status, occupation, household income, and the number of household members are determining factors for WTP for water quality improvement.

	Jianjun et al., 2016; Roldán et al., 2021	Other factors such as awareness of environmental protection, the relative importance of the environment to the economy, the ages of children in the household, the level of transparency of information and participation in the decision-making process, and the need for water quality improvements can also influence WTP for water quality improvement.
	Hao et al., 2023	Reported that age, education level, income level, minor family members and government trust are the main factors that significantly influence residents' WTP
Water Reliability Improvement	Moffat et al., 2011	Found that WTP for improved water quality and reliability is significantly influenced by income and age
	Ayanshola et al., 2013	The study revealed that gender, water quality and household income level significantly impact WTP for reliable and sustainable water supply.
	Osman et al., 2019	Income, age, household size, and residential area are drivers of respondents' WTP for improved water reliability.

4.3 Willingness to Pay for Irrigation Water Supply Improvement

The majority of the world's water is used in agriculture. In irrigated agricultural systems, water availability is a key source of uncertainty because of the substantial impact it has on farm revenue. A reliable and adequate water price guideline is required to aid farmers in optimizing their water allocation and ensure an efficient agricultural water system.

Various factors may affect farmers' WTP for irrigation water and improvements to the irrigation water supply service. However, several determinants are more commonly associated with such WTP than others. A significant group of such variables includes characteristics of the farm itself, cropping patterns, crop yields and profitability, crop water needs, farm size, farm location, farm ownership, etc. In addition, the socio-economic context is a further important category (Azzi et al., 2018). It has been shown that factors such as income, age of the farmer, level of education, experience, agricultural training, risk attitudes, usage of family labor, and family size are strong predictors of WTP for water or improvements in water supply (Gül & Uzunkaya, 2017). **Error! Reference source not found.** presents a selection of studies on WTP for irrigation water supply and the factors that influenced them.

Table 11: Willingness to Pay for Improved Irrigation Water Supply Summary Literature

Author(s)	Significant Factors of WTP	Findings
Alhassan et al., 2013	Location of farm, land ownership, and land lease prices as the significant and influencing factors	The mean WTP was found to be US$ 8.50/ha/year, and the median was US$ 7.29/ha/year.
Biswas & Lingappan, 2015	Education, gender, caste, age and location	The average WTP for farmers to improve the irrigation water supply in Karnataka, India, was estimated to be US$ 5.09/acre/year, and the estimated median WTP stood at approximately US$ 3.35/acre/year.
Aydogdu, 2016	Price of irrigation water, education, location, irrigation type (gravity or	The survey results showed that the farmers in the plain were paying an average of

	pumping), and attitudes toward associations	5.43% of their net income from agriculture as water fees, and the average WTP average is 10.73% of their net income for irrigation supply improvements in the GAP region in Turkey.
Azzi et al., 2018	Farm ownership, access to groundwater resources, cropping patterns, farmers' agricultural training and risk exposure	The average farmer's WTP was estimated to be equal to 0.0349€$/m^3$ This represents a 64% increase concerning the current water tariff in northern Algeria's West Mitidja irrigation district.
Kidane et al., 2019	Initial bid, land tenure security, age of a farmer, households' income from irrigation farming and source of water being used	The study found that, on average, farmers' WTP for irrigation water supply improvement in Eritrea is about 5% of the average household income from irrigated farms.
Deh-Haghi et al., 2020	Famers' living place, use of recycled water, education, and information sources	The study's result showed that most farmers (91.7%) were willing to pay the lowest bid level of 42.86 USD per ha for using treated wastewater in crop irrigation in western Iran.
Abdelhafidh et al., 2022	Agricultural training and education level of farmers	The average farmer's WTP for irrigation supply improvements was estimated to be equal to 0.08 $\$/m^3$ which averages 63.3% more than the price currently paid in the North of Tunisia.

4.4 Estimating WTP for Improved Water Supply for Irrigation Water Supply Methods

Estimating the Willingness to Pay (WTP) for agricultural water necessitates a nuanced approach that accounts for productivity and cost of production factors directly linked to agricultural operations. This estimation process is pivotal for determining how much farmers are willing to invest in irrigation water, considering the significant role water plays in crop production and farm profitability.

Productivity Factors

Productivity factors include crop yields, types of crops grown, and the efficiency of water use. These elements are crucial because they directly influence the return on investment from water used in irrigation. Higher yields and more valuable crops can increase a farmer's WTP, as the economic benefits of reliable and adequate water supply become more tangible. For instance, a farmer growing high-value crops that are particularly sensitive to water stress might value water more than a farmer growing less sensitive, lower-value crops (Scheierling et al., 2006). Techniques such as crop simulation models can be used to estimate how changes in water availability or irrigation efficiency impact crop yields and, consequently, farm revenues.

Analyzing Cost of Production Factors

The cost of production encompasses the expenses associated with water, labor, fertilizers, and other agricultural inputs. The estimation of WTP is influenced by the overall impact of these costs on farm profitability. If improved water management or the adoption of efficient irrigation technologies reduces the total cost of production or enhances crop value significantly, farmers are likely to exhibit a higher WTP for water. Economic analyses that incorporate production function approaches or partial budgeting can help quantify the impact of water on the cost of production and, by extension, on WTP.

i. **Direct Water Costs**: This involves the cost associated with obtaining, delivering, and applying water to crops. Lowering these costs through efficient water use or subsidized pricing can influence WTP by making higher-priced but reliable water sources more attractive.

ii. **Input Cost Savings**: Improved water supply can reduce the need for other inputs, such as less reliance on drought-resistant seed varieties or reduced labor for water management. Estimating WTP involves assessing these cost savings against the price of water.

iii. **Operational Efficiency**: The adoption of water-saving technologies can lead to operational efficiencies that reduce overall production costs. Farmers' WTP for water is influenced by the balance between the costs of these technologies and the savings from reduced water use.

Estimation Techniques

Contingent Valuation Method (CVM): CVM can be used to directly ask farmers about their WTP for additional units of water or improvements in water supply under hypothetical scenarios. This method is particularly useful in capturing the subjective valuation of water based on expected productivity gains and cost savings.

Conjoint Analysis: This technique involves presenting farmers with a set of hypothetical irrigation services that vary in attributes (e.g., reliability, quality) and costs. By analyzing farmers' preferences for these attributes, one can infer their WTP for improvements in water supply services.

Production Function Analysis: This approach quantifies the relationship between water use and crop output, allowing for the estimation of the marginal productivity of water. By understanding this relationship, one can estimate the value farmers place on additional units of water, reflecting their WTP based on productivity gains.

Accurately estimating the WTP for agricultural water requires a comprehensive understanding of how water influences farm productivity and production costs. By employing a combination of direct survey methods and economic modeling techniques, researchers and policymakers can derive meaningful estimates of farmers' WTP. This, in turn, aids in the development of water pricing and allocation policies that reflect the true economic value of water in agriculture, encouraging efficient and sustainable water use.

4.4.1 Averted Cost Methodology

The averted cost methodology is a valuable approach in environmental economics and water resource management for estimating the economic value of ecosystem services or the benefits of infrastructure projects, including those related to water supply improvements. This method calculates the costs that are avoided by having a particular service or project in place, essentially measuring the economic benefits through the lens of cost savings or damage prevention.

In the context of estimating the Willingness to Pay (WTP) for agricultural water, the averted cost methodology can be particularly insightful. It focuses on the costs that farmers would incur in the absence of reliable and efficient water supply systems. These might include lower crop yields due to water stress, higher costs for alternative water sources, or even the loss of crops in extreme cases. By assessing the value of water supply improvements through the costs they help to avoid, this methodology provides a direct link between water service enhancements and their economic value to farmers.

Application in Agricultural Water Use

- Drought Mitigation: The averted cost methodology can estimate the economic benefits of irrigation systems that prevent yield losses during droughts. By comparing the potential revenue losses from reduced yields without such systems to the costs of implementing and operating them, one can infer the WTP for reliable irrigation services (Hanemann, 2006).
- Alternative Water Sources: If farmers need to resort to more expensive water sources due to the unreliability of their primary water supply, the averted cost methodology can quantify the savings from improved water supply infrastructure. This includes the cost differences between these sources and the infrastructure costs, offering a basis for WTP estimations (Tietenberg & Lewis, 2016).
- Soil Salinity and Erosion Control: The method can also apply to valuing water management practices that prevent or mitigate soil degradation. The costs averted by reducing soil salinity or erosion—such as lower fertility treatment costs and the avoidance of land degradation—can be used to gauge the economic value of sustainable water use practices (Postel & Thompson, 2005).

The averted cost methodology effectively quantifies the economic benefits of ecosystem services and water projects by highlighting direct cost savings, aiding in policy support and investment decisions. Despite its usefulness, it struggles with accurately estimating costs and may overlook non-economic benefits, potentially underestimating the full value of ecosystem services. Additionally, its reliance on precise baseline scenarios poses challenges for valuation accuracy. Integrating this method with other valuation approaches can offer a more rounded perspective on the economic importance of environmental and water management initiatives.

4.5 Importance of Application of WTP to Investment Decision-Making

Incorporating WTP in water investment decision-making adds an economic perspective to the review process, allowing for more effective and sustainable water resource management. The willingness of consumers to pay for increased water supply reliability is a valuable metric for policymakers to consider in assessing the viability of demand-side instruments for more efficient resource allocation. (Guerrero-Baena et al., 2019). The following highlights how WTP might be used in water investment decision-making:

- Taking into consideration an individual's WTP for increased water availability and quality is essential when deciding whether or not to invest in water infrastructure such as dams, reservoirs, water treatment facilities, or distribution networks. This data is useful for determining whether people are willing to pay the estimated project expenses for the anticipated benefits.
- Water conservation is typically driven by water pricing or water-use restrictions. Understanding individual WTP for water conservation can help policymakers set appropriate pricing structures or implement regulations that reflect their perception of the value of water.
- Investments in pollution control methods are typically necessary to address water pollution and contamination. Assessing the WTP of impacted populations for enhanced water quality helps

explain these expenditures better. For instance, the WTP for purified potable water can be compared with the implementation costs of water treatment technologies.

- Numerous water projects affect ecosystem services, including biodiversity. Incorporating environmental aspects into decision-making, such as evaluating the WTP for protecting or restoring critical ecosystem services, leads to more sustainable and comprehensive water management.
- Cost-benefit analysis of any water infrastructure project would be inadequate without the WTP data; the net economic benefit of an improved water supply is computed as the difference between the customers' maximum WTP and the actual cost of the service provided. This allows for a more accurate estimation of the benefits of an improved water supply.

Aggregating the Willingness to Pay (WTP) for water at the basin or system level is a multi-step process that involves extensive data collection and analytical rigor. One starts by conducting surveys across different stakeholder groups such as households, industries, agricultural users, and ecological services. It's important to consider that water has varying values for different uses, whether it's for agriculture, industry, or personal consumption. The time sensitivity of the willingness to pay, such as immediate needs versus long-term improvements, is also a vital factor to account for.

Once data is collected, the next task is to integrate these disparate WTP values into an aggregated figure that can be utilized. While a simple average of all WTP values can provide a basic idea, it may not capture the complexities of water usage in a particular basin or system. A more nuanced approach is to use weighted averaging, where the WTP of each stakeholder group is adjusted based on the proportion of water they consume or the size of the population in that group. For instance, if agriculture is a dominant sector that consumes a significant portion of water, it would make sense to give more weight to the WTP values obtained from agricultural users.

Another advanced method of aggregation involves calculating the consumer surplus for each user group, essentially quantifying the benefit users derive over what they have to pay. These can then be summed to arrive at an aggregate consumer surplus, representing the collective WTP. In some cases, techniques that aim to equalize the marginal utility of water across all uses are employed, leading to an aggregated WTP that seeks to maximize the overall benefit.

After calculating an aggregated WTP, it can be incorporated into a broader cost-benefit analysis to provide a complete picture of the economic impacts of potential water investments. Multi-Criteria Decision Analysis (MCDA) can also be useful in this context, as it incorporates not just economic considerations, but also social and environmental factors.

It is advisable to fine-tune the aggregated WTP through demographic adjustments and sensitivity analyses. This involves making adjustments based on variations in income levels, age, and other demographics and analyzing how sensitive the aggregated figure is to changes in factors like water quality, price levels, and availability.

5 Estimation of Water Variability

The variability of water resources and water supply systems is of fundamental importance for designing strategies and creating supply portfolios which achieve desired levels of reliability. The main strategy for a reliable portfolio is to combine water supplies with low variability with existing sources with higher variability. An ideal portfolio consists of one where the variability of different sources is out of phase – creating a balanced aggregate supply.

First, this Chapter reviews basic terminology and characterization of variability water resources and water supplies, including various algebraic indicators and frequency distributions – using rainfall as an example. Third, the Chapter reviews variability considerations for streamflow, surface water dams, and other water supply systems. The last section of the Chapter outlines technical resources for water resource/water supply data and tools and technical references.

5.1 Basic Terminology and Characterization of Variability

5.1.1 Time Scale and Variability

Table 10 below provides a guide to the terminology of variability, with consideration of different time scales. Annual and Inter-Annual are the most important variations for water supply planning and portfolio development.

Table 12: Hierarchy of Time Scale and Variability

Time Scale	Variability	Period of Data	Importance
Short	Diurnal	Hourly	Short-run water storage systems
Short - Medium	Monthly	Days	Short-run water storage systems Agricultural water needs
Medium	Seasonal Annual	Months	Potable and agricultural water needs
Medium to Long	Inter-Annual	Years	Potable and agricultural water needs, medium-term water storage systems
Medium to Long	Inter-Annual - Decadal	Decades	Climate oscillations (El Nino Southern Oscillation, North Atlantic Oscillation)
Long	Inter-Annual – 30 Years	30 Years	World Meteorological Organization (WMO) Reference Periods used for characterization of climate change

Figure 12 shows a typical graph of Annual Variability - in this case, for Rainfall in Morocco over the long-term period of 1901-2020[17]. This pattern is typical of a Mediterranean climate with a cool, rainy winter and a hot, dry summer.

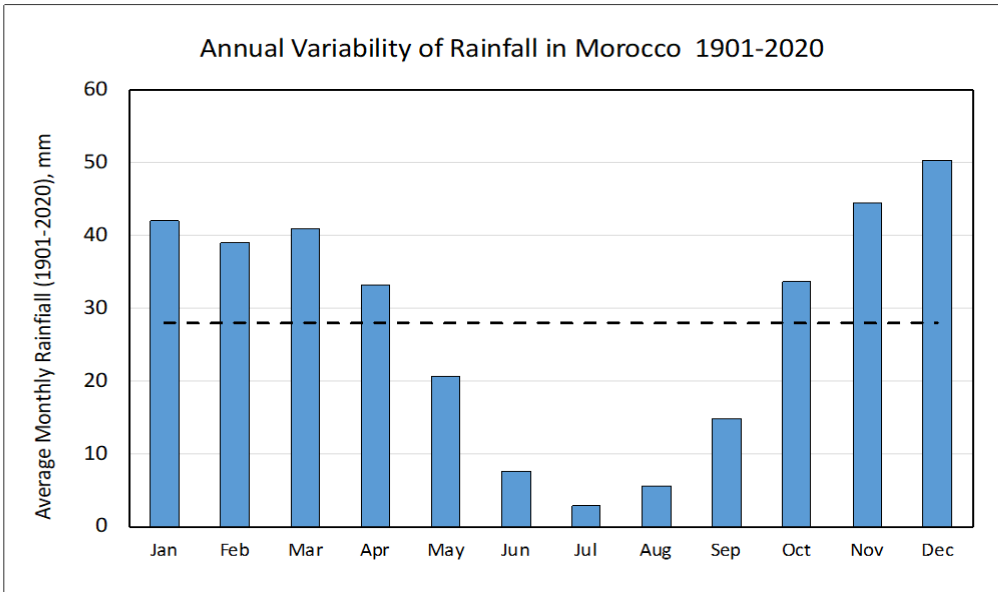


Figure 11

One portrayal of the Inter-Annual Variability of rainfall in Morocco is provided in Figure 13, which shows the monthly rainfall in each of 12 years, equally spaced at ten years intervals. Visually, the Inter-Annual Variability seems highest in the rainy months.

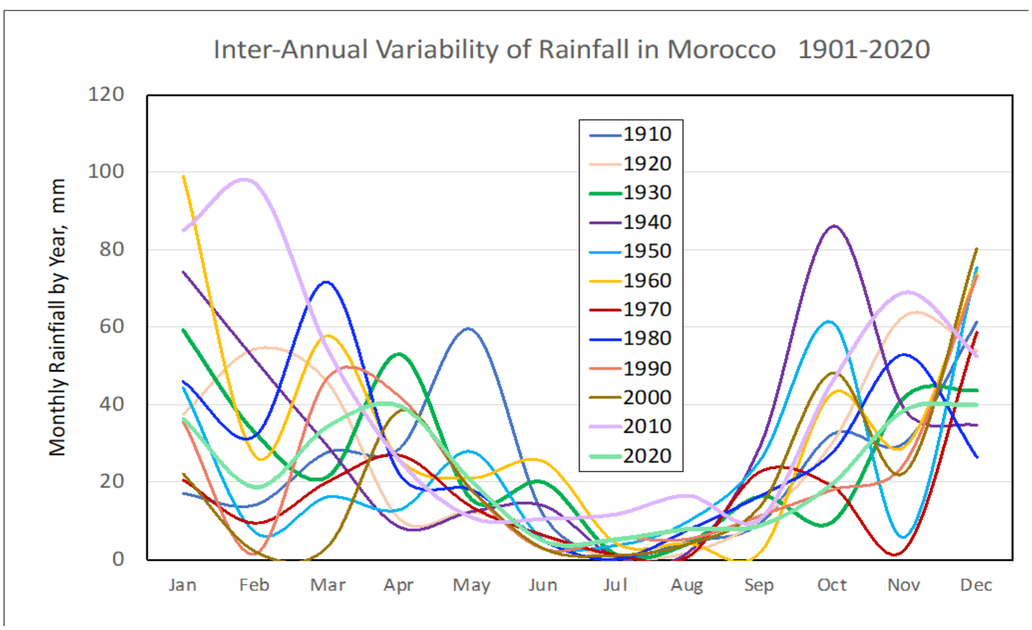


Figure 12

[17] Source: Climate Research Unit (CRU), University of East Anglia, Downloaded from the World Bank Climate Change Knowledge Portal (CCKP) : https://climateknowledgeportal.worldbank.org/

Figures 14 and 15 provide an alternate portrayal of Inter-Annual variation for the months of July and October, respectively. The Figures show monthly rainfall for each year (Annual), average monthly rainfall by decade (Decadal) and average monthly rainfall over the four 30-year periods defined by WMO. Note that the vertical scale for July is much smaller than the scale for October – by a factor of about 8 times. It is quite evident that a shorter time scale leads to more variability.

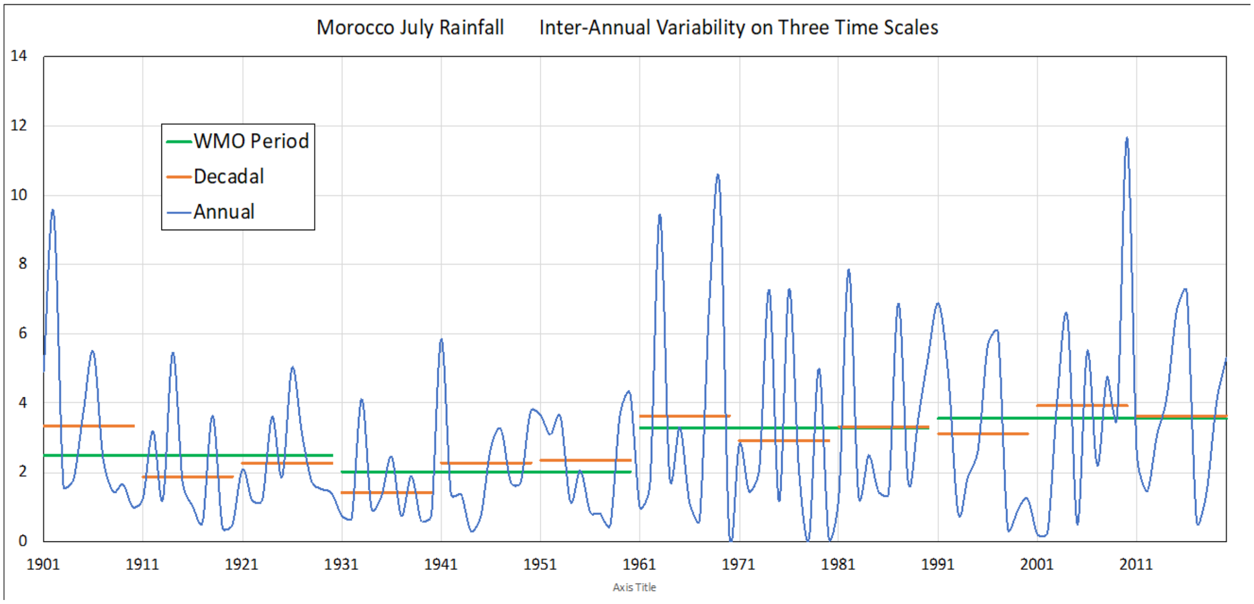


Figure 14

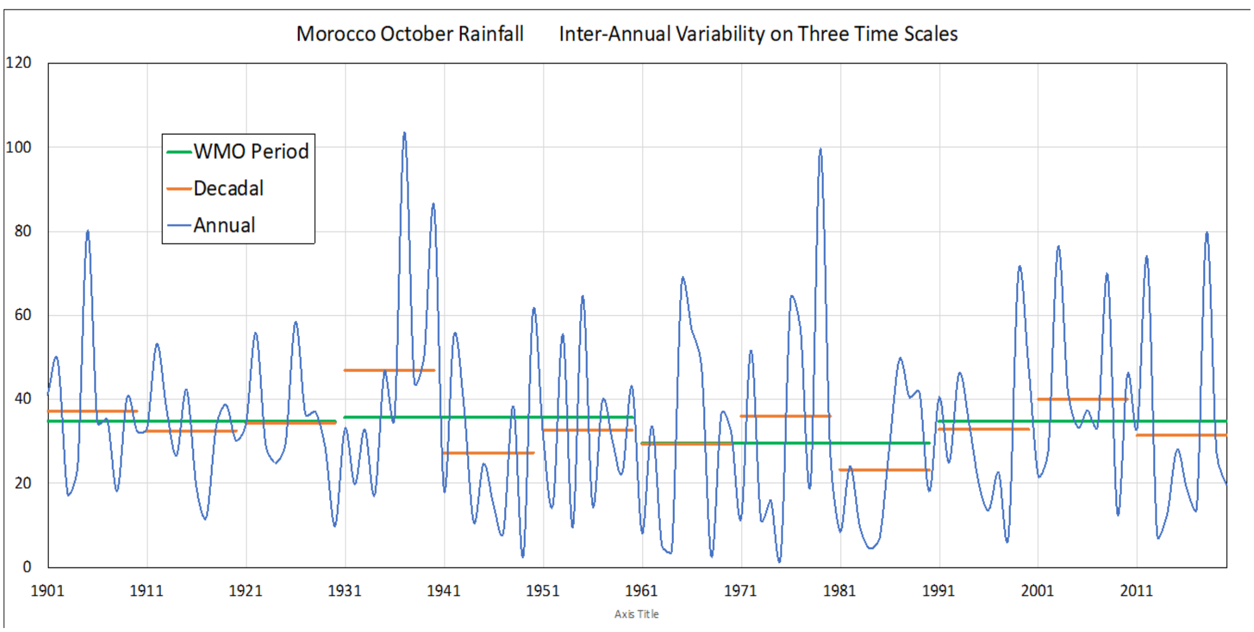


Figure 13

5.1.2 Basic Characterization of Variability

The key parameters for characterizing variability include: Mean, Minimum, Maximum, Quartiles, Standard Deviation, and Coefficient of Variation (Standard Deviation / Mean). Figure 16 below shows a box and whisker plot for rainfall in Morocco, as well as a data table, which includes the key parameters noted previously. The large spread in the winter months is consistent with the pattern in Figure 17. It is particularly noteworthy that the summer months (especially July) have the lowest rainfall, but they also have the highest values for standard deviation/mean (coefficient of variation).

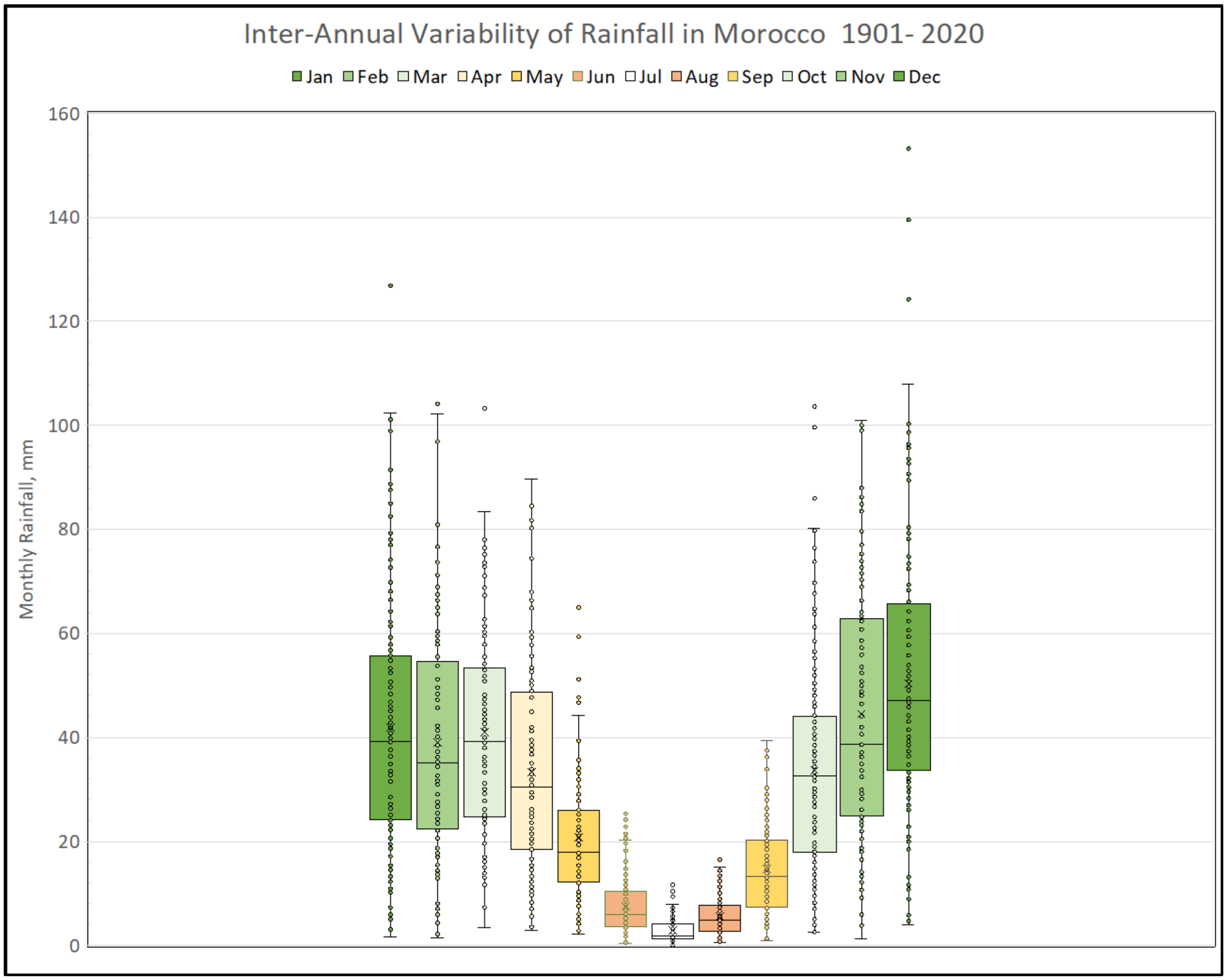


Figure 15

1901-2020	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min	1.69	1.43	3.38	2.97	2.14	0.32	0.07	0.53	0.98	2.45	1.16	3.95
10th Perc	10.89	13.44	16.52	11.20	8.55	2.27	0.58	1.41	4.09	9.38	14.11	17.94
25th Perc	24.24	22.66	24.85	18.54	12.15	3.61	1.15	2.68	7.44	18.10	24.90	34.38
50th Perc	39.29	34.97	39.21	30.36	17.90	5.96	1.86	4.75	13.19	32.66	38.70	47.04
75th Perc	55.56	54.49	53.42	48.07	25.69	10.25	4.02	7.57	20.22	43.32	62.55	64.98
90th Perc	77.16	68.20	71.06	59.24	36.25	14.84	6.51	11.27	27.99	61.53	79.98	89.49
100 Perc	126.93	104.09	103.28	89.75	65.03	25.37	11.66	16.48	39.36	103.64	100.89	153.22
Mean	42.01	39.02	40.97	33.22	20.70	7.59	2.84	5.54	14.74	33.68	44.47	50.32
Std Dev	24.74	22.47	19.54	19.21	12.41	5.53	2.42	3.64	9.08	20.97	24.30	28.06
Std Dev/Mean	0.589	0.576	0.477	0.578	0.600	0.729	0.852	0.656	0.616	0.623	0.546	0.558

Figure 16

5.1.3 Probability Distributions

Another fundamental method of characterizing variability is through the use of frequency distributions, such as the Normal distribution and the Weibull distribution.

The Normal distribution is commonly used to characterize climate data, stream flows and many other natural phenomena. Its shape is easily determined from the mean and standard deviation. The cumulative percentage or Z-scores can be used to determine the frequency that the distribution exceeds a specific value. This relationship is used to determine the reliability of a particular portfolio of water supply in relation to an estimate of demand.

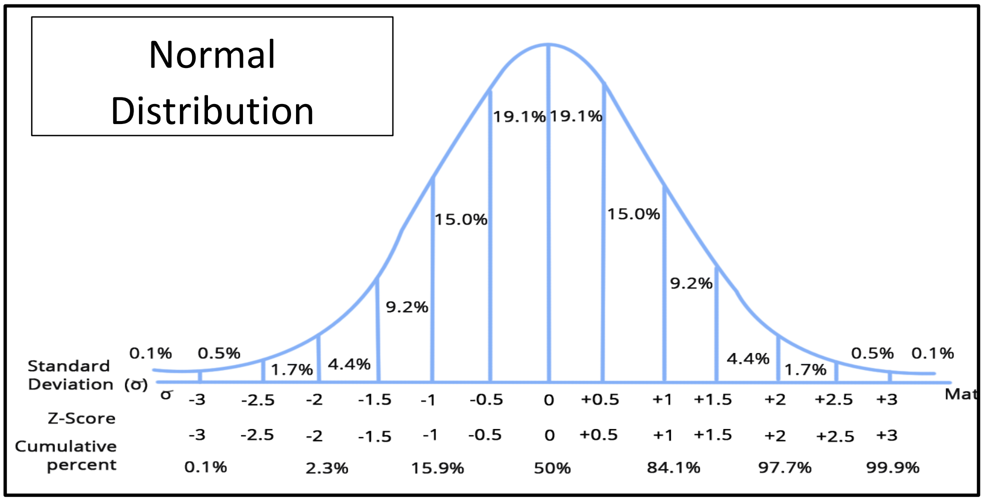


Figure 17

There are many alternative distributions which have been applied in climate and hydrologic modeling. One such distribution is the Weibull distribution, which is actually a simplified version of the gamma distribution. The Weibull has two parameters, including α, the shape parameter, and β, the scale parameter, whose influence on the form of the distribution is shown in Figure 19.

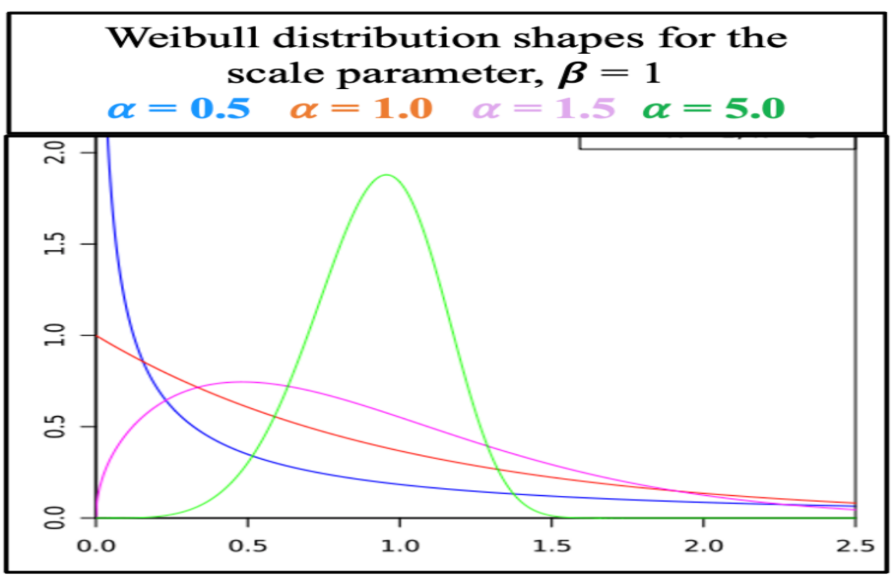


Figure 18

The Figures below compare the frequency distributions of rainfall in Tunisia for January, July and October – including observed frequency (vertical bars), a Normal Frequency distribution based on the mean and standard deviation of the observed rainfall record, and the Weibull Distribution, using a visual "best fit" for the scale and shape parameters. The visual best fit usually occurs by choosing a value of beta close to the mean and a value of alpha to create a good visual curve fit. It seems quite clear, visually, that the Weibull is able to characterize the frequency of observations much more closely than the Normal Distribution, especially in the critical dry summer month of July.

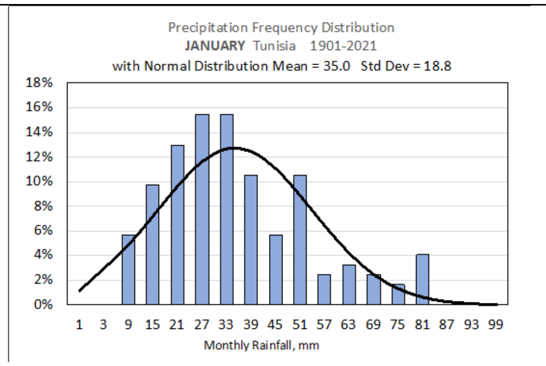
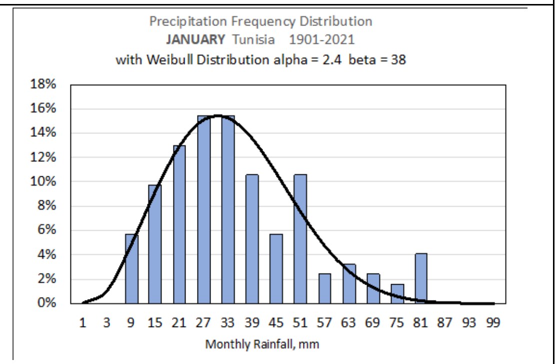
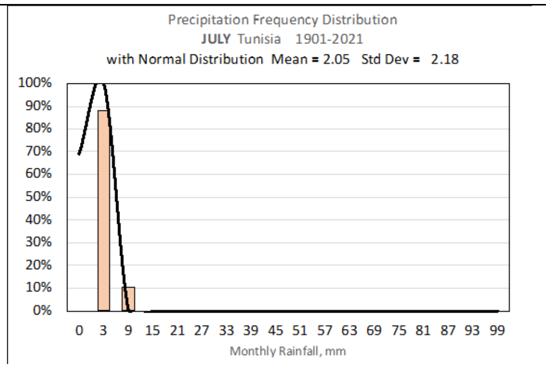
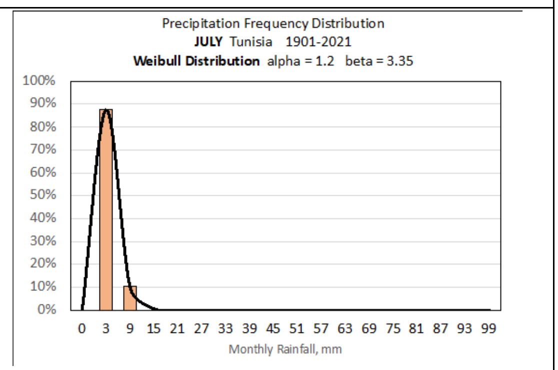
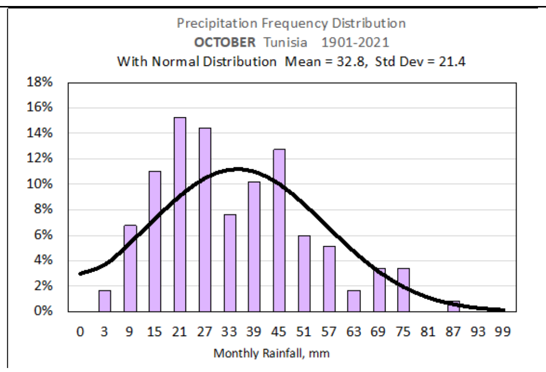
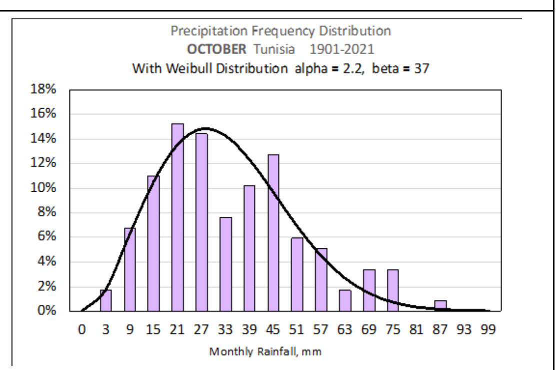
	Normal Distribution	Weibull Distribution
January Coefficient of Variance = 0.537		
July Coefficient of Variance = 1.06		
October Coefficient of Variance = 0.615		

Figure 19

While these results make the Weibull distribution seem appealing, a deterministic approach to solving for the parameters alpha and beta requires a maximum likelihood algorithm (Clarke 2002), which adds considerable complexity to the modeling required for calculating the reliability of a water supply portfolio.

Therefore, the Normal distribution has been used in this project, even though it may not be the most exact distribution.

5.2 Streamflow Variability

One of the earliest and simplest indicators of streamflow variability was proposed by Lane (1950) - which is the standard deviation of the log of stream discharge.

Probability distributions are widely used today. Figure 21 shows a comparison of different probability density functions for low flows in the example from the Tana River, the longest and largest river in Kenya. Langat et al. (2019). The authors indicate a preference for the Weibull and Gamma distributions for low-flow conditions but favor other distributions for mean streamflow and maximum streamflow.

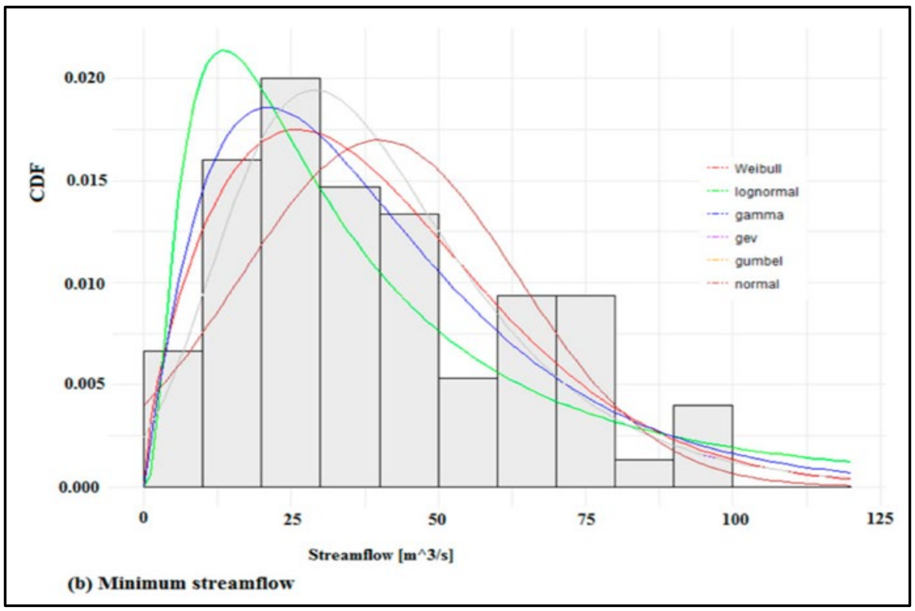


Figure 20

Streamflow modeling is also a solid basis for estimating variability. Figure 22 shows the mass balance of the CLIRUN-II streamflow model described in detail in (Strzepek K. et al). Water enters via precipitation and leaves via ET and runoff. The difference between inflow and outflow is reflected as a change in storage in the soil or groundwater. Soil moisture is modeled as a two-layer system with soil (upper) and groundwater (lower) layers. These two components correspond to a quick and slow runoff response to effective precipitation. A variety of sub-models are used to calculate the full mass balance. A model such as this could be used in engineering studies for the preparation of various water supply project alternatives, including direct surface water use, groundwater use and surface water systems with dam storage – see the section below.

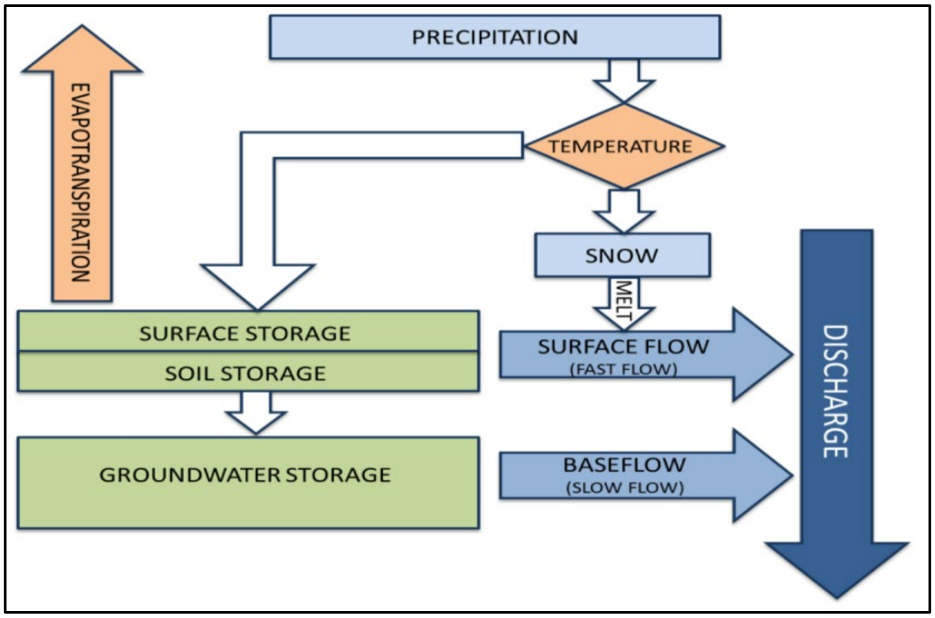


Figure 21

5.3 Variability of Supply from Surface Water Dams

The potential supply from surface water dams depends on many factors, including the surface water inflow, dam storage capacity (accounting for sedimentation and unavailable storage), precipitation, evaporation, groundwater inflow and outflow, and releases for purposes other than water supply, as shown in Figure 23.

In general, the yield will increase as the storage capacity increases, but only up to a certain yield – more capacity will not increase the yield unless inflow increases.

A time-step-based mass balance model is needed to compute the available storage in the reservoir. The mass balance model will need to account for annual and interannual variability of inputs and outputs such as surface water inflow, precipitation and evaporation, etc. The model can then estimate the potential water supply – across different months and out into years in the future. The WEAP model reviewed later in this Chapter can be used for the mass balance and yield estimation.

Development and/or use of such a model is not included in the SPOT model. Users will need to use records of actual water production from a surface water dam over a historical period – accounting for annual and interannual variability to characterize existing surface water/dam sources and potential new surface water/dam supplies.

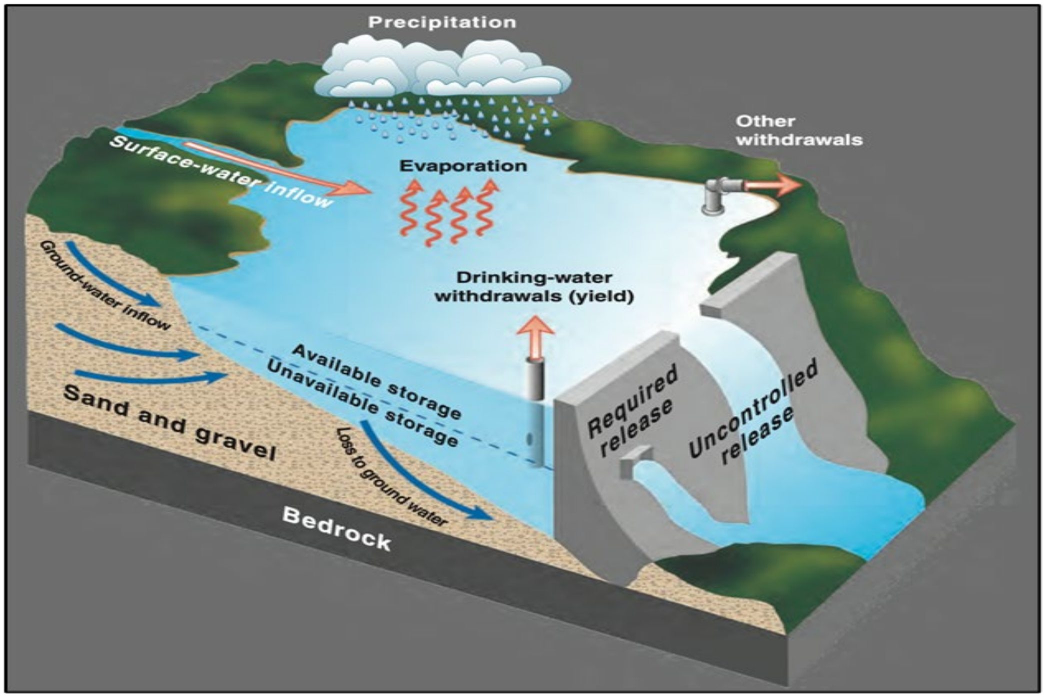


Figure 22

5.4 Variability Characteristics of Water Supply Systems

Table 13: Characteristics of Water Supply Systems

Water Source / Water Supply System	General Variability Characteristics / Considerations
Surface Water	Water supplies which simply extract water from a surface water source (river), commonly known as "run of the river", will have a variability directly linked to the streamflow variability.
Surface Water with Storage	As described in the section above, the variability of water supply from a surface water dam depends primarily on the surface water inflows and the storage capacity as well as other parameters, including precipitation, evaporation, and groundwater inflows and outflows.
Groundwater	Groundwater supplies will generally have low variability, but two exceptions are important to recognize. First, a phreatic aquifer, since it is "fed" by surface water, will mirror to some extent the annual and inter-annual variability of rainfall, but the variability will be dampened when the volume of the phreatic aquifer is large. Second, a confined aquifer can often have a significant declining inter-annual variability if the aggregate with drawls exceeds the sustainable yield of the aquifer.
Water Reuse	The volume and variability of water supply from water reuse will mirror the sewerage inflow to the plant, which in turn will mirror the potable water consumption. Therefore, the variability of water reuse will depend on the annual and interannual variability of potable water demand.

Aquifer Storage and Recovery	Aquifer storage systems will typically be recharged in rainy months – when "excess" surface water can be injected into aquifers or allowed to seep into aquifers from infiltration ponds or galleries. The stored water can then be accessed in the dry months or other periods of high demand. Therefore, the variability can be "managed" to be out of phase with surface water sources, providing at least some balance to the water supply portfolio.
Seawater Desalination	The variability of seawater desalination will essentially be zero. The supply from a seawater desalination plant will, of course depend on the operating schedule of the facility, which can be managed to be out of phase with surface water sources, providing at least some balance to the water supply portfolio.

More precise data on the variability of supply of any and all of these sources can be obtained from actual time-series information at the project site or other locations nearby or with similar conditions.

In order to develop and analyze a potential water supply portfolio, correlations between the time series of water production supply facilities are required to determine the variance and reliability of the assembled portfolio. Essentially, correlation is the measure of how two variables are related to one another. The principal correlation coefficient, ρ, is the Pearson correlation coefficient, whose mathematical formula is provided below, where cov indicates the covariance between the two parameters. Correlations between two variables can determined in Excel and other software.

$$\rho_{X,Y} = \mathrm{corr}(X,Y) = \frac{\mathrm{cov}(X,Y)}{\sigma_X \sigma_Y}$$

Kidson (2009) defines three categories of correlation, including synchronicity, independence and reverse synchronicity. Table 12 provides general guidance on the value of the correlation coefficients between various water supply sources.

Table 14

Supply Correspondence	Correlation Coefficient	Examples with Approximate Correlations
Synchronicity	$0 < \rho < 1$	• "Base Load" Surface water & Surface water 2 from the same basin: $\rho = 1$ • "Base Load" Surface water & Surface water 2 from different basins: $0.5 < \rho < 0.8$ • "Base Load" Surface water & Groundwater in the same basin: $0 < \rho < 0.5$ • "Base Load" Surface water & Direct Potable Water Recovery: $0 < \rho < 0.5$
Independent	$\rho = 0$	• "Base Load" Surface water & "Base Load" Desalination $\rho = 0$ • "Base Load" Surface water & "Base Load" Aquifer Storage & Recovery $\rho = 0$
Reverse Synchronicity	$-1 < \rho < 0$	• "Base Load" Surface water & "Peaking" Desalination $\rho = -1$ • "Base Load" Surface water & "Peaking" Aquifer Storage & Recovery $\rho = -1$

5.5 Sources of Data and Tools on Water Resources, Climate, and Water Supply Variability

- **Observed Historical Climate Data – World Bank Climate Change Knowledge Portal**
  The CCKP includes a wide variety of data on climate and related topics by country and by major watershed. Climate data includes historical data on annual variation and decadal variation for mean minimum and maximum temperature, as well as precipitation. Graphical depictions highlight water and climate variability. The portal also allows downloads of these parameters on a monthly basis from 1901-2021 – as compiled by the CRU at the University of East Anglia – see below. The

CCKP also provides climate parameters for CMIP6 and CMIP5 for various time periods and scenarios. The CCKP also links to the World Bank Climate Risk Country Profiles, the Climate and Disaster Risk Screening Tools, and the Water, Economy and Climate Change GSG: CLEAR Water Dashboards (WBG access only).
LINK: https://climateknowledgeportal.worldbank.org/

- **Observed Historical Climate Data - Climatic Research Unit (CRU) of the University of East Anglia (UEA)**. The CRU TS version 4.05 gridded dataset is derived from observational data and provides quality-controlled temperature and rainfall values from thousands of weather stations worldwide. Data is presented on a 0.5° latitude by 0.5° longitude grid over all land domains except Antarctica.
  LINK: https://crudata.uea.ac.uk/cru/data/hrg/

- **Baseline and Future Water Indicators – Aqueduct 4.0** - World Resources Institute & Utrecht University
  Aqueduct 4.0 is the latest tool to model a broad variety of water resource risk indicators – in river basins across the planet. Outputs include the parameters in Figure 2-VV for the current time as well as 2030, 2050 and 2080 using several scenarios of the CMIP 6 climate change model. Outputs can be downloaded in geospatial (GDB) format as well as conventional CSV file format. WRI (2023) describes the modeling construct, input data sources and interpretations of the results.
  Figures 25 and 26 below show a sample output – the interannual variability of water resources in Northwestern Africa for the current period and for the 2050 Business as Usual Scenario.
  LINK: https://www.wri.org/aqueduct

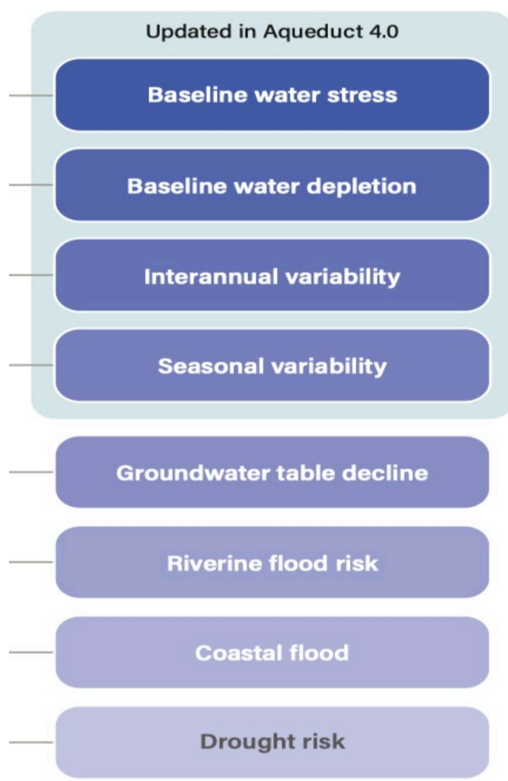


Figure 23

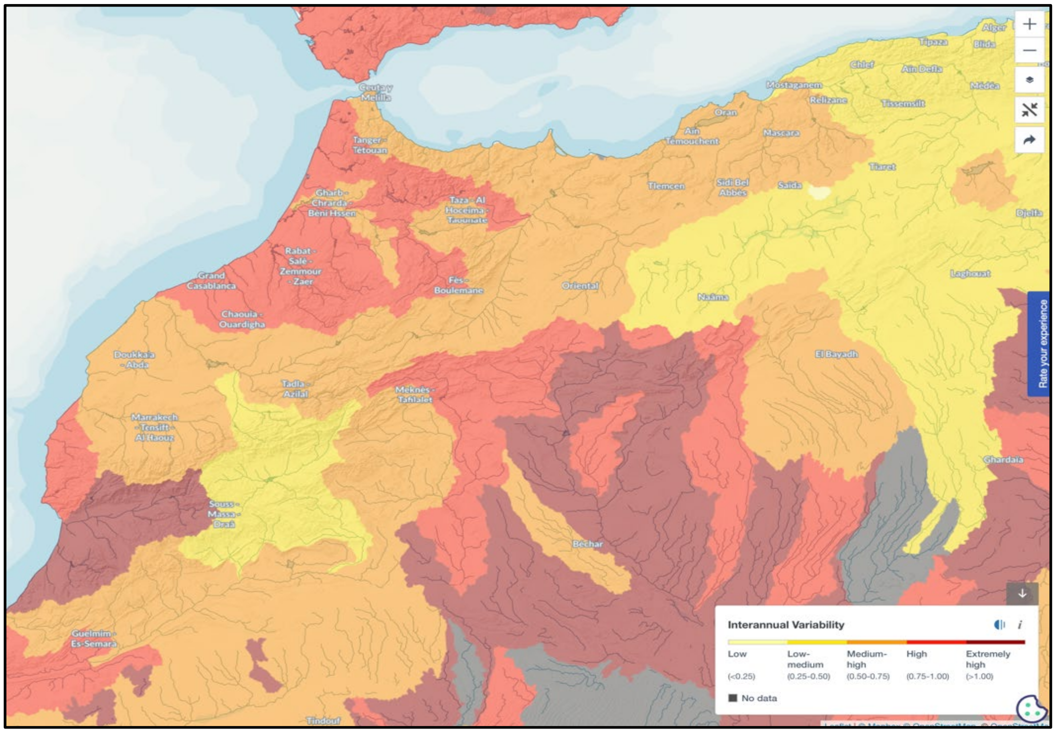


Figure 24: Current Interannual Variability of Water Resources in Northwestern Africa 2020 Source Aqueduct 4.0

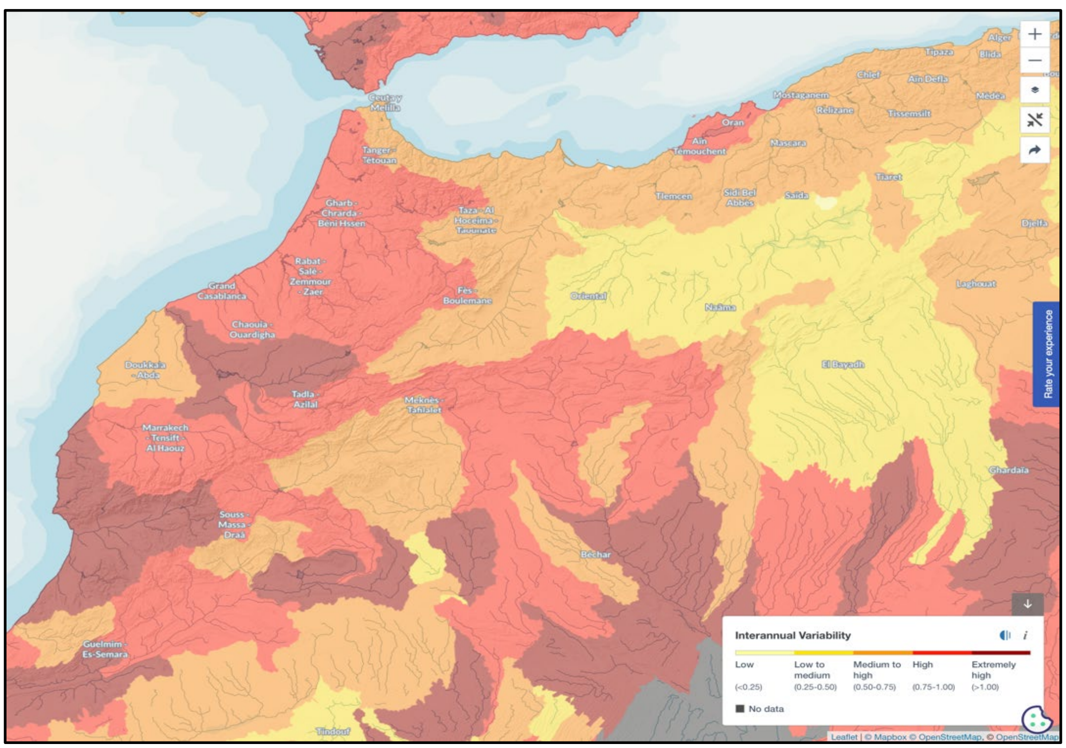


Figure 25: Future Interannual Variability of Water Resources in Northwestern Africa 2050 Source Aqueduct 4.0

- **Climate Variability and Change: A Basin Scale Indicator Approach to Understanding the Risk to Water Resources Development and Management.** This study evaluates the effects of climate change on six hydrological indicators across 8,413 basins in World Bank client countries. These indicators—mean annual runoff (MAR), basin yield, annual high flow, annual low flow, groundwater (baseflow), and reference crop water deficit - were chosen based on their relevance to the wide range of water resource development projects planned for the future. To generate a robust, high-resolution understanding of possible risk, this analysis examines relative changes in all variables from the historical baseline (1961 to 1999) to the 2030s and 2050s for the full range of 56 General Circulation Model (GCM) Special Report on Emissions Scenario (SRES) combinations evaluated in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4).
  LINK:http://www.un.org/waterforlifedecade/pdf/2011_world_bank_climate_variability_change_eng.pdf

- **Water and Agriculture: AQUASTAT** is FAO's global information system on water and agriculture, developed by the Land and Water Division. In AQUASTAT, three types of water withdrawal are distinguished: agricultural, municipal (including domestic), and self-abstracted industrial water withdrawal. For Africa, Asia, Latin America and the Caribbean, AQUASTAT obtains water withdrawal values from ministries or other governmental agencies at a country level, although some data gaps are filled from UN Data.
  LINK: http://www.fao.org/nr/water/aquastat/main/index.stm

- **Country Level and Gridded Estimates of Wastewater Production, Collection, Treatment and Reuse. Utrecht University and United Nations University.** This dataset provides a consistent and comprehensive outlook of global wastewater production, collection, treatment and reuse at both the country-level and 5 arc-min resolution (gridded) for the year 2015. Country-level estimates of wastewater reported from various sources are used as the basis, supplemented with predictions based on multiple linear regression using social, economic, hydrological and geographical predictor variables. Country-level wastewater data are provided in both volume flow rate (million m3 yr-1) and percentage terms. Wastewater data is downscaled to gridded (5 arc-min; m3 yr-1) estimates based on simulations of domestic and industrial return flows from the Water Futures and Solutions (WFaS; Wada et al., 2016) using the approach developed for PCRaster GlOBal Water Balance model (PCR-GLOBWB2; Sutanudjaja et al. (2018)).

  An estimated 40.7 Billion m^3/year of treated wastewater is intentionally reused. Substantial differences in per capita wastewater production, collection and treatment are observed across different geographic regions and by level of economic development. For example, just over 16 % of the global population in high-income countries produces 41 % of global wastewater. Treated wastewater reuse is particularly substantial in the Middle East and North Africa (15 %) and Western Europe (16 %), while comprising just 5.8 % and 5.7 % of the global population, respectively.
  LINK https://doi.pangaea.de/10.1594/PANGAEA.918731

- **Water Evaluation and Planning (WEAP)** WEAP is a software tool for integrated water resources planning and policy analysis. WEAP operates on the basic principle of a water balance and can be applied to municipal and agricultural systems, a single watershed or complex transboundary river basin systems. Moreover, WEAP can simulate a broad range of natural and engineered components of these systems, including rainfall-runoff, baseflow, and groundwater recharge from precipitation; sectoral demand analyses; water conservation; water rights and allocation priorities, reservoir operations; hydropower generation; pollution tracking and water quality; vulnerability assessments; and ecosystem requirements. A financial analysis module also allows the user to investigate cost-benefit comparisons for projects.

  WEAP is an excellent platform to produce estimates of water resource/supply flows and variability, which will serve as very suitable inputs to the SPOT Model.
  LINK: https://www.weap21.org/index.asp?action=201

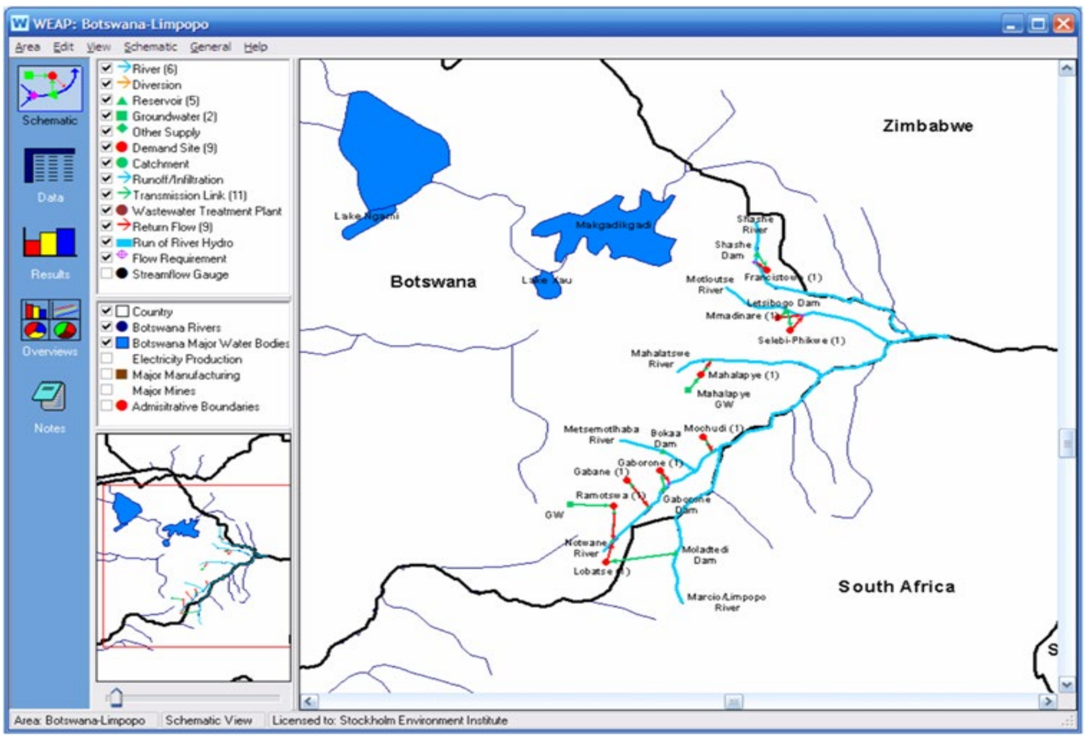


Figure 26

6 Determination of the Efficient Frontier and the Appropriate Level of Reliability

6.1 Determination of the Efficient Frontier of Water Resources Portfolio

The efficient frontier is an important illustrative device and tool in modern portfolio theory (Markowitz, 1952; Sharpe, 1964). The overarching objective of an efficient water resource portfolio is the ability to address the risks and water availability issues in meeting water demand while doing so cost-effectively. This means a water resource portfolio can be described as efficient when the risks are minimized for a given average unit cost. The economic efficiency principle also requires that the average unit cost not exceed the value of water determined by the consumers' willingness to pay.

Adapting it to the present context, one could put unit cost (rather than expected return) on the Y-axis and portfolio risk on the X-axis. An efficient water resource portfolio is such that the average unit cost can only be decreased by an increase in the risk exposure of the water resource system. Points to the right of the curve are inefficient, as other combinations would reduce the risks of the system while maintaining the average unit cost (Markowitz, 1952; Sharpe, 1964).

In practice, we will most likely be looking only at efficient solutions in the lower-risk area. Water regulators would enforce high-reliability targets for utility companies. Even when such regulatory enforcement is not in place, it is likely that, in the context of water resources planning, high-reliability solutions will tend to be preferred.

The study conducted in Lima by the World Bank defined water reliability as meeting 100% of demand 90% of the time, measured monthly. (Groves et al., 2015)

The main concern with having less than 100% reliability in a planned water system (unlike other systems) is the eventual shortage that will likely take place with substantial consequences on the economy at hand.

The World Bank Lima water strategy study addresses various uncertainties in the context of implementing Lima's Long-Term Water Resources Master Plan. These uncertainties are crucial to consider because they may significantly affect the success of water management strategies (See Annex F).

6.2 Determination of the Appropriate Level of Reliability of the Bulk Water Supply System

Water resource planners tend to fix a standard high level of reliability based on pragmatic considerations influenced by the findings from well-designed studies in similar conditions. The underlying idea is that the cost to users of an unreliable supply is significantly greater than the cost of assuring a high level of reliability and that it may not be worth the effort to arrive at a precise value for every type of use in the water system under consideration.

In certain instances, a deeper examination may be necessary to test the pragmatic level that we adopt when establishing a bulk water system. The methodology used will explore how user utility (based on willingness to pay) decreases in the presence of a risky water supply (holding the mean level of supply constant). A tradeoff between costs to obtain reliability and user utility will be compared with one another. To illustrate the matter, Morocco will be used as an example case study.

In Morocco, water availability has been steadily decreasing over the years. For instance, it dropped from 2000 m3/person/year in 1970 to 1000 m3/person/year in 2007. Forecasts indicate that this trend is likely to continue, potentially leading to even greater water scarcity in the future. Given these factors, it is crucial to apply efficient water resource planning principles to address water scarcity challenges in the country.

To develop an efficient water resource portfolio for Morocco, historical hydrological information was used to estimate water supply using a "design drought" year. Several alternative scenarios were added, assuming climate change impacts on the historical data. An efficient portfolio of water investments was prepared for each scenario, and the efficient frontier was determined.

The Moroccan water sector's efficient frontier revealed several options, including the expansion of conventional water supply sources, investments in wastewater treatment and reuse, and increased utilization of desalination technologies. By minimizing risk and optimizing costs, the efficient water resource portfolio for Morocco allowed for more reliable water supplies to be provided to its population and various sectors, including agriculture, industry, and domestic use.

In a case study titled "Developing Key Indicators for Adaptive Water Planning" that was published in the Journal of Water Planning and Management, an in-depth approach for developing key indicators to support adaptive water planning was utilized. The authors introduce a comprehensive framework that enables decision-makers to monitor and adapt their water management plans to respond effectively to changing conditions. By identifying these indicators, water planners can optimize resource allocation and enhance the robustness of their plans against uncertainties, such as climate change, population growth, and technological advancements. The paper details the methodology used for developing these key indicators, as well as an application of this methodology in a real-world case study: the Colorado River Basin (Annex E).

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Annexes

Annex A: Some Critiques of Modern Portfolio Theory as a Tool for Water Supply Planning

In an article on the application of MPT to flood control in the Netherlands, Aerts et al. (2014) outline the opportunities and limitations of MPT application to water supply, which are shown in the table below.

Opportunities and Limitations of Applying Modern Portfolio Theory to Integrated Water Resources Management

Opportunity	Limitation
A systematic methodology for assessing risk, variance and returns related to portfolios of water management resources	Applying MPT in multi-objective cases is difficult since multiple types of returns would require complex mathematical programming approaches. This could complicate the case rather than structure a problem.
MPT can support current planning while addressing long-term uncertainty	Historical data on variances and returns of water management measures are difficult to obtain.
MPT reveals the correlation between pairs of potential water management measures and policies	It is often challenging to quantitatively compare and obtain empirical information on correlations of returns and variances.
MPT provides a methodology to identify a set of measures which are robust to uncertainty	Complex dependencies between strategies exist in how they limit flood damage, and their combined effects on returns are less straightforward than in the financial sector.
MPT provides input to the discussion on how to conceptualize vulnerability to long-term developments, such as climate change.	MPT is not very well suited for cases with "deep uncertainty", such as unknown or unquantifiable climate change impacts.

Source:_Aerts, et al (2014)

Zheng (2016) raises additional concerns as to the applicability of classical MPT to water supply assets:

- The Markowitz model cannot reflect complex interactions among individual infrastructures. One of the key differences between "hard" water assets and financial assets is the existence of capture and storage dynamics within surface water systems.
- Financial portfolio optimization allows adjustment of capital allocation over time, but most water asset investments are irreversible, implying there will be no capital reallocation to the same asset once the investment decision is made.
- MPT assumes financial assets have a normal distribution, but hydrological variables, such as inflow and precipitation, rarely follow a normal distribution. Studies have found that hydrological inputs follow either lognormal or gamma distributions.

A key constraint with MPT and Water Supply is difficulties establishing standard deviations and correlations in locations where extensive hydrologic records do not exist.

Annex B: Estimated Default Grid Emissions Factors for MENA Countries

		Combined Margin Grid Emission Factor, gCO2/kWh				Operating Margin Grid Emission Factor, gCO2/kWh (including for use in PCAF GHG accounting)
	Country	Firm Energy (e.g., Hydro, Geothermal)	Intermittent Energy (e.g., Solar, Wind, Tidal)	Energy Efficiency	Electricity Consumption	
1	Afghanistan	193	331	193	193	414
2	Algeria	397	479	397	397	528
3	Bahrain	454	624	454	454	726
4	Djibouti	575	686	575	575	753
5	Egypt	406	498	406	406	554
6	Iran	421	528	421	421	592
7	Iraq	788	971	788	788	1080
8	Israel	258	343	258	258	394
9	Jordan	382	474	382	382	529
10	Kuwait	400	572	400	400	675
11	Lebanon	567	709	567	567	794
12	Libya	493	602	493	493	668
13	Morocco	547	660	547	547	729
14	Oman	320	419	320	320	479
15	Palestine	517	643	517	517	719
16	Qatar	258	411	258	258	503
17	Saudi Arabia	374	510	374	374	592
18	Somalia	582	689	582	582	753
19	Sudan	398	609	398	398	736
20	Syria	546	650	546	546	713
21	Tunisia	348	423	348	348	468
22	United Arab Emirates	310	464	310	310	556

Source: International Financial Institutions Technical Working Group on Greenhouse Gas Accounting (2022)

Annex C: Other Studies on Determining the Appropriate Level of Reliability of a Bulk Water Supply System

Numerous other studies follow a similar approach in determining the appropriate level of reliability of the bulk water supply system as discussed throughout the guidelines to those elaborated upon before. The following is a quick summary of such papers:

Title: Developing Key Indicators for Adaptive Water Planning

Authors: David G. Groves, Evan Bloom, Robert J. Lempert, Jordan R. Fischbach, Jennifer Nevills, and Brandon Gosh

Summary:

The paper presents a novel approach for developing key indicators to support adaptive water planning. The authors introduce a framework that enables decision-makers to monitor and adapt their water management plans to respond to changing conditions effectively. By identifying these indicators, water planners can effectively allocate resources and enhance the robustness of their plans against uncertainties, such as climate change, population growth, and technological advancements.

Title: Integrating a climate change assessment tool into stakeholder-driven water management decision-making processes in California

Authors: David R. Purkey, Annette Huber-Lee, David N. Yates, Michael Hanemann, Susan Herrod-Julius

Summary:

This paper focuses on integrating a climate change assessment tool into the stakeholder-driven water management decision-making processes in California. The authors emphasize the importance of considering climate change impacts on water resource management and the necessity of involving stakeholders in the decision-making process. To achieve this, they developed and applied a model called the Water Evaluation and Planning System (WEAP), which allows users to evaluate various water management strategies and policies under different climate change scenarios.

The paper discusses the process of engaging stakeholders in developing the WEAP model by organizing workshops and eliciting feedback. This ensured the model addressed stakeholders' concerns and facilitated better communication among different interest groups. The authors also highlight the importance of transparency and flexibility, as well as the need for continued stakeholder involvement for the successful implementation of water management plans.

Robust decision-making (RDM) in water planning is an approach to cope with the uncertainty and complexity inherent in water resources management. It emphasizes designing water management strategies that can perform well across a wide range of plausible future scenarios. The goal is to make decisions that remain effective even in the face of significant uncertainty about future conditions, such as climate change, population growth, and technological advances. This has been the main focus of portfolio generation and the inclusion of technologies that are not correlated with the variation in water availability in basins.

The adaptive approach, also known as adaptive management or adaptive water resources management, is a structured, iterative process for continually improving management policies and practices by learning from the outcomes of previously implemented management strategies. It involves monitoring, evaluating, and adjusting management strategies based on observed outcomes and updated scientific understanding.

Both RDM and the adaptive approach share a focus on dealing with uncertainty and complexity, but they differ in their emphasis and methods:

RDM focuses on making robust decisions upfront, i.e., selecting strategies that are expected to perform well across a wide range of possible future scenarios. It uses scenario planning, simulation models, and sensitivity analyses to explore how different strategies would perform under various conditions.

The adaptive approach, on the other hand, emphasizes learning and adapting over time. It involves designing flexible management strategies and monitoring systems that allow decision-makers to continually update their understanding of the system, identify the need for change, and adjust strategies as new information becomes available.

In practice, robust decision-making and the adaptive approach can be used in combination to create a comprehensive framework for managing water resources under uncertainty. This involves selecting robust strategies that perform well across a range of future conditions while also building in the flexibility to learn and adapt as new information emerges. This approach can help decision-makers to more effectively manage water resources, even in the face of considerable uncertainty about future conditions.

The Water Evaluation and Planning System (WEAP) is a user-friendly, integrated water resource management (IWRM) tool designed for the analysis, simulation, and planning of water systems. It was developed by the Stockholm Environment Institute (SEI) and is widely used by planners, researchers, and policymakers to assess water resources and develop management strategies under various climate, socio-economic, and infrastructure conditions.

WEAP allows users to create a detailed representation of water systems, including catchments, rivers, reservoirs, demand centers, and infrastructure. It incorporates both water supply and demand, as well as environmental, economic, and social aspects. The software provides a range of capabilities, such as scenario analysis, water allocation, cost-benefit analysis, and water quality assessments.

WEAP operates on a principle of "water balance," which ensures that water entering and leaving the system is accounted for at all times. Users can simulate different scenarios, such as climate change impacts, population growth, or changes in water policy, and evaluate the potential effects on water availability, allocation, and demand.

By enabling the comparison of various water management strategies and policies, WEAP helps decision-makers identify the most effective and sustainable options for meeting present and future water needs while considering environmental, economic, and social factors. This makes it a valuable tool for integrated water resource management and planning.

The following are more papers that utilized WEAP, including foundational papers:

1. Yates, D., Sieber, J., Purkey, D., & Huber-Lee, A. (2005). WEAP21 - A demand-, priority-, and preference-driven water planning model: Part 1: Model Characteristics. Water International, 30(4), 487-500.

   This paper provides an in-depth overview of the WEAP model, discussing its characteristics and capabilities. It is a foundational paper for understanding the model.

2. Joyce, B., Mehta, V., Purkey, D., Dale, L., & Hanemann, M. (2011). Modelling the impacts of climate change on water and agricultural sectors in California: A case study of the Mokelumne River Basin. Climatic Change, 109(S1), 377-395.

This paper applies the WEAP model to the Mokelumne River Basin in California, focusing on assessing the potential impacts of climate change on water supply, demand, and agricultural systems and identifying adaptation strategies.

3. Cai, X., McKinney, D. C., & Rosegrant, M. W. (2003). Sustainability analysis for irrigation water management in the Aral Sea region. Agricultural Systems, 76(3), 1043-1066.

   The study utilizes the WEAP model to evaluate the sustainability of irrigation water management in the Aral Sea region, considering various water allocation strategies and examining their impacts on the environment and the economy.

4. López-Morales, C. A., & Mesa-Jurado, M. A. (2018). Evaluating adaptation strategies for integrated water resource planning under uncertainty: A case study in the Conchos Basin, Mexico. Water Resources Management, 32(3), 863-879.

   This paper employs the WEAP model to evaluate different water resource adaptation strategies in the context of uncertainty, using the Conchos Basin in Mexico as a case study. The research provides insights for integrated water resource planning and decision-making.

5. Erdil, A., & Kahya, E. (2020). A basin-scale approach to the Water Evaluation and Planning (WEAP) model for water resources management planning in a data-scarce region. Environmental Science and Pollution Research, 27(9), 8827-8843.

   This study applies the WEAP model to a data-scarce region in Turkey, demonstrating the effectiveness of the model in water resources management planning and identifying potential water-saving measures.

   These papers represent examples of the diverse applications of the WEAP model for water source planning, demonstrating its usefulness in addressing various water management challenges across different geographic and socio-economic contexts.

Annex D: Supplemental Excerpt on Estimation of Water Volatility

The estimation of the volatility of water availability from different sources is crucial for efficient water resource planning. This involves analyzing historical hydrological information to estimate water supply using a "design drought" year when the total supply from conventional technologies is lowest. Additionally, several alternative scenarios can be added, assuming climate change impacts on the historical data. An efficient portfolio of water investments can be prepared for any particular scenario. In order to deal with the extreme uncertainty introduced by climate change, some studies have taken the multi-pronged approach of creating various scenarios of different aspects of supply and demand.

There is some emphasis on the need for an enhanced paradigm in water resources planning and management due to the increasing uncertainty introduced by climate change in recent decades. The traditional static design paradigm (utilizing historic values) may no longer be as sufficient for addressing these new challenges as recent findings have shown stark differences in the rate of change of water availability across regions with increasingly haphazard fluctuations. New literature proposes a water resources management paradigm that adapts to changing conditions, focusing on three key principles:

Forecasts: Utilize real-time observations and forecasts on multiple timescales (daily, weekly, seasonal, and annual) to enable adaptive decision-making based on the available information. This requires designing operational systems that can adjust dynamically according to the forecasts.

Flexibility: Design water systems that can manage the consequences of "failure" by assuming design values will eventually be wrong. These systems should have multiple components that work in a continuous fashion and can be called upon only when needed (i.e., "on-demand infrastructure").

Integration: Integrate structural and nonstructural systems to create water systems that are designed for all floods and droughts, incorporating innovations in communication, information technology, and economic mechanisms (Brown, 2010).

Much of the literature on water source planning with an emphasis on the impacts of climate change incorporates multiple methodologies to account for the dramatic fluctuations in water availability from present water sources within various regions. Recent studies have focused on developing water source plans that are both robust and flexible.

Annex E: Methodology to Develop Key Indicators for Adaptive Water Planning

The authors use a five-step methodology to develop key indicators for adaptive water planning:

Identify vulnerabilities and objectives: This step involves engaging stakeholders and decision-makers to identify the primary vulnerabilities and objectives of the water management system. This crucial step ensures that the subsequent analysis is customized to address the specific concerns and goals of the system. By identifying vulnerabilities, the authors can determine which aspects of the water management system are most susceptible to uncertainties and prioritize their efforts accordingly.

Develop scenarios: The authors create a diverse set of scenarios representing a wide range of plausible futures. These scenarios incorporate uncertainties related to climate change, population growth, technological advancements, and other factors. By capturing the variety of possible future conditions, the authors can assess the effectiveness of water management plans under different circumstances, thereby providing valuable insights into the adaptability of these plans.

Evaluate performance metrics: For each scenario, the authors evaluate the performance of the water management plans using various metrics. These metrics include water supply reliability, cost-effectiveness, environmental impacts, and other factors relevant to the specific vulnerabilities and objectives identified in Step 1. This evaluation helps identify the strengths and weaknesses of each plan under different future conditions and serves as the basis for identifying robust strategies.

Identify robust strategies: The authors use a decision-making framework called Robust Decision Making (RDM) to pinpoint strategies that perform well across multiple scenarios. RDM is a valuable tool for evaluating management options that are robust against future uncertainties and adaptable over time. This step provides the foundation for developing key indicators by highlighting the factors that contribute to a plan's success or failure under various conditions.

Develop key indicators: Based on the insights gained from steps 3 and 4, the authors identify a set of key indicators that can help decision-makers monitor the system's performance and adapt the management plans accordingly. These indicators are tailored to the specific vulnerabilities and objectives identified in Step 1 and represent the critical factors driving the system's performance under uncertainty.

Application:

The authors apply their methodology to the Colorado River Basin, demonstrating the practical utility of their approach in supporting adaptive water planning in a real-world context. The case study showcases how the methodology can identify key indicators that inform decision-makers about crucial aspects of the water management system's performance. It also highlights the importance of a robust and flexible planning process capable of adapting to the challenges posed by future uncertainties.[18]

[18] Groves, D. G., Bloom, E., Lempert, R. J., Fischbach, J. R., Nevills, J., & Goshi, B. (2015). Developing Key Indicators for Adaptive Water Planning. *Journal of Water Resources Planning and Management*, 141(7). https://doi.org/10.1061/(ASCE)WR.1943-5452.0000471

Annex F: World Bank Lima Water Strategy Study

The World Bank Lima water strategy study addresses various uncertainties in the context of implementing Lima's Long-Term Water Resources Master Plan. These uncertainties are crucial to consider because they may significantly affect the success of water management strategies. The key uncertainties discussed in the paper include:

1. **Climate Change:** One of the most significant uncertainties is the impact of climate change on water availability, precipitation patterns, and the frequency and intensity of extreme weather events. Climate change may exacerbate water scarcity and stress in the region, making it more challenging to meet the water needs of a growing population.
2. **Population Growth:** Lima's population is expected to continue growing, leading to increased demand for water resources. The rate of population growth and the spatial distribution of the population are uncertain, making it difficult to predict future water demands accurately.
3. **Socioeconomic Factors:** The author acknowledges uncertainties in economic growth, urbanization, and social factors that may influence water demand and availability. Changes in these factors can affect the water consumption patterns and preferences of the population, as well as the willingness and ability to invest in water infrastructure and management.
4. **Technological Innovations**: Uncertainty regarding the development and adoption of new technologies in water management is another factor discussed in the paper. Technological advancements can significantly impact the efficiency of water use, the capacity for alternative water sources (e.g., desalination, water reuse), and the resilience of water infrastructure.
5. **Policy and Regulatory Environment:** The implementation of the Master Plan may be influenced by uncertainties in the political and regulatory environment. Changes in government priorities, policies, or regulations could impact the availability of resources, the support for specific projects, and the overall effectiveness of water management strategies. This is of particular relevance for desalination and reuse initiatives, because regulatory frameworks for these supply sources are absent or nascent in many countries, suggesting that future changes are highly likely as regulators learn and adapt to these new technologies.
6. **Hydrological Models:** The paper highlights uncertainties associated with the use of hydrological models to predict future water resource conditions. Model limitations and the inherent uncertainty of predicting complex natural systems can lead to inaccuracies and discrepancies in the projections.

To address these uncertainties, the study proposes a robust decision-making framework that incorporates adaptive pathways, scenario analysis, stakeholder engagement, diversification, and continuous monitoring. This approach helps ensure that the overarching plan remains flexible and responsive to changing conditions and emerging challenges, promoting a resilient and sustainable water supply for Lima's growing population.

- **Adaptive Pathways:** Adaptive pathways are a sequence of actions and investments designed to address water challenges over time. They offer flexibility by allowing decision-makers to adjust and modify the course of action as new information becomes available or conditions change. Adaptive pathways involve identifying key decision points at which the implementation process can be reassessed and revised based on the current situation and available knowledge. This approach ensures that the Master Plan remains adaptable and responsive to emerging challenges and changing circumstances.

- **Scenario Analysis:** Scenario analysis is a technique used to evaluate the potential impacts of various future scenarios on water resources management. It helps decision-makers understand the range of uncertainties associated with different factors, such as climate change, population growth, and technological innovations. By analyzing multiple scenarios, the framework can assess the effectiveness and robustness of proposed solutions under different conditions. This allows for the identification of strategies that perform well across a wide range of plausible futures, making the Master Plan more resilient to uncertainties.
- **Stakeholder Engagement:** Stakeholder engagement involves actively involving a diverse set of stakeholders, including government agencies, water utilities, private sector organizations, and the public, throughout the decision-making process. Engaging stakeholders ensures that multiple perspectives, priorities, and concerns are taken into account in the development and implementation of the Master Plan. This approach not only helps to identify potential challenges and opportunities but also fosters acceptance and support for the proposed solutions.
- **Diversification:** Diversification refers to the development of a diverse portfolio of solutions and approaches to manage water resources. This may include infrastructure investments (e.g., reservoirs, pipelines), demand management strategies (e.g., water conservation, pricing), and technological innovations (e.g., water reuse, desalination). By incorporating a wide range of solutions, the framework increases the resilience and flexibility of the water management system, allowing it to adapt more effectively to changing conditions and uncertainties.
- **Continuous Monitoring:** Continuous monitoring involves regularly tracking the performance of implemented solutions, water resource conditions, and stakeholder feedback. This information allows decision-makers to evaluate the effectiveness of the Master Plan and identify any necessary adjustments or improvements. By incorporating a continuous learning process, the framework ensures that the Master Plan remains up-to-date and responsive to emerging challenges and new information.

The robust decision-making framework integrates adaptive pathways, scenario analysis, stakeholder engagement, diversification, and continuous monitoring to create a flexible and resilient water resources management strategy. This approach allows Lima's Long-Term Water Resources Master Plan to effectively address uncertainties and adapt to changing conditions, ensuring a sustainable and secure water supply for the city's growing population.[19]

[19] Grove et al, 2015