Yemen Country Report

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1 Introduction

The project carried out in Yemen under the Netherlands' Climate Assistance Program (NCAP) explored the linkages between water scarcity and climate change. While there were numerous activities and outputs of the project spread over the period 2006 to 2008, efforts focused on the overriding goals of (1) achieving a better understanding of both the level of vulnerability of rural/urban communities to future changes in local climatic regimes; and (2) identifying types of adaptation activities that would build resilience against increasing water scarcity.

Yemen is an arid Middle Eastern country, occupying an area of 527,970km^2 at the south of the Arabian Peninsula. It is bordered to the north by Saudi Arabia, to the east by Oman, and to the south and west by its 1,900km coastline along the Gulf of Aden and the Red Sea. With an annual population growth rate of about 3.5% – one of the highest in the world – Yemen's population is putting increasing pressures on its limited water resources and straining the ability of the government to provide vital social services. As of 2000, Yemenis numbered approximately 18.3 million, an increase of nearly 4 million over the course of the previous six years. During the same time, poverty increased nearly threefold, particularly in rural areas, where three quarters of Yemenis live. Yemen is burdened with low human and economic development, serious environmental challenges, and a high degree of vulnerability to current and future climatic variability and change. It is widely acknowledged within government policy dialogues that Yemen's major environmental resource problem is water scarcity, a situation prone to exacerbation under climate change. According to the country's First National Communications to the UN Framework Convention on Climate Change (UNFCCC), temperature across the country is expected to rise, while precipitation is expected to decrease, leading to increased pressures on the country's delicate balancing act between water resources and water consumption.

Rainfall varies widely, depending on its five ecological zones: hot and humid coastal plains, temperate highlands, high plateaus and uplands, desert interior, and islands in the Red Sea. Annual rainfall varies from less than 50mm in the coastal plains, rising with the topography to between 500 and 800mm/year in the western highlands, and dropping again to below 50mm/year in the desert interior zone. The rains come primarily in spring and summer, and are determined by two main mechanisms: the Red Sea Convergence and the Inter Tropical Convergence Zone. Temperature depends primarily on elevation, and in the coastal areas, is determined by distance from the Red Sea and Indian Ocean. Average annual temperatures range from less than 12°C in the Highlands (with occasional freezing) to about 30°C in the coastal plains.

Historically, as per capita availability is falling steadily with growing population, scarce water resources have become increasingly precious. In 1955, Yemen's per capita water availability was about 1,100m^3. By 1990, it had fallen to less than half of this level, about 460 m^3/person/year, and is projected to drop to 150 m^3/person/year by 2025 under business-as-usual scenarios of increased demand – to say nothing of future climate change-related impacts. Whereas surface water is largely seasonal and unreliable, groundwater is being extracted in extreme excess of natural recharge levels.

Yemen continues to make development strides, yet profound poverty and other challenges persist. The 1998 Household Budget Survey showed that about 18% of the population lived under the food poverty line, with about 42% incapable of meeting basic food and nonfood requirements. Unfortunately, these percentages remain largely unchanged today and reflect the entrenchment of poverty conditions among approximately 7 million people. Moreover, other factors such as adult literacy (at 54% of the general population over 15 years of age; significantly higher for women) and GDP per capita (at US$760/year) combine to place Yemen near the bottom of the Human Development Index in 2007.

The rest of this report describes the processes, activities, results, and lessons learned from the Yemen NCAP project. The next section describes the rationale and key objectives of the project. Section 3 presents key results and finding, section 4 presents lessons learned, and an annex is included that provides an overview of the key outputs of the project.

2 Rationale and Objectives

Of the many sectors that are vulnerable to climate change in Yemen, water resources are considered the most vulnerable, with potentially grave environmental and social effects, compounded by the country's poverty alleviation challenges. The sustainable exploitation of Yemen's water resources are a high priority under national environmental and agricultural policies, as well as multilateral environmental agreements to which it has signed on (i.e., the UNFCCC, UNCCD and UNCBD).

It is important to note that the focus on water scarcity benefited from and built upon the significant level of capacity enabled by the earlier Netherlands Climate Change Studies Assistance Program (NCCSAP) which ran from 1996 to 2000. Dutch water specialists provided technical backstopping support for the preparation of the vulnerability chapter of the country's First National Communication under the UNFCCC. Support was also provided in the analysis of climate change impacts on agricultural activities.

While presently engaged in a range of national efforts to manage its scarce water resources under known climatic conditions, Yemen's vulnerability to increased climatic variability and future climate change threatens and may ultimately thwart such efforts. Indeed, addressing poverty through improved agricultural production is among Yemen's development objectives. Production is consistently quite low, however, due in part to the vulnerability of rain-fed agriculture to rainfall variability and prolonged drought. Layered on top of the prevailing conditions of poverty, environmental and climatic factors create a number of pressing challenges for Yemen.

Desertification, brought on by recurrent droughts and human land-use pressures, has consumed significant land area and continues to threaten precious arable land resources. Today, arable land constitutes roughly 3% of Yemen's land area, with agriculture contributing 20% of Yemen's GDP and supporting 53% of employment, with traditional subsistence agriculture dominating production. Adaptation-related activities that build upon existing national processes forge new linkages where possible – and break new ground where needed – have the potential to reduce the vulnerability of water resources to climate change. The research and implementation processes of the NCAP project offered an opportunity to better understand linkages between climate change and water scarcity.

The primary aim of the NCAP project was to identify and mainstream priority adaptation activities that would build resilience against increasing water scarcity among vulnerable communities, sectors, and ecosystems in three representative areas. Within this overarching goal, there were four major objectives for each case study area: (1) assess current and future vulnerability of water resources to climate change; (2) identify potential adaptation strategies within a stakeholder-driven process; (3) formulate a pilot adaptation measure which has been identified as the highest priority option from the stakeholder process; (4) integrate the results into national policy discussions and legislative action.

Sadah Basin, Sana'a Basin, and the urban/peri-urban area including and surrounding Aden City were selected as representative case study areas. The location of each site is shown on the map below. The rationale for the selection of these particular sites was that each represented a different ecological zone and development context. This offered an opportunity to examine and compare various dimensions of vulnerability to water scarcity, as well as to explore a plausible range of potential adaptation strategies.

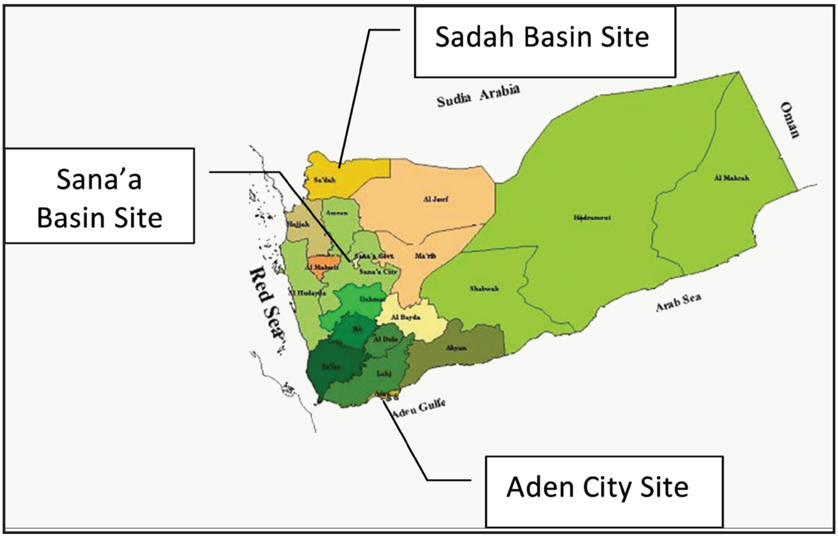

Figure 1: Case study site locations

There were four key project activities in each case study area: extensive stakeholder consultations; data collection; integrated modeling of water demands and supply; and multicriteria assessment to prioritize adaptation options. Stakeholder consultations were undertaken using rapid rural appraisal techniques and focused on local perceptions of water scarcity, climatic factors, and development challenges. These structured stakeholder discussions were synthesized into a set of inputs for water resource modeling and prioritization of adaptation initiatives.

Moreover, a wide range of data from national and international sources was collected and synthesized for each case study site (subject to availability constraints). This included information on poverty and social indicators, water use and resources, surface runoff, surface and groundwater availability, groundwater depletion and management, crop production areas, soil cover, maps, and meteorological information. As with stakeholder discussions, the output of this effort was a synthesized body of knowledge that fed directly into water modeling activities and the assessment of adaptation options.

Water balance modeling was used to evaluate water demands and scarcity across all sectors for each of the case study sites. The Water Evaluation and Planning (WEAP) software, a user-friendly modeling platform that takes an integrated approach to water resources planning, was used to document and simulate current and future domestic and agricultural water use demands, climatic and hydrological parameters, and groundwater declines. The WEAP model served as the framework for the analysis of both a reference scenario (i.e. water supply and demand in the absence of adaptation strategies and under a climate sequence developed by repeating historical climate data), supply and demand conditions superimposed on two possible future climate sequences developed from downscaled global climate model data, and a set of Alternative Scenarios, all simulated through the year 2025. These latter scenarios represented potential water resource management strategies, identified through stakeholder consultations, which have the potential to reduce the vulnerability of communities to water scarcity.

Prioritization of adaptation initiatives was carried out within a stakeholder-driven multicriteria assessment (MCA) process. An MCA is a structured approach to determine overall preferences of various interest groups (e.g. farmers, politicians) among alternative options, where the options can accomplish several objectives. Because the Yemen NCAP project took place concurrently with its National Adaptation Program of Action (NAPA) project, the NCAP benefited from the capacity already developed for the MCA within the NAPA process. The output of this activity was a ranked set of potential adaptation options.

3 Key Results and Findings

In this section, the key results and findings for the Yemen NCAP project are presented for each case study site following a brief overview of the physical and socioeconomic characteristics of each site. The discussion of key findings covers current vulnerability (based on available data and stakeholder consultations), future vulnerability (based on WEAP modelling), desirable adaptation options (also based on WEAP modelling) and a prioritized set of adaptation options (based on MCAs).

3.1 Sadah Basin

An intermountain basin, the Sadah Basin is situated in Yemen’s western highlands about 250km north of Sana’a. The basin is characterized by sparse rainfall and high evapotranspiration rates. The plain is surrounded by mountains reaching 2,750m above sea level (ASL). Elevations in the plain itself range from 1,840 to 2,050m ASL, with gentle gradients towards the southeast where water collects in the Marwan Wadi, which flows northerly into the Najran Wadi. There are no permanent or seasonal streams and only after heavy rains will surface water runoff discharge into the Marwan Wadi. As such, there are no major flood risk areas.

In the late 1970s, and continuing to present times, socioeconomic development in the region emphasized irrigating agriculture with groundwater extraction from various aquifers underlying the region. This decision has had enormous implications for water scarcity in the Sadah Basin, as it has produced a gradual replacement of rain-fed agriculture with irrigated agriculture and aided rapid groundwater depletion.

3.1.1 Current Vulnerability

Understanding the current vulnerability of water resources in the Sadah Basin area relied on input from stakeholder consultations and existing studies. Stakeholders consulted included farmers, NGO representatives, and officials in key government offices. The information collected helped to identify causes of water use inefficiency, how people were responding to growing scarcity, and potential obstacles to adopting alternative water management practices. The primary finding of these studies was that the high current vulnerability of Sadah Basin water resources to climate variability and change, according to stakeholder testimony, is largely due to the current rapid depletion of groundwater, low efficiency of water use, low coverage of water and sanitation services.

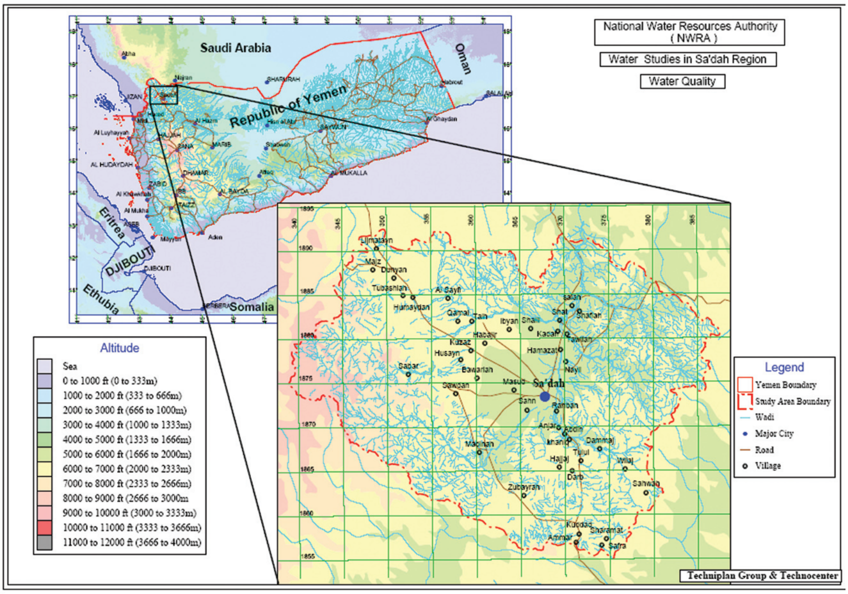

Figure 2: Water sub catchments of the Sadah Basin

While there were no specific studies on the vulnerability of water resources to climate change in the Sadah Basin, the YOMINCO/TNO (1983), the DHV (1992) and Techniplan/NWRA (2002) studies addressed the issue indirectly. The YOMINCO/TNO study mainly investigated water resources through geophysical surveys, a well inventory and aquifer tests. The DHV study updated the well inventory and investigated other issues related to water management, such as the socio-economic context. The Techniplan/NWRA study dealt with remote sensing aspects of the Sadah Basin and illustrated the dominant aquifers and aquicludes in the basin and outlined the most significant flow directions. Figure 2 summarizes the hydrology of the Sadah Basin based on these sources of information.

The combination of stakeholder consultations and available data was instrumental in establishing a baseline of information to understand current vulnerability. Between 1983 and 2001, the total groundwater extraction doubled. The doubling of the number of wells between 1983 (1,100 wells) and 1992 (2,330 wells), and again between 1992 and 2002 (4,989 wells) – coupled with improved well-design – increased gross groundwater extraction by about 30%. Whilst the farmers mainly exploit the groundwater resources of the Wajid sandstone aquifer; further groundwater depletion poses large economic risks to farmers. Farmers are concerned that not only are existing wells' yields continuously deteriorating, but water quality is also declining. Researchers found high rates of salinity and pollution from improper waste management were affecting the quality of well water.

Simultaneously with the above trends, groundwater recharge has declined. In 1983, net aquifer recharge was estimated at 10 million m^3. Between 1983 and 2001, total groundwater extraction grew from 45 to 90 million m^3/year while net aquifer recharge dropped to just 7 million m^3/year, or about a 30% decline from previous levels. By the end of 1998, the active zone of the aquifer had been exhausted.

In principle, Yemen's national water management plan is "basin co-management" whereby stakeholders and state institutions are considered partners in managing water resources at the catchments level. However, in practice the current Sadah Basin Committee is widely acknowledged to be ineffective. Attempts to establish more community-based water management organizations have been consistently constrained by limitations in the National Water Resource Authority's resources and on-site presence.

Regarding current coping strategies to deal with water scarcity, some water harvesting does occur for irrigation purposes. Compared to groundwater pumping, however, water harvesting is still a minor tool used by farmers. Moreover, there are no wastewater treatment plants, therefore reuse of wastewater (i.e. greywater) is not an option. In any event, overall stakeholder sentiment is critical of the notion of wastewater reuse as residents remain confused and skeptical of the potential benefits from a plant. This negative perception is related to problems experienced in other cities, e.g. the Sana'a wastewater treatment plant which most associate with pollution and odors.

3.1.2 Future Vulnerability

There are seven major hydrological sub-basins that have been identified using diagrams obtained from provincial reports as shown in figure 2. These sub-basins include Nushur, Razamat, A'kwan, Dammaj, A'lat and A'yn, Sabar and As Sa'id, and al Haniyah and A'wayrah.

Modeling of water supply accounted for groundwater and surface water resources. Groundwater for the entire basin was assumed to be 3,728 million m^3 of stored water based on available statistics for the basin. Four existing surface storage structures (i.e. dams to capture flash flood waters) having a combined annual capacity of 1.7 million m^3 were also modeled (i.e. dams on the Dammaj, the Sabar, the Nushur and the Marwan *wadis*).

Water demand was distinguished between agricultural and household demand. Agricultural water demand associated with irrigated areas was divided among the three major crop types: grapes (40%); cereals (30%); and wheat (30%). While other crop types such as vegetables and fruit orchards are cultivated in the basin, limited data availability hindered adequate modeling of these water demands. Domestic water demand was projected using historical population growth rates for the urban population of Sadah City and the disbursed rural population surrounding the city.
The reference scenario repeated historical climate data for the Sadah Basin through to 2026. Two climate change scenarios simulated the magnitudes of changes in precipitation and temperature; the OSU Core and the UKH1 dry scenarios[1]. The UKH1 serves as a worst case scenario in which annual precipitation decreases by up to 32% relative to the 1960 to 1990 baseline and that temperature would increase by up to about 2.2°C relative to the historical baseline by 2050. These assumptions were based on previous climate modeling work undertaken during the earlier NCCSAP program.

Without the identification and implementation of suitable adaptation measures, and assuming patterns of growth described above, the key finding of the Scenario analysis is that the aquifers underlying the Sadah Basin will be completely depleted by around 2024, essentially regardless of climate change. This is illustrated in figure 3 which shows full groundwater depletion virtually unchanged for the reference, OSU Core and UKH1 Dry scenarios. It is against this alarming conclusion that stakeholders and the research team consulted about potential strategies to mitigate or avoid this calamitous outcome.

3.1.3 Adaptation Strategies

In consultation with stakeholders in the region, three Adaptation Scenarios were developed to explore ways to reduce future vulnerability, as described below:

Improved irrigation efficiency: This adaptation scenario considered the introduction and aggressive penetration of drip irrigation techniques that dramatically increase irrigation efficiency.

1 Downscaled climate models from Global Circulation Models (GCM) for Yemen: OSU (Oregon State University GCM); UKH1 (U.K. Meteorological Office High Resolution General Circulation Model).

Increased storage capacity: In this adaptation strategy scenario, five new dams are added to the *wadis* starting in 2010, each with a 0.5 million m^3 storage capacity. These dams would be coupled with rain harvesting technologies to enhance groundwater recharge and increase rainfall runoff collection during dry months.

Greywater use: This scenario focuses on the construction and operation of a wastewater treatment plant with a capacity of 50,000 m^3/day for Sadah city. The effluent from this plant is available for use as agricultural irrigation in the Alat and A'yn sub-basin as well as for reuse in the city beginning in 2008.

A key finding of the Adaptation Scenario analysis is that, taken in isolation, none of the options is able to delay the depletion of aquifers underlying the Sadah Basin by more than a few years. The drip irrigation scenario avoids total groundwater depletion by only an additional two years relative to reference conditions; building new dams delays depletion by only one year; and the greywater use option has a negligible impact (due to the limited volume of water produced and stakeholders benefited). The failure of these options to forestall the ruin of the region's productive domestic and agricultural sectors merely underlines the urgency to consider multiple concurrent and/or more intensive options.

The adaptation strategies above fed into an MCA process in which the results were discussed with stakeholders in an effort to prioritize adaptation options. Of the initial three strategies, only the first two were prioritized as the use of treated wastewater was viewed as too limited in its ability to benefit a large section of the population of the Sadah basin.

Given the meager impact of each option applied individually, stakeholders advised the implementation of all three options concurrently. Figure 4b shows the additive effect of the adaptation strategies. That is, the red line to the right represents the combined effect of grey water, drip irrigation, and new dams. It is important to note that even this aggressive adaptation scenario is not able to stabilize annual groundwater demand relative to annual groundwater supply, and primarily serves to delay the inevitable groundwater depletion by only a few years.

The implications of this finding are staggering from a policy perspective. Achieving future water long-term supply/demand equilibrium in the Sadah Basin through the use of very aggressive targets for efficiency, recycling, and additional storage capacity is impossible. The failure to reconcile supply and demand suggests that the region is on the cusp of a major environmental disaster in the not too distant future. In other words, no matter the degree to which the capacities of regional water sector agencies are enhanced, or the rigor by which water demand mandates are monitored and enforced, it is too late for the region to achieve a sustainable water use trajectory through incremental improvements. That this situation exists regardless of climate change highlights the nature of the sustainable development crisis at hand in the region.

Other more intensive, more politically unpalatable strategies are likely to need exploring, and soon. These range from the very expensive (e.g. long distance water hauling) to the severe (e.g. strict water rationing for domestic use), to the draconian (e.g. relocation of existing communities). Exploring these sorts of options will be enhanced through seeking a goal of greater community participation in decision-making. Discussions of the Sadah Basin Committee and beyond would be more effective if all parties involved made a concerted effort to work together and avoid conflict, rather than acting individually.

3.2 Sana'a Basin

The Sana'a Basin is located in the Central Highlands of Yemen and includes the capital city of Sana'a. At an elevation ranging from 2,000 to 2,200m ASL, the basin is characterized by localized rainfalls with intense precipitation events of relatively short duration. Rainfall is the source of runoff in the wadis and of ground water recharge.

The Sana'a basin had a population of 2 million in 2004, constituting about 8% of the country's total population. It is important to note that Sana'a city is among the world's fastest growing cities, the population residing in the city itself is growing at about 5.5% per year and in the surrounding rural areas, the population is growing at about 3.2% per year. Population growth and subsequent increased reliance on groundwater extractions have led to a lowering of the groundwater table at alarming rates over the past 20 years. Existing government plans for expanding irrigated agriculture over the 2016 to 2020 period suggest this heavy reliance will only increase.

3.2.1 Current Vulnerability

Hydrologically, the Sana'a Basin can be divided into an upper (northern) unit referred to as the Wadi Al Kharid Hydrological Unit and a lower (southern) unit referred to as the Musyareka Hydrological Unit. On the basis of surface water drainage systems and topography, a total of 22 distinct sub-basins have been identified for planning purposes. There are six major aquifers in the Sana'a Basin: Northwestern, Northeastern, Central Plains, Eastern, Southwestern, and Southern. The urban area surrounding Sana'a draws water from the Central Plains aquifer.

Driven in large part by population growth, steady improvement in governmental services, and high system losses, water consumption in urban areas has increased from 57 million m^3 to 70 million m^3 between 1995 and 2000, which implies an average annual growth rate of 4.2%. In rural areas, beneficiaries of water supply projects have grown from 6.8 million to 7.7 million over the same period, implying an average annual growth rate of 2.5%. It is important to note that current water supply sustains probably no more than half the amount demanded, as there is substantial unmet demand in the region.

Trends in water consumption have put enormous strain on the basin's limited groundwater resources. Indeed, the Sana'a basin experienced dramatic declines in its groundwater table in recent years, a fact that has been cited by all stakeholders as the region's most pressing development challenge. In 2004 alone, the groundwater table dropped by about 7m in the eastern region and about 8m in the western region of the basin. These declines come in addition to water table declines of previous years, all of which reflect increasing access to groundwater in recent years.

The decline in groundwater is partially due to technological advancement. At one time in Yemen's distant past, traditional, shallow hand-dug wells (about 15m deep) were the norm and dotted the basin. In the 1970s, farmers began to deepen these wells up to 30m using locally available metal tools. In the 1980s, modern drilling techniques were introduced, enabling well depths between 200 and 250m that make use of diesel pumping systems. Today, most boreholes are more than 400m deep and the "water reservoir" continues to become further and further away from the surface.

3.2.2. Future Vulnerability

To assess future vulnerability of groundwater resources using a WEAP process, groundwater in the basin was divided into five major aquifer systems according to a characterization conducted by WEC (2001). These comprised the Central Plain, Southwestern, Southeastern, Eastern, and Western aquifers. Modeling the aquifer systems in this way made it possible to represent differences in groundwater storage and availability across the basin.

A number of assumptions were integrated into the reference scenario. Population growth in Sana'a city was assumed to continue at high rates, 5% per year through to the end of the planning period in 2026. Agriculture in sub-basins 9 and 16 (surrounding Sana'a city) was assumed to continue recent patterns of a decline of about 3% per year, and a 1% per year decline in sub-basins south of Sana'a. On the other hand, agriculture in the sub-basins north of Sana'a was assumed to increase by about 3% annually, consistent with recent patterns and government plans. In addition, the treatment capacity of the Sana'a waste water treatment plant (WWTP) was assumed to increase to 0.1 million m^3/day in 2012, consistent with expansion plans.

To gauge the impact of climate change on water resources in the Sana'a Basin, two climate change scenarios were developed to represent possible changes in precipitation and temperature; the OSU Core and the UKH1 Dry scenarios[2]. Compared to the reference scenario, basin-wide annual precipitation under the OSU Core scenario increases by approximately 17 million m^3, or 2%, by 2025. In contrast, annual precipitation decreases by as much as 73 million m^3 (approximately 10% of the reference scenario value) during the same period for the UKH1 Dry scenario. Temperature increases, relative to the reference, in both scenarios by an average of between 1.0 and 1.3°C for the OSU Core and UKH1 Dry scenarios, respectively.

The effect of these climate change projections on annual irrigation requirements and groundwater depletion are summarized in figure 5a, which shows that an observable impact of climate change on irrigation demand, however small. The effect of climate change on groundwater depletion (figure 5b) in the Central Plain aquifer, for example, is also very small; groundwater is depleted by the year 2017 under all of the climate trajectories explored in this study. Full groundwater depletion also occurs in the Eastern and Northwestern aquifers while the remaining three aquifers in the Sana'a Basin (i.e. Northeastern, Southwestern, and Southern aquifers) are, in comparison, not particularly vulnerable to projected future water supply/demand conditions as they show relatively stable storage capacities over time.

Without the identification and implementation of suitable adaptation measures – and assuming patterns of growth described above – the key finding of the analysis is that supply/demand patterns are the primary drivers of vulnerability. Climate change exacerbates this vulnerability, rendering water scarcity issues more acute, particularly regarding the need for additional irrigation.

3.2.3 Adaptation Strategies

Several adaptation strategies were developed and explored in the WEAP model for the basin, as briefly outlined below. It is important to note that not all of these options were simulated uniformly across all the sub-basins or aquifers. Several strategies were more localized in nature, informed by both physical and strategic considerations (e.g. improving water distribution systems is relevant for the urban area of Sana'a).

Drip irrigation: Improve irrigation efficiency by introducing drip irrigation techniques.
Improved indigenous methods for wadi flow use/infiltration: Simulate the impact of increased small dam construction as a means to improve *wadi* flow infiltration and decrease losses to evaporation. A 20% increase in the infiltration rate of *wadi* flow is implemented in 2010 in each of the major *wadis* in the basin.

Alternative crop production: Shift from qat production to a crop less water intensive and one that can enhance local food security. A 3% per year decrease in the areas cultivated with qat by replacing it with wheat was implemented starting in 2008.

Improved water distribution systems: Implement measures to reduce the high losses in the municipal water distribution system and introduce water saving fixtures on the demand side in sub-basin 16. This strategy is modeled in the WEAP by reducing the annual water use rate in Sana'a by 1% per year starting in 2008 and reducing losses in the distribution system from an initial value of 30% to 10% over the planning period.

2 Downscaled climate models from Global Circulation Models (GCM) for Yemen: OSU (Oregon State University GCM); UKH1 (U.K. Meteorological Office High Resolution General Circulation Model).

Promotion of lower population growth in Sana'a city: The population growth rate in this scenario is simulated as 2%, compared to 5% in the reference scenario.

Use of greywater: Use wastewater treatment plant (WWTP) effluent for agricultural irrigation requirements in sub-basin 9. In this scenario, treated wastewater is applied to irrigation areas rather than letting the water flow into the Al Khared *wadi*.

Under reference conditions, the groundwater situation appears sustainable, despite a drastic decline, when considering the basin aquifer storage as a whole, which levels off at approximately 65% of total groundwater storage at year 2020 and beyond (i.e. about 3.4 million m^3 in 2020 and beyond compared to about 5.2 million m^3 in 2007). However, when results for each of the six aquifers are represented individually, the disparities among trends in groundwater storage become apparent and pose major adaptation policy implications. Whereas groundwater storage in the Northeastern, Southeastern and Southwestern aquifers appears to be sustainable under the conditions simulated in the reference scenario, groundwater drops precipitously and becomes *fully depleted* in the Central Plains, Eastern and Northwestern aquifers over the time period studied.

For these three vulnerable aquifers, the adaptation strategies identified above were modeled individually to assess their potential role in stabilizing water demand. The options fail to substantially mitigate the calamitous nature of future water/supply conditions in the Central Plain aquifer within the study time period. The most efficient adaptation strategy only delays the full depletion of the aquifer by 5 years beyond the point of depletion in the reference scenario. Only when the strategies are superimposed (i.e. simulated together) do the aggregate water savings, with the addition of the final strategy (the use of treated wastewater effluent for irrigated agriculture in sub-basin 9;), enable groundwater decline to level off. Note though that with all six strategies in place, groundwater storage in the Central Plains aquifer still continues to decline with time, albeit far more gradually than without the measures. This indicates that additional measures would need to be implemented in order to produce a flat, or sustainable, groundwater storage trajectory. Though not shown here, the Eastern and Northwestern aquifers show similar patterns.

The effect of implementing the adaptation strategies on unmet demand shows clear differences regarding the effectiveness of individual options. Those strategies that are implemented in all of the sub-basins (e.g. the introduction of irrigation efficiency and, promoting improved indigenous wadi flow infiltration) rather than targeted on specific sub-basins (e.g. improving urban efficiency in sub-basin 16 and using WWTP effluent for irrigation in sub-basin 9) provide greater savings of total groundwater reserves.

3.3 Aden City

Aden City is the chief port of Yemen and is one of the largest natural harbors in the world with an area of about 70km^2 of sheltered water surrounded by Jebel Shamsan, Khoremakser, and the shore extending to the hills of Little Aden. With a population of almost 600,000 in 2004, it then represented about 3% of total population of Yemen.

Average annual rainfall ranges from 30mm per year to as much as 50mm per year. Weather patterns are driven by humid winds that run parallel to the coast without penetrating inland. Temperatures are generally hot with average temperatures ranging from 27 to 30°C (42°C maximum) and relative humidity ranging between 60% in the night to 80% in the early morning. The city is surrounded by mountainous areas in the south and a coastal plateau in the north. The region also includes a number of ancient *wadis*, such as the Alkhosaf *Wadi*, the Alaidaroos *Wadi* and the Altaweelah *Wadi* which are all located in the old town of Aden (Crater) where traditional cisterns have been erected for flash flood protection.

Like other areas of the country, Aden City is growing rapidly – about 3.8% annually. However, with no perennial rivers, the water supply system needed to meet the demands implied by this growth depends largely on groundwater in the Tuban & Bana Delta Basins, located outside Aden in the Lahej & Abyan governorates. While lacking in surface water, seasonal flash flooding is nonetheless essential for aquifer recharge through *wadi* bed infiltration and spate irrigation inflow to the main *wadis*.

3.3.1 Current Vulnerability

Aden City is currently highly vulnerable to water scarcity issues. As a growing urban center and a regional hub of economic activity, it is plagued by water consumption far in excess of available freshwater supplies. The most vulnerable communities are middle-income and lower-income households, particularly those in coastal areas dependent on agriculture. Yemen's Poverty Reduction Strategy Paper (PRSP) addresses the linkage between poverty and the environment, yet has not incorporated the potential impacts of climate change on these vulnerable communities.

Indeed, Aden City is in the midst of a water crisis. As no perennial rivers flow through Yemen, the city relies predominantly on diminishing groundwater supplies to meet its domestic, agricultural, and industrial sector demands. The only surface water available is from *wadis* near the Gulf of Aden that originate from rainfall in the southern escarpment of the country. The city depends on four well fields to extract groundwater, and in peri-urban communities groundwater is provided by an extensive system of wells. Groundwater sources are also located in other governorates, but accessing those supplies is a potential source of acute political tension.

Despite these constraints, existing economic development plans call for agricultural sector expansion as well as the attraction of foreign investment for industrial development. Without adequate planning, such plans are likely to be highly maladaptive due to the fact that groundwater resources, already heavily exploited, are constrained by weak natural recharge rates that depend on *wadi* bed inflow. While previous studies have identified sustainable extraction rates that would prevent future deterioration of water quantity and quality, by and large, these measures have not been implemented.

The water crisis that Aden City faces results from a number of interrelated causes. Overexploitation of groundwater results in an average drop of 1m in the water table per year. This overexploitation is driven by a combination of increasing population levels, entrenched poverty levels, and low distribution efficiencies. The domestic sector consumes 60% of available water – while commercial (12.6%), industrial (2.7%), and institutional (24.1%) uses account for the remaining 40%. There is also widespread structural collapses of old water wells, active and unplanned construction of irrigation wells, and serious water pollution associated with the increased use of fertilizers and pesticides.

3.3.2 Future Vulnerability

The WEAP model for the Aden area divides the system into two major sub-basins representing the Abyan and Tuban deltaic systems upstream from the city of Aden. These sub-basins comprise the ephemeral Tuban and Bana (Abyan) *wadis* which convey flash floods during the rainy season from uplands located outside of the model boundaries. A groundwater aquifer for each of these two sub-basins was included in the model.

Water demand was simulated for three urban centers: Aden, Lahej, and Abyan, which were given annual growth rates of 3.8%, 2.6%, and 2.4%, respectively, through the period of analysis to 2026. Additional urban infrastructure incorporated in the model included a wastewater treatment plant that serves Aden and discharges effluent to the sea, and a desalination plant with a capacity of 8.4 million m^3/day, but that due to cost, does not currently supply any water to Aden. Irrigation demand for agriculture was also simulated in each of the two sub-basins and for the peri-urban area around Aden.

Results for two climate projections based on the OSU Core and UKH1 Dry climate models were incorporated in the model. The OSU Core projection predicts a 10% increase in precipitation for the area by 2050, while the UKH1 Dry data projects a 16% decrease. The OSU Core climate simulation was assumed to be the "expected" level of climate change while the UKH1 Dry simulation captures a possible "worst case" drier climate trajectory. These projections were superimposed on a reference climate sequence that was based on historical precipitation values over the period 1952 to 1980. A simplified hydrological simulator was used for the Aden model due to lack of data availability for constructing models similar to those used for Sadah and Sana'a. As such, temperature was not included as a variable in this model.

The changes in precipitation represented by the OSU Core and UKH1 Dry climate projections had relatively small impact on groundwater resources in the two sub-basins surrounding Aden. Under reference climate conditions, both aquifers are nearly fully depleted by 2025, although depletion of the Lahej aquifer is more rapid (2015 compared to 2019 for Abyan) because of a greater reliance on groundwater compared to *wadi* flow in Lahej. The UKH1 climate projection, for example, shifts the point of depletion only several months earlier in Abyan and no substantial shift is observed for Lahej.

3.3.3 Adaptation Strategies

Several adaptation strategies were developed and applied in the Basin EAP model for comparison study as briefly outlined below.

Desalinization: This strategy involves supplying Aden city with desalinated water from the Al-hiswa hydropower plant at a capacity of approximately 22,000 m^3/day.

Improved irrigation efficiency: Enhancing irrigation efficiency can be accomplished by several means: implementing drip irrigation technology; conveying irrigation water through plastic piping, and rehabilitation of traditional earth and sand irrigation channels used with spate irrigation methods to transfer surface and groundwater to fields.

Use of greywater for recharge: With this strategy, treated wastewater from the Aden wastewater treatment plant would be injected into the Lahej aquifer. This strategy would provide an effective method to store treated water before use, minimizing evaporative losses of the treated wastewater. It would also involve injecting treated wastewater from the Abyan and Lahej wastewater treatment plants (planned to go into operation in 2009) into the Abyan and Tuban aquifers.

Use of greywater for irrigation: This involves the direct use of treated wastewater from the Aden wastewater treatment plant for irrigation in the Lahej catchment area. This water would be stored in a surface container while awaiting use. It would involve the direct use of treated wastewater from the planned Abyan and Lahej treatment plants for irrigation in the Lahej and Abyan catchments.

Improved water distribution systems: Distribution system losses for the urban centers of Aden, Abyan, and Lahej would be reduced in this scenario. Initial loss rates of 34.2%, 33.1%, and 33.8% for Aden, Abyan, and Lahej, respectively are decreased by 2.5% each year in each of the city starting in 2007.

The adaptation strategies simulated aid in mitigating depletion of the two aquifers on which the Aden, Lahej, and Abyan urban area and surrounding agricultural areas are dependent. For the Abyan aquifer, use of improved irrigation technologies (here, a 25% saving from drip irrigation is represented) mitigates groundwater depletion much more so than all the other strategies, which shift the time of full depletion by only several months.

In contrast, two strategies provide similar levels of improvement to groundwater storage in the Lahej aquifer: improved irrigation technology (again, the 25% savings from drip irrigation is represented), and either re-using or recharging Aden wastewater. The improvement due to re-use or recharge of Aden wastewater is substantial compared to the Reference condition where wastewater (WW) is discharged directly to the ocean. Therefore, in the “WW Re-use” and “WW Recharge” scenarios, the treated Aden wastewater becomes an additional source of water for meeting demands – a source that is not available in the reference scenario.

Implementing all strategies in parallel benefits the Abyan aquifer more than such a plan would benefit the Lahej aquifer. For the Abyan aquifer, the cumulative impact of all strategies results in a sustainable trajectory, while for Lahej aquifer, storage continues to decline, although much less dramatically compared to the reference condition. Note that for this comparison, only one permutation of wastewater use (recharge to the aquifer) was included because the scenarios were developed with the intent of simulating either re-use or recharge, but not both occurring simultaneously. Including both permutations would erroneously double the water savings from use of wastewater.

4. Lessons Learned and Strategic Recommendations

The choice of adaptation strategy depends on the dictates of the particular case study region, including both physical and stakeholder inputs. While pilot adaptation measures were not implemented as part of the effort, considerable effort was spent on scoping out the highest priority pilot scale adaptation for each area with help from local institutions. Using an MCA analysis among local stakeholders, the highest priority initiative was identified in each area as an input to future planning efforts. The scoping effort included a sequenced plan for implementation and monitoring of the initiative as well as a cost estimate for required materials and labor. A brief summary is offered below.

Sadah Basin: Drip irrigation and building small dams were identified as the highest priority initiatives, with drip irrigation preferred from a long-term perspective, especially for drought conditions. Monitoring of the effectiveness of the initiative would be based on rapid rural appraisal techniques carried out in conjunction with local institutions and government extension offices. Even with strong local support for these initiatives, they will be insufficient to stop full depletion of the aquifer in the near future under reference scenario assumptions.

Sana’a Basin: Stakeholders identified improving indigenous methods for *wadi* flow use as the highest priority initiative. The farming communities along this *wadi* are well aware of the need to harvest *wadi* storm flows. The area is littered with small structures in varying states of disrepair designed primarily to divert spate flow onto adjacent land to replenish soil moisture and groundwater. Approximately 23 check dams would be constructed on the main watercourse of the Asser *Wadi* watershed to reduce runoff flow and to enhance groundwater recharge.
Aden City: The implementation of drip irrigation was identified as the best strategy in terms of water savings both in terms of distribution and application of water on farmlands. This strategy was preferred by stakeholders over others, but is more expensive. As the majority of farmers are poor and barely coping with existing living costs, subsidization or donor support would be needed for implementation.

The key lesson learned from the study is that Yemen will continue to suffer from a pressing water crisis in the absence of strategies to stabilize water supply and demand patterns. Of particular note is the fact that climate variability and climate change is less influential than current and predicted patterns of agricultural and household water consumption. At the present time, annual withdrawals from groundwater resources exceed renewable resources by wide and unsustainable margins, and are likely to continue into the future without a vigorous policy intervention. Indeed, the analysis in the NCAP project has revealed that a collapse of water supply systems is likely to take place towards the end of the next decade in several important aquifers suggesting that timely interventions are urgently needed. At the technological level, improved efficiencies through drip irrigation and improved water distribution systems will have demonstrable effects when combined with other supporting adaptation initiatives.

The key strategic recommendation is that the time has arrived for water crisis management planning in Yemen. The situation in the Sadah Basin illustrates the critical nature of the looming collapse of waster supply systems in all but one of the basins in the country. For these locations, as the analysis for Sadah has demonstrated, conventional approaches to adaptation will not be sufficient. As a first step, efforts need to be undertaken to systematically identify all such basins and characterize them relative to remaining exploitable water resources and business-as-usual consumption projections. Secondly, a crisis-level set of strategies should be formulated and analyzed relative to costs, benefits, and level of community hardship implied. With this information in hand, Yemen should codify such options into a robust, sustainable water development strategy, amenable to international donor support.

Annex – List of Outputs

- Yemen – Workplan
- Yemen – First progress report
- Yemen – Second progress report
- WEAP modeling applications for each case study area with developed scenarios detailing the relevant future water balance projections and possible adaptation strategies
- Synthesis report of current vulnerability, livelihood and hydrological issues in the Sadah case study area, including findings of stakeholder consultations and relevant data collected
- Synthesis report of current vulnerability, livelihood and hydrological issues in the Sana'a case study area, including findings of stakeholder consultations and relevant data collected
- Synthesis report of current vulnerability, livelihood and hydrological issues in the Aden City case study area, including findings of stakeholder consultations and relevant data collected
- Synthesis report of current vulnerability, livelihood and hydrological issues in the three case study areas, including findings of stakeholder consultations and relevant data collected
- Analysis of future vulnerability, livelihood and hydrological issues in the Sadah case study area, including findings of stakeholder consultations and relevant data collected
- Analysis of future vulnerability, livelihood and hydrological issues in the Sana'a case study area, including findings of stakeholder consultations and relevant data collected
- Analysis of future vulnerability, livelihood and hydrological issues in the Aden City case study area, including findings of stakeholder consultations and relevant data collected
- Synthesis of future vulnerability, livelihood and hydrological issues in the three case study areas, including findings of stakeholder consultations and relevant data collected
- Synthesis of stakeholder-driven MCA results, including formulation of pilot adaptation initiatives in the three case study areas