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Yemen
Assessing the Impacts of Climate Change and Variability on the Water and Agricultural Sectors and the Policy Implications

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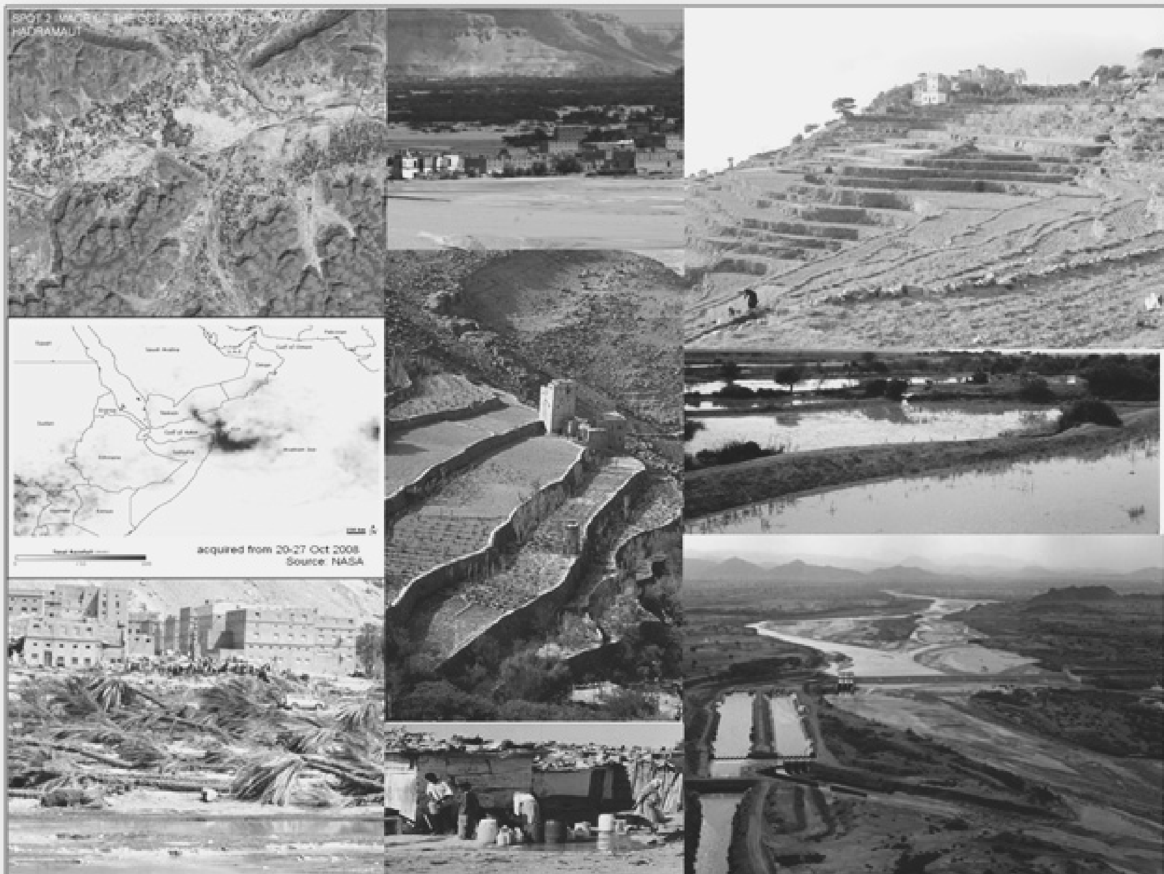
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Assessing the Impacts of Climate Change and Variability on the Water and Agriculture Sectors, and the Policy Implications

ACRONYMS

AFPPF	Agriculture and Fisheries Production and Promotion Fund
AREA	Agricultural Research and Extension Authority
BCM	Billions of cubic meters
CAMA	Civil Aviation and Meteorological Authority
CWMP	Community Water Management Project
DCG	Donor core group
EPA	Environmental Protection Agency
ET	Evapotranspiration
GCM	Global climate model
GSCP	Groundwater and Soil Conservation Project
IDA	International Development Association of the World Bank
IIP	Irrigation Improvement Project
IPCC	International Panel on Climate Change
ITCZ	Inter Tropical Convergence Zone
IWRM	Integrated water resource management
MAI	Ministry of Agriculture and Irrigation
MCM	Millions of cubic meters
MOPIC	Ministry of Planning and International Cooperation
MWE	Ministry of Water and Environment
NAPA	National Adaptation Program of Action
NWRA	National Water Resources Authority
NWSSIP	National Water Sector Strategy and Investment Program
PPCR	Pilot Program for Climate Resilience
RALP	Rainfed Agriculture and Livestock Project
SBWMP	Sana'a Basin Water Management Project
TDA	Tehama Development Authority
WSSP	Water Sector Support Program
WUA	Water user association

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Acknowledgements and Contributions

The report is the outcome of World Bank's two-part study on climate change modeling and downscaling, and climate change and variability impacts assessment in water and agriculture sectors, conducted under the auspices of the Environmental Protection Authority (EPA) under the Ministry of Water and Environment (MWE) of the Government of Yemen (GOY). The key collaborating partner institutions from the GOY also include the Ministry of Planning and International Cooperation (MOPIC), Ministry of Agriculture and Irrigation (MAI), National Water Resources Authority (NWRA), Agricultural Research and Extension Authority (AREA), Yemen Remote Sensing Center (YRSC), Tehama Development Authority (TDA), and Civil Aviation and Meteorological Authority (CAMA). The leadership, support and guidance provided by the senior government officials of these institutions have been critical for the progress of this work. In particular, the task team wishes to thank the extraordinary support and guidance provided by H.E. Abdul Rahman Al-Eryani (Minister, MWE) and the Chairman of EPA, Mr. Mahmoud Shidewa, and his team at EPA and in particular Mr. Anwar Noaman (head of the Climate Change Cell). The task team also wishes to thank teams from NWRA, MAI, YRSC AREA, MOPIC, TDA, and CAMA for their keen interest in the topic and for their support of the study by providing necessary data and guidance along the way.

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The initiative was led by Bekele Debele Negewo, with a core team comprising Christopher Ward, Naji Abu Hatem, Raffaello Cervigni, Dorte Verner, and Kanta Kumari Rigaud. This report was prepared on the basis of preparatory studies by Rob Wilby and by a team from HR Wallingford under the leadership of Steven Wade, and including Kit Nicholson, Georg Petersen, Gamal Al-Harrani and Abdulla Noaman. The report was written by Christopher Ward, Fellow of the Institute of Arab and Islamic Studies, University of Exeter, with inputs and guidance from the team.

Key Messages

- Although there is a wide divergence in projections of rainfall in Yemen, there is general agreement amongst climate change models that temperatures will steadily rise, and that there is likely to be an increase in variability and intensity of rainfall.

- Weather and water resources data in Yemen are too scant to confirm past climate and water resource trends, and modeling produces only illustrative results.

- At the extremes, a 'hot and dry' scenario would increase aridity and reduce agricultural output, and a 'warm and wet' scenario would bring benefits to agriculture. Climate variability is likely to increase and to have negative impacts on agriculture, and more intense rainfall events could increase the risk of floods.

- Yemen is suffering growing water stress. Groundwater reserves are likely to be mostly depleted in another two to three decades, irrespective of climate change, reducing agricultural output by up to 40%.

- Climate change and variability impacts on the water balance would be different for different areas. The biggest risks are further reduced water availability, particularly in lowland areas if the weather turns hotter and drier, and floods due to possible heavier rainfall.

- Farmers are likely to have to adjust to warmer temperatures and to manage risks from more unpredictable rainfall patterns and from heavier rains. Increasing temperatures could increase output if water is available.

- Climate change and variability will add to other natural resource challenges the country is already facing, to create a need for a wide range of adaptive measures. Most of these measures will be needed in any case, particularly in the context of dwindling groundwater resource.

- Yemen should invest in a 'knowledge response' to climate variability and change, particularly forecasting and early warning, together with improved data collection and sharing, and public awareness and stakeholder involvement, and should assess a range of resilience measures and technologies.

- Suggested adaptation measures include:

  (1) investment in improved <u>knowledge base</u> related to hydro-meteorological <u>data collection and analyses</u>, <u>forecasting and early warning system</u> with robust <u>dissemination strategy</u>, and development and use of <u>tools to guide decision making</u>.
  (2) investment in efficient <u>irrigation</u> system and more use of groundwater for <u>supplementary irrigation</u>—this needs to be accompanied by appropriate incentive policies for efficient water resources management and use, such as removing the incentives that encourage over-exploitation of the groundwater and replacing them with those that ensure water saving, and enforcing regulations and policies that are already in place.
  (3) strengthening the <u>traditional agricultural and water harvesting techniques.</u>
  (4) <u>adapting farming practices</u>, including changing cropping patterns, growing shorter cycle or later maturing varieties, changing the cropping calendar, etc.

(5) adoption of integrated management of the water resource at all levels, including looking at water also as an economic good.

- The suggested adaptation measures are already part of Yemen's National Water Sector Strategy and Investment Program (NWSSIP), and of the National Adaptation Program of Action (NAPA). Investment and implementation of these programs needs to be strengthened and accelerated.

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Executive Summary

PART I: CLIMATE CHANGE PROJECTIONS

1. Introduction

- Although there is a wide divergence in projections of rainfall in Yemen, there is general agreement amongst climate change models that temperatures will steadily rise, and that there is likely to be an increase in variability and intensity of rainfall.

Background on climate change and variability. The IPCC Fourth Assessment Report confirms that climate change will certainly have a significant impact on world weather patterns, and that some regions and sectors are likely to be particularly affected. The robustness of the projections decreases at smaller scales and in the outer years. Building on this assessment, the 2010 World Development Report discusses impacts on livelihoods, food and water in developing countries that are expected to be severe, particularly for the poor. For the Middle East and North Africa Region (MENA) as a whole, a warming trend is certain. Although patterns of change in precipitation under climate change are not yet clear, water is certainly the region's top vulnerability.

Yemen is largely arid, with little rainfall available for use. Although data are very sparse, the country appears to have experienced some increase in temperatures in the twentieth century. However, high variability in rainfall between years and regions of the country makes it hard to detect a past trend in precipitation. Global Climate Models (GCMs) produce a wide range of predictions for the twenty first century for the area. Yet, although there is a wide divergence in projections of the trend of average annual and seasonal rainfall, there is general agreement amongst the models that temperatures will steadily rise, and that there is likely to be an increase in variability of rainfall and in heavy precipitation events.

The particular challenges of climate change and variability for Yemen. Yemen is particularly vulnerable to climate change and variability impacts because of its water dependence and current high levels of water stress. This natural resource challenge is compounded by demographic pressure, weak governance and institutions, and by a deteriorating economic situation. The economic and social outlook is not bright, and planning and international support will certainly be needed to help Yemen to adapt to the further stresses caused by climate change and variability.

Scope of the study. In the light of these challenges, the government has developed a National Adaptation Program of Action (NAPA). In support of this, the World Bank commissioned a series of studies of climate change in two phases: the first phase projected climate change scenarios for Yemen, and phase two assessed climate change impacts on the agricultural and water sectors, and outlined possible policy and program responses.

The present study is essentially a digest of the work done to date, and is intended as a contribution to Government's process of assessing vulnerability and adaptation options by: (i) assessing possible impacts on the water balance and on agriculture and rural livelihoods; and (ii) reviewing adaptation options and the priorities for government policies, strategies and investments.

2. Study Methodology and Limitations

- Weather and water resources data in Yemen are too scant to confirm past climate and water resource trends, and modeling produces only illustrative results.

Study methodology. The study compiled projections for climate change for Yemen over the twenty first century, 'downscaled' from a range of global models and under a range of assumptions about future emissions. The projections confirmed that national and local predictability of climate is low for Yemen: temperatures will certainly rise - the median temperature projection suggests a warming of over 4 °C by 2100 – but there is little agreement on the direction or magnitude of changes in rainfall, other than to confirm the likelihood of increasing unpredictability and of concentration of rainfall in more intense events. A hydrological model was constructed to estimate actual evapotranspiration (ET), runoff and recharge and so project changes to the water balance.

In order to provide a useful picture for decision makers, in the absence of consistent climate change projections amongst various models and lack of adequate historical climate data, the study prepared three simplified climate change scenarios (see box below) to illustrate the range of possibilities up to 2080. These scenarios were then applied to produce illustrative outcomes for the water balance and for impacts on agricultural production.

Three simplified scenarios

- A "hot and dry" scenario of higher warming of 2 to 4.5 °C, with aridity dramatically increased due to the combined effects of low rainfall and high ET.
- A "mid" scenario, with considerable warming of 1.6 to 3.1 °C over the twenty first century but no significant change in rainfall.
- A "warm and wet" scenario with lower warming of 1 to 1.6 °C and an increase in rainfall.

Source: HR Wallingford

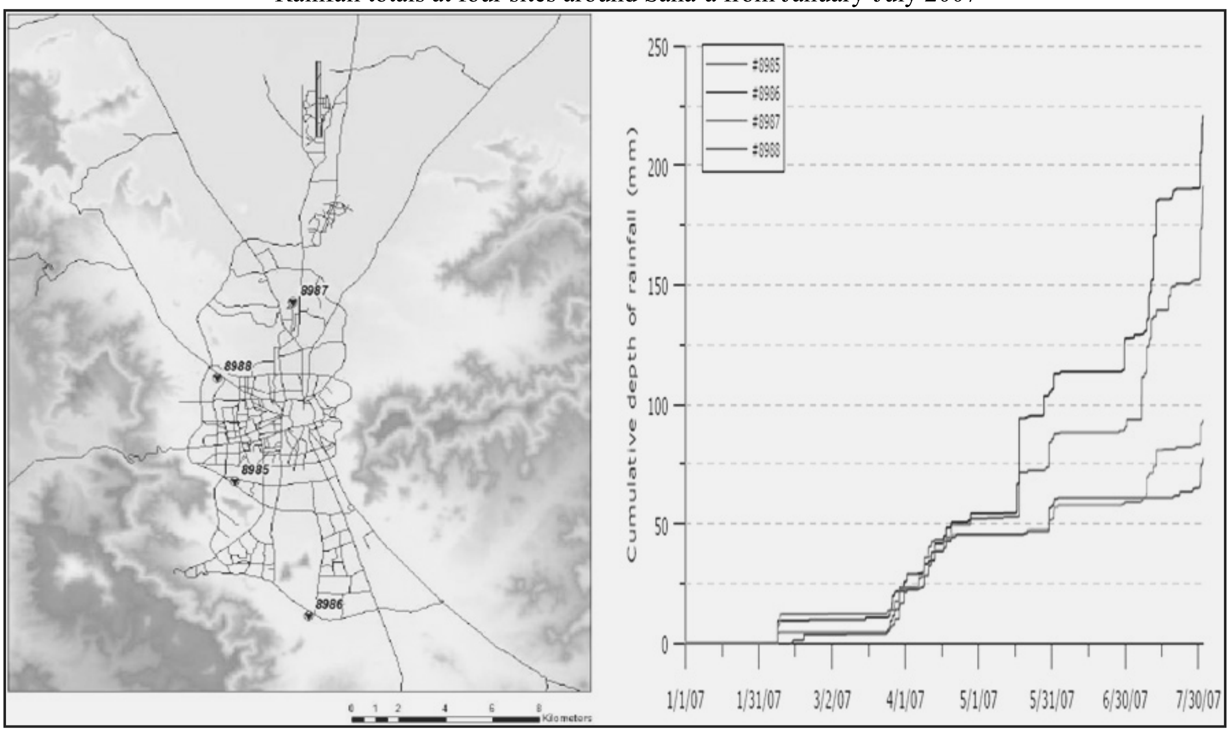
Methodological and data limitations. Modeling results have to be treated carefully, as there are limitations to the methodology and data. Where there are large variations in GCMs, 'downscaling' risks multiplying errors, especially in the context of imperfect local information. The use of simplified scenarios makes results easy to grasp, but these scenarios have significant limitations. Moreover, the statistical downscaling methodology—also adopted under this study—has its own intrinsic limitations by not adequately projecting extreme events. There are also data limitations, as climate and water resources data in Yemen are poor and erratic, and only useful to build a general picture of the resource balance. Agricultural data are also weak.

3. Climate Change and Variability in Yemen

- At the extremes, a 'hot and dry' scenario would increase aridity and reduce agricultural output, and a 'warm and wet' scenario would bring benefits to agriculture. Climate variability is likely to increase and to have negative impacts on agriculture, and more intense rainfall events could increase the risk of floods.

The distribution of climate in Yemen is extremely variable in space and time. The inter-annual, seasonal and monthly variations in climate are significant. Similarly, there is a significant variation in the distribution of rainfall among various parts of Yemen. The Figure below depicts the spatial distribution of rainfall in Sana'a City measured at four stations, showing significant differences in total rainfall over a period of observation.

Rainfall totals at four sites around Sana'a from January-July 2007

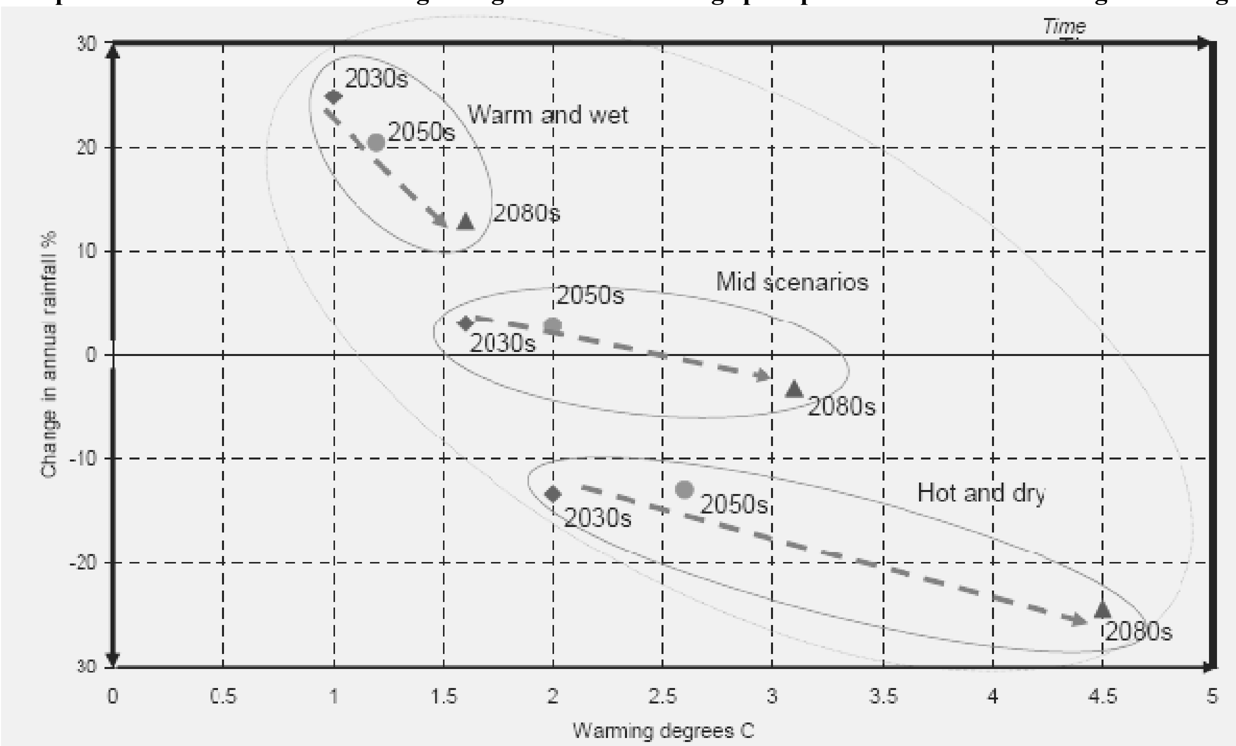


Source: Zabara et al (2007)

The results projected under the three scenarios. The three simplified scenarios were projected for the 2030s, 2050s, and 2080s. The 'mid' scenario is a robust central estimate, and the outer scenarios provide a plausible boundary of possible climate futures. The figure below maps the three scenarios over time, showing both the uncertain rhythm of the expected ultimate decline in annual rainfall (gray hatched lines), and the wide range of predictions about the intensity of the warming effect (coloured symbols). The outer grey oval indicates that there is a larger range of possible changes over the twenty first century than are captured in the three scenarios.

Broad characterization of impacts of the three scenarios. Under the 'hot and dry' scenario, agriculture would suffer from increased aridity, the 'mid' scenario would bring a warmer climate, and the increased water availability of the 'warm and wet' scenario would probably bring benefits to agriculture. Under all three scenarios there is agreement that Yemen will be getting warmer, most likely at a faster rate than the global average (by between 1°C and 4.5 °C by 2100). There is no agreement on average rainfall, but there will probably be greater variability, with an increased frequency of intense rainfall events, and therefore possibly an increased risk of floods.

Simplified climate scenarios showing changes in annual average precipitation and annual average warming



Source: HR Wallingford

4. Water and Agriculture in Yemen

- Yemen is suffering growing water stress. Groundwater reserves are likely to be mostly depleted in another two to three decades, irrespective of climate change, reducing agricultural output by up to 40%.

Water resources and uses. Yemen's water resources depend on rainfall, almost all of which is rapidly lost to evapotranspiration (ET). About 6% of rainfall runs off as surface water and flows into stream beds, often as violent spate torrents. Occasionally, very large rainfall events occur outside of normal patterns and cause destructive floods, as in Hadramout and al-Mahra in October 2008. Alluvial and rock aquifers have large reserves of groundwater, and are partly recharged annually. Agriculture is estimated to use 93% of available surface and groundwater. However, rapid increases in water abstraction and use have affected the water balance. The rate of groundwater overdraft is currently twice the recharge rate, and is increasing, bringing depletion of water reserves, inequity, and shortages, with negative socio-economic consequences. Reforms to tackle water problems have been underway for a decade but no headway has been made in reining in the rate of overdraft.

Agriculture and agricultural water. Agriculture remains the most important productive sector, and a vibrant commercial agriculture has developed in recent years. However, productivity is poor, and water shortages are emerging. As a result, rural incomes are stagnating, and poverty and inequity are on the rise. Up to now the sector and the rural economy remain surprisingly buoyant, when compared to other countries in the region. Much of this can be attributed to the mining of groundwater, and to the explosion of qat production. The exhaustion of most groundwater reserves, expected in another two to three decades, could lead to reductions in output of more than 40% by 2030, irrespective of climate change.

Towards an agricultural agenda. To further develop agriculture and agricultural water management, three linked sets of actions are indicated: (i) macroeconomic solutions to enforce relevant laws and regulations, remove incentives to water mining and inefficient water use, and introduce incentives that improve water use efficiency; (ii) technical solutions to develop and disseminate the technology needed for improving value added, particularly returns to the scarcest resource, water; and (iii) management solutions to give more responsibility and ownership for both resource management and service provision to farmers and farmer institutions, and to improve the quality and cost effectiveness of public services to agriculture.

PART II: ASSESSING THE EFFECTS OF CLIMATE CHANGE AND VARIABILITY

5. Climate Variability and Change Impacts in the Water Sector

- Climate change and variability impacts on the water balance would be different for different areas. The biggest risks are further reduced water availability, particularly in lowland areas if the weather turns hotter and drier, and floods due to possible heavier rainfall.

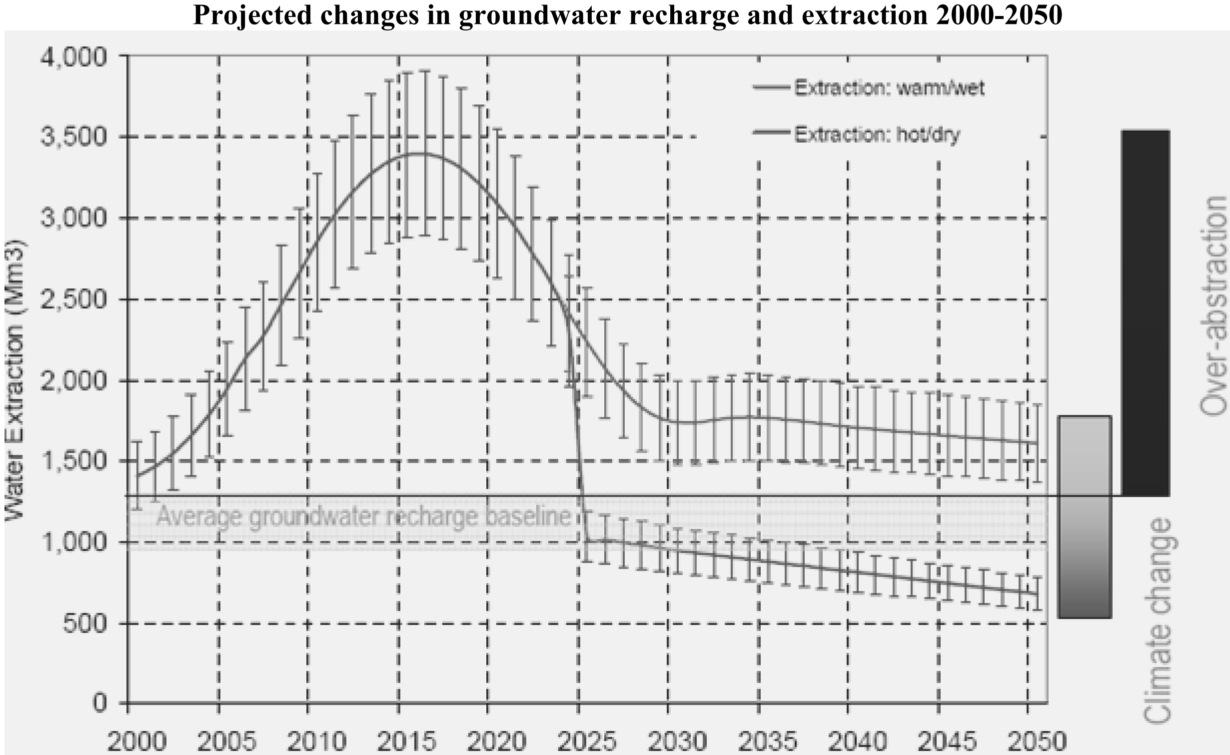
Impact on ET, runoff and recharge. The spatial and temporal variability in Yemeni climate, especially for rainfall, is significant, leading to major variations in water balance components, including on ET, runoff and recharge. For example, significant variations in rainfall distribution will lead to more droughts or more floods based on the magnitude, duration and frequency of rainfall in the area. Similarly, the increase in temperature due to climate change impacts would lead to higher ET, affecting the availability of water for other uses. Despite the limitations associated with the downscaling methodology adopted in this study, the additional impacts of climate change on climate variability have been projected to be significant, further complicating the variations in the water balance components.

Changes in ET, runoff and recharge were forecast to the 2080s under the three scenarios, but results provided no certainty about the expected direction or size of change in either runoff or recharge. The ‘mid’ scenario showed modest variations in runoff, the other scenarios showed, respectively, an improved and a deteriorating picture. A similar spread of outcomes was forecast for recharge. However, all scenarios suggest increased variability and a deteriorating trend from mid-century.

The high level of uncertainty makes planning a difficult task, and often study recommendations emerged irrespective of climate change. For example, in Wadi Surdud, measures to improve watershed management and the management of water resources were indicated, while in Wadi Hadramawt, climate variability in terms of timing, frequency and intensity of rainfall is likely to be a significant risk, and results suggested adaptation strategies will be needed to deal with increased flood risk. In both cases, the measures were recommended whether the climate changed or not.

Impact on groundwater. Modelling results predict that groundwater reserves will be exhausted in about two to three decades[1]. Thereafter, groundwater extraction would be limited to recharge levels, higher in the case of the 'warm and wet' scenario, lower in the case of the 'hot and dry' scenario (see figure below). Higher recharge under the 'warm and wet' scenario may delay exhaustion of reserves for a few years, but under all scenarios groundwater extraction will drop well below present extraction levels. Under the 'warm and wet' scenario, groundwater availability after 2025 would be about half present extraction rates, under the 'hot and dry' scenario, about one quarter.

Projected changes in groundwater recharge and extraction 2000-2050



6. *Climate Variability and Change Impacts in Agriculture*

- Farmers are likely to have to adjust to warmer temperatures and to manage risks from more unpredictable rainfall patterns and from heavier rains. Increasing temperatures could increase output if water is available.

Impacts under the three scenarios. Based on responses to water and to temperature, the marginal impact of climate change on crop production was forecast for the three scenarios (see table below). Overall, a number of key points can be drawn from the analysis:

- Agricultural production is sensitive to climate change, although the direction of change is unpredictable. Under the 'warm & wet' (optimistic) scenario, crop production could increase by

[1] According to the modeling exercise conducted under this study, different aquifers and basins respond differently, based on the natural rate of groundwater recharge and current water reserve in the aquifer.

more than 10%, whilst under the 'hot & dry' (pessimistic) scenario, production could go down by at least 10% (and even by a quarter towards the end of the century).

- There are significant differences in the response of different crops to changes in temperature and water availability, and these allow scope for farmer coping strategies.

- Some areas of Yemen are more adversely affected than others, pointing to areas of comparative advantage, and areas where adaptation measures are more likely to be needed.

- Increasing temperature could assist crop production in some areas, particularly the cooler highland areas where increased precipitation, runoff and recharge make water more available, and where the growing season may be extended.

- By contrast, where temperatures are significantly higher and precipitation significantly lower, ET would increase but runoff and recharge would reduce and the net effect of higher temperatures on production would be negative.

- Unpredictability is likely to increase, suggesting that more tactical use of dwindling groundwater for supplementary irrigation could be a useful strategy to cope with dry spells and drought.

However, the main constraint to agriculture will remain the reduction in groundwater availability caused by over-extraction.

Marginal impact of climate change scenarios on crop production

	Mid			Hot and Dry			Warm and Wet		
	2030	2050	2080	2030	2050	2080	2030	2050	2080
Temperature (°C)	+1.6	+2.0	+3.1	+2.0	+2.6	+4.5	+1.0	+1.2	+1.6
Rainfall change	+3%	+3%	-3%	-13%	-13%	-24%	25%	20%	13%
Crop Production	1.0%	1.1%	-6.3%	-10.7%	-11.2%	-27.2%	14.1%	11.7%	6.5%

PART III: ADAPTING TO CLIMATE CHANGE AND VARIABILITY

7. Adaptation to Climate Change and Variability in Yemen

- Climate change and variability will add to other natural resource challenges, to create a need for a wide range of adaptive measures. Most of these measures will be needed in any case, particularly in the context of dwindling groundwater.

Farmer responses to climate change and variability. It is certain that in the coming years, farmers will have to adapt to growing water scarcity and climate change impacts. They will seek out and adopt a range of adaptive measures, and public support and market development can help increase the range and facilitate implementation. The following are the most likely farmer responses to climate change and variability:

1. Warmer temperatures, at least in the highlands, could improve yields. Farmers may change their cropping calendar to take advantage of a longer growing season, and are likely to manage risks

from climate variability by adopting more drought tolerant varieties and (where available) supplementary irrigation.

2. Increasing unpredictability of rainfall suggests farmers may adapt by using supplementary irrigation, growing drought tolerant or shorter cycle crops, or lengthening the growing season.

3. Concentration of rain events suggests farmers would seek more surface irrigation, water harvesting and supplementary groundwater irrigation.

4. Declining groundwater availability may cause farmers to return to traditional agricultural and water harvesting techniques.

5. Changes in water availability and temperature may encourage farmers to switch to better adapted cropping patterns.

6. Declining water availability and unpredictable rainfall may sharpen the need for efficient groundwater and surface irrigation, especially supplementary irrigation.

7. The poor outlook for agricultural water, not only due to climate change, may increase the willingness of stakeholders to adopt an integrated approach to water resources management at national, basin and local levels.

Adaptation options for the agriculture and water sectors. The study grouped farmer responses in five 'adaptation options': (1) Investment in efficient irrigation systems, and use of groundwater for supplementary irrigation; (2) Investment in improved knowledge base related to climate and water resources issues; (3) strengthening traditional agricultural and water harvesting techniques; (4) adapting farming practices, including changing cropping patterns, growing shorter cycle or later maturing varieties, changing the cropping calendar etc; and (5) adoption of integrated management of the water resource at all levels. The table below summarizes the policy and program measures appropriate to each of the five adaptation options.

Adaptation options and suggested measures

Adaptation options	Suggested measures
1. Investment in efficient ***irrigation*** systems, and use of groundwater for ***supplementary irrigation***	▪ Piped conveyance and distribution ▪ Improved spate irrigation and pressurized irrigation (drip, bubbler) ▪ Improved irrigation management, including market-based approach to irrigation efficiency ▪ Drought bridging through supplementary irrigation ▪ Wastewater reuse ▪ Incorporating flood preparedness into surface irrigation management
2. Investment in improved knowledge base related to climate and water resources issues	▪ Improved network of hydro-meteorological station ▪ Improved data collection and analyses, including robust data sharing among agencies ▪ Early warning system and seasonal forecasting with long lead time, plus robust dissemination strategy ▪ Development of state-of-the-art tools in order to guide decision making
3. Strengthening traditional ***agricultural and water harvesting techniques***, and sustaining the ***livestock*** economy	▪ Promoting water harvesting, fog harvesting ▪ Terrace rehabilitation ▪ Promoting improved livestock and rangeland systems
4. Adapting farming practices: changing ***cropping patterns***, growing shorter cycle or later maturing ***varieties***, changing	▪ Varietal research (on short cycle or drought tolerant varieties, high value low water using crops etc.) ▪ Farming systems research

the ***cropping calendar*** etc	
5. Adoption of ***integrated management of the water resource*** at all levels	▪ Develop capacity for planning and regulation on a partnership basis ▪ Water resource evaluation and monitoring ▪ Incentive structure to encourage efficient and sustainable use ▪ Licensing, registration, regulation ▪ Promote basin level planning and management ▪ Support WUAs as the lowest building block of water resource management ▪ Watershed management in key catchments

8. Conclusions and Recommendations

- Yemen should invest in a 'knowledge response' to climate variability and change, particularly in forecasting and early warning, together with improved data collection and sharing, and public awareness and stakeholder involvement, and in assessing a range of resilience measures and technologies.
- The suggested adaptation measures are already part of Yemen's National Water Sector Strategy and Investment Program (NWSSIP), and of the National Adaptation Program of Action (NAPA). Investment and implementation of these programs needs to be strengthened and accelerated.

Strategic responses to climate change and variability in water and agriculture. Yemen will need to develop both a 'knowledge response' and adaptation measures to the risks and opportunities of climate change and variability in water and agriculture.

The knowledge response. Given the uncertainty over climate models, a program of forecasting and early warning, together with improved data collection and sharing, public awareness and stakeholder involvement, and the assessment of a range of resilience measures and technologies, are the key preparedness measures best adapted to Yemen's situation. This knowledge response is integral to the preparations underway for Yemen's Pilot Program for Climate Resilience (PPCR).

Accelerating key measures already programmed in water and agriculture. Climate change adaptation measures need to be mainstreamed into the broader measures already in preparation or under implementation for dealing with the challenge of adjusting to a more water scarce economy. Here Yemen has the advantage of two excellent strategic documents: the National Water Sector Strategy and Investment Program (NWSSIP), updated in 2009, and the National Adaptation Program of Action (NAPA). All of the adaptation options discussed fit within one or other of these programs, and most of them fit within both, as the table below shows. In addition, almost all the adaptation options can be implemented through existing organizations and programs. The challenge will be to accelerate financing and implementation of the most important measures.

Matching adaptation options and measures with existing national strategies and programs

Adaptation option	Suggested measures	NWSSIP Update	NAPA Project #
1. Investment in efficient ***irrigation*** systems, and use of groundwater for ***supplementary irrigation***	▪ Piped conveyance and distribution ▪ Improved spate irrigation and pressurized irrigation (drip, bubbler) ▪ Improved irrigation management, including market-based approach to irrigation efficiency ▪ Drought bridging through supplementary irrigation ▪ Wastewater reuse	2.1.1 2.1.1 3.1.2 2.1.1 -	2.1 2.1 - - 2.4

	▪ Incorporating flood preparedness into surface irrigation management		
2. Investment in improved knowledge base related to climate and water resources issues	▪ Improved network of hydro-meteorological station ▪ Improved system of data collection and analyses, including using latest technologies such as remote sensing and GIS ▪ Early warning system and seasonal forecasting with long lead time, plus robust dissemination strategy ▪ Development of state-of-the-art tools in order to guide decision making	3.1.2 - 2.1.1*	2.3 - 2.5
3. Strengthening the traditional ***agricultural and water harvesting techniques***, and sustaining the ***livestock*** economy	▪ Promoting water harvesting, fog harvesting ▪ Terrace rehabilitation ▪ Promoting improved livestock and rangeland systems	2.1.4 4.1.1 -	7.1 8.2 10.2
4. Adapting farming practices: changing ***cropping patterns***, growing shorter cycle or later maturing ***varieties***, changing the ***cropping calendar*** etc	▪ Varietal research (on short cycle or drought tolerant varieties, high value low water using crops etc.) ▪ Farming systems research	3.1.1 3.1.1	9.1 2.6, 9.2
5. Adoption of ***integrated management of the water resource*** at all levels	▪ Develop capacity for planning and regulation on a partnership basis ▪ Water resource evaluation and monitoring ▪ Incentive structure to encourage efficient and sustainable use ▪ Licensing, registration, regulation ▪ Promote basin level planning and management ▪ Support WUAs as the lowest building block of water resource management ▪ Watershed management in key catchments	1.1.1* 1.1.2*, 1.2.1* 1.2.3* 1.1.5*, 3.2.2* 1.1.7* 3.1.4 4.1	 2.2 10

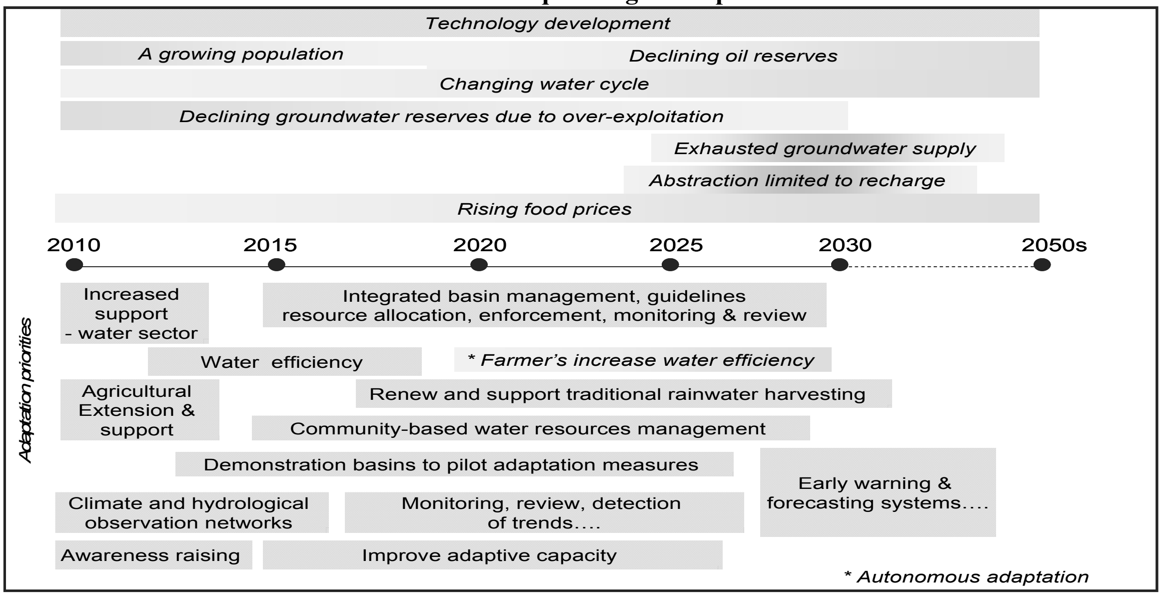
*NWSSIP references are to the Irrigation Program except items marked * which form part of the IWRM Program.*

Making it happen. The chart below illustrates a possible implementation timeline and sequencing. In order to move from analysis to action, it is recommended that government agree with civil society and international development partners to review and decide on the preparedness and adaptation options and measures discussed in the study as follows:

1. Review the case for adopting the proposed knowledge response (adaptation option 1), take a decision, seek funding and implement (lead responsibility: EPA/CAMA/NWRA)
2. Review the proposed expansion of action on *surface and groundwater* (adaptation option 2) and its fit within the ongoing GSCP/NIP, take a decision, and seek extra funding within NWSSIP/WSSP (lead responsibility: MAI/ NWRA)
3. Review the proposed expansion of action on *rainfed agriculture, water harvesting and livestock* (adaptation option 3) and its fit within the ongoing RALP, take a decision, and seek extra funding within NWSSIP/WSSP (lead responsibility: MAI)
4. Review the proposed expansion of action on *varietal and farming systems research and other relevant adaptive research* (adaptation option 4), take a decision, and seek funding, preferably within NWSSIP/WSSP (lead responsibility: AREA/MAI)
5. Review the proposed expansion of action on *integrated water resource management* (adaptation option 5), including *watershed management* and its possible fit with RALP, take a decision, and seek extra funding within NWSSIP/WSSP (lead responsibility: NWRA for national and basin levels, MAI with NWRA for local level and WUAs)

Financing from the PPCR under the Strategic Climate Fund (SCF) might be channeled to EPA (for the preparedness measures) and through WSSP and other relevant programs for the adaptation options.

An illustrative timeline and sequencing for implementation



Source: HR Wallingford

Value added from this study. This study has identified key likelihoods and risks, and proposed adaptation and preparedness responses for the consideration of decision makers. The long term horizon of the study allows policy makers to prioritize and sequence responses as part of the overall development effort for poverty reduction. The study also demonstrates how response to climate change risks can be mainstreamed into what Yemen has already initiated in terms of reform and adaptation in the water and agriculture sectors. Finally, the study sets out a series of action steps that propose a way of moving from vision to action.

Yemen: Assessing the Impact of Climate Change and Variability on the Water and Agriculture Sectors, and Policy Implications

PART I: CLIMATE CHANGE PROJECTION

Chapter 1: Introduction

- Although there is a wide divergence in projections of rainfall in Yemen, there is general agreement amongst climate change models that temperatures will steadily rise, and that there is likely to be an increase in variability and intensity of rainfall.

A. Background on Climate Change

Projected climate change globally

In 1988, in response to concerns from leading climate scientists about climate change, the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) established the Intergovernmental Panel on Climate Change (IPCC) to assess the scientific basis of risk of human-induced climate change, its potential impacts, and options for adaptation and mitigation.

The IPCC used a range of global climate models (GCMs) and scenarios for future global emissions to project possible changes to world climate over the twenty first century. Three working groups examined, respectively: (1) the physical science basis for climate change; (2) impacts, adaptation and vulnerability; and (3) mitigation options and policy implications. The results of the IPCC's work are contained in the three working group reports and the main report that together make up the IPCC Fourth Assessment Report (2007). Essentially, the Report concludes that:

- Average annual rainfall is likely to increase in some regions (mainly higher latitudes) and decrease in others (mainly in the sub-tropics)
- It is likely that there will be warmer average temperatures and more frequent hot days and nights over most land areas, which will intensify snow and permafrost melt and increase ET
- Wind patterns will continue to change, affecting storm tracks and temperature patterns in both hemispheres
- The sea level will rise, affecting industries, settlements and societies in coastal and river flood plains
- Heat waves, floods, storms, fires and droughts will become more common and more intense

Some regions and sectors are expected to be particularly affected. Although the IPCC concludes that all regions will be affected, effects are expected to be most pronounced in the Arctic, Sub-Saharan Africa, small islands and the Asian megadeltas. The most vulnerable sectors are expected to include water resources in the mid-latitudes and dry tropics, low latitude agriculture, and human health where adaptive capacity is low.

Confidence in the IPCC projections is now general, although not universal, but limitations have to be recognized. First, the IPCC is an intergovernmental body and its conclusions are thus not only a peer-reviewed appraisal of the evidence but also subject of political agreement. Second, the GCMs and emissions scenarios on which projections are based project a range of possible changes, and the projections often reflect only an average or consensus judgment on a vast range of possible outcomes. Third, all conclusions are tentative as they are based on currently available data and information. Finally, GCMs project changes in atmospheric conditions at a global scale, and the margin of error increases rapidly when these global conditions are successively 'downscaled' to the level of regions, countries, basins and local areas. The margin of error also increases rapidly into the outer years of the projections. The potential of GCMs to correctly project changes in precipitation and temperature, including annual and seasonal changes and extreme events, is thus limited, and diminishes as the scale diminishes and the projection horizon extends. Policies for adaptation and mitigation thus have to be flexible and kept under constant review.

Development impacts of global climate change

Impacts on livelihoods, food and water are expected to be severe, particularly for the poor. The 2010 World Development Report (WDR 2010) assessed implications of global climate change for development. Human impacts would include a threat to rural livelihoods and to food security, and growing water shortages: between 1 billion and 2 billion people may no longer have enough water to meet their needs. The impact is expected to be greatest on developing countries and on the poor. [WDR 5B]

Countries should act promptly to assess their vulnerability and commence adaptation and mitigation measures. WDR 2010 concluded that the window of opportunity to choose the right policies to deal with climate change whilst promoting development is closing. Adaptation and mitigation now are essential in developing countries: postponing mitigation could double mitigation costs and increase human suffering. There is a need for countries to be prepared: access to high-quality meteorological data to characterize present climate variability; credible climate change scenarios to support decision-making; technical capacity to undertake impacts assessment, options appraisal, and adaptation planning; and institutional and sectoral structures in place to deliver climate-proofed development programs and projects. [4.3B]

Climate change and variability in MENA

Although patterns of change in precipitation under climate change are not yet clear, water is certainly MENA's top vulnerability. There is now increasing confidence in projected patterns of warming and sea level rise for the MENA region, but there is less confidence in the changes in regional patterns of rainfall and the incidence of extreme rainfall events. However, it is clear that water is the major vulnerability in MENA, the world's driest region. Per capita water availability is already predicted to halve by 2050 even without the effects of climate change. The increased water scarcity will particularly threaten agriculture, which accounts for some 85% of water use. Vulnerability is compounded by heavy concentration of population and economic activity in flood prone coastal zones, and by social and political tensions that resource scarcity could heighten. [WDR: 6]

B. Climatology of Yemen

Yemen is a largely arid sub-tropical country where temperature depends primarily on elevation, and in the coastal areas, is determined by distance from the sea. Mean annual temperatures range from less than 12°C in the highlands (with occasional freezing) to 30°C in the coastal plains [4.5A, EPA, 2004:8]. Characteristically for arid areas in the sub-tropics, there is a large difference between day and night time temperatures. Box 1 describes the five eco-climatic zones.

Box 1: Yemen's five eco-climatic zones

Yemen is characterized by five major eco-climatic zones:

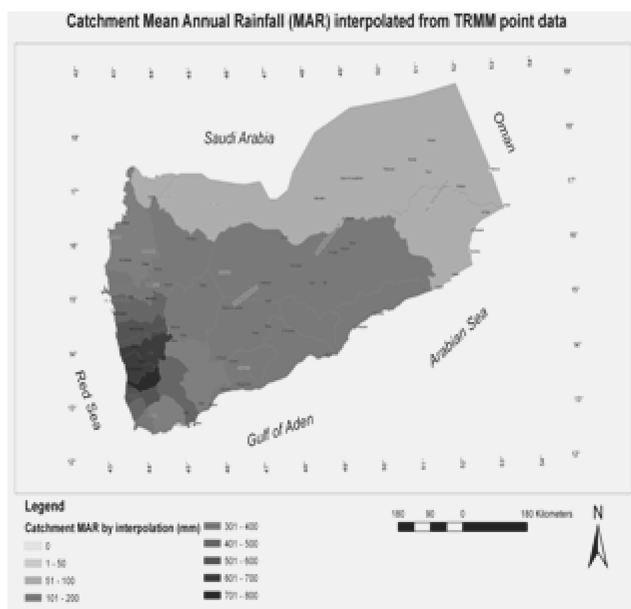
- A hot and humid coastal Tehama plain, 30-60 km wide, along the Red Sea and the Gulf of Aden
- The Yemen Highlands, a volcanic region with elevations between 1,000 and 3,600m parallel to the Red Sea coast, with temperate climate and monsoon rains
- The dissected region of the Yemen High Plateaus and the Hadramawt - Mahra Uplands, with altitudes up to 1,000 m
- The Al-Rub Al-Khali desert interior, with a hot and dry climate
- The islands, including Socotra in the Arabian Sea and more than 112 islands in the Red Sea.

Source: 4.4, EPA, 2004:7

Rainfall Variability in Yemen

Most of Yemen is very dry, but regional factors and altitude make the highlands wetter. Much of Yemen has a dry (< 600 mm annual precipitation) to very dry (<100 mm) climate. Average annual rainfall above 250 mm is only found in the south and west parts of the massif (see Figure 1), with a maximum annual rainfall near Ibb of 1,510 mm. Two factors produce considerably greater rainfall in the highlands - the trade winds that blow in moist air from the Indian Ocean, and the steep increase in elevation. Generally the annual frequency of rain days increases with elevation, and the 'mean wet days amount' (mean amount of rain each rainy day, a measure of intensity) shows a strong decline from west to east. [1.3B]

Figure 1. Estimated mean annual rainfall for 1989-1999 for major basins



Rainfall in the highlands comes in two distinct summer seasons, but on the coast rain falls mainly in winter. In the highlands, there are two distinct rainy seasons, the *saif* (April-May) and the *kharif* (July-September). The north-west trade winds blow during April and May (entering the "Red Sea Convergence Zone") and producing the *saif* rains. Later in the summer, the sun moving north warms the climate and creates a trough of low pressure – the "Inter-Tropical Convergence Zone". Warm, dry air from the north converges with very moist air being blown in from the Indian Ocean. The convergence drives up the hot moist air and cools it to produce the monsoon *kharif* rains of July to September. Rain typically falls in one rather short event, rarely longer than an hour or two. On the coast, a winter cyclonic regime driven by frontal rainfall from the north accounts for up to 80% of annual rainfall. [4.5, EPA, 2004:8]

Aridity

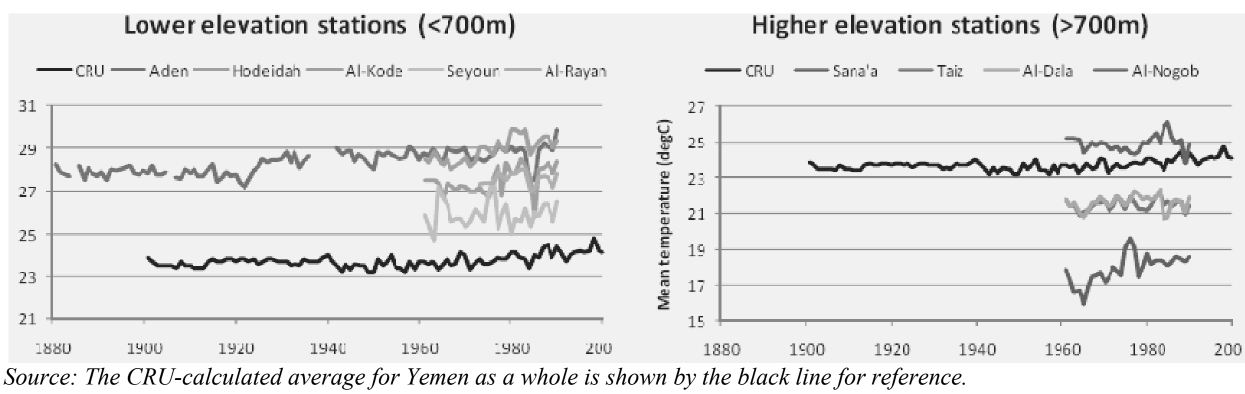
Yemen is largely arid, and little rainfall is available for use. The rates of ET are also key to determining how much rain will be available for use. In Yemen, with its low humidity and high temperatures, potential ET is very high, ranging from 1800 mm to 2500 mm. In all cases, potential evaporation is much higher than rainfall, so that rain quickly evaporates from the ground back to the atmosphere. The amount of rainfall that is retained in the soil profile for beneficial use by agriculture is no more than a small fraction of the total 37 billions of cubic meter (BCM) which falls as rainfall. Two thirds of the country is classified as hyper-arid (the deserts and parts of the coastal plain), and most of the rest is classified as arid. The highland areas around Hajjah, al Mahweet and Taiz are classed as semi-arid, and only small pockets near to Ibb are rated as sub-humid. [Source: WRAY 35: 56]

C. Historical climate trends in Yemen

Temperature

Although data for Yemen are very sparse, there appears to have been some increase in temperatures in the twentieth century. Climate indices derived for the Middle East and the Arabian Peninsula show rising mean and nocturnal temperatures since the 1950s. The only station with a long time series of data, Aden, showed a rise equivalent to about 1.4°C during the twentieth century. The University of East Angelia Climatic Research Unit (CRU)[2] calculated warming of 0.5°C throughout the entire 20th century (see Figure 2 below). There is some evidence to suggest that warming since the 1960s has been more rapid, particularly at higher elevation sites such as Sana'a. No site has shown a cooling trend since the 1960s. [4.20, 1.3A, 1.9]

Figure 2: Temperatures at selected stations in Yemen 1880-2000



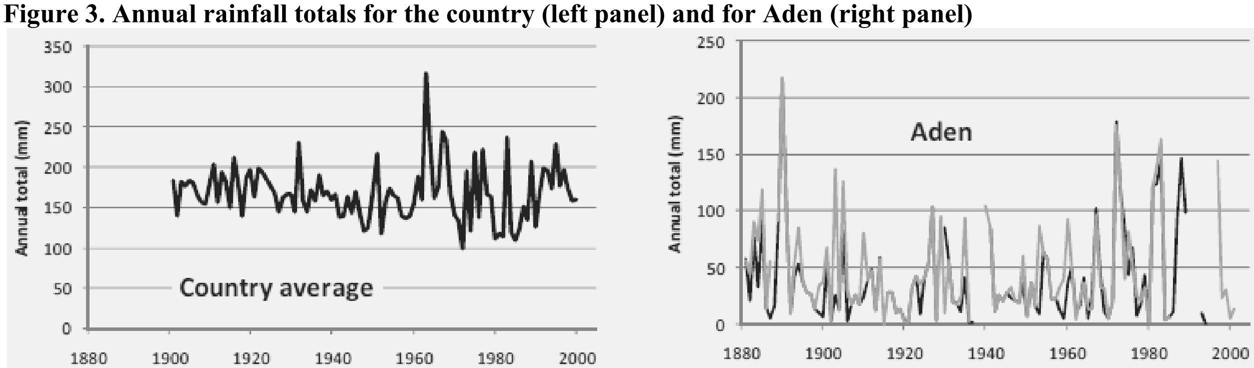
Source: The CRU-calculated average for Yemen as a whole is shown by the black line for reference.

[2] The UEA Climatic Research Unit's (CRU) 0.5° global gridded data set provides a country-average indicator of rainfall for 1901 to 2000 (http://www.cru.uea.ac.uk/~timm/cty/obs/TYN_CY_1_1.html).

Rainfall

High variability in rainfall between years makes it hard to detect a trend in precipitation. Since the 1950s, summer precipitation totals have declined across a swathe of the Sahel, extending into the Yemen highlands. However, local data for Yemen are lacking and there are differences between datasets. The CRU country summary indicates a weak drying trend of -1% per decade throughout the 20th century, consistent with the majority of sites (most notably Sana'a and Taiz).[3] [4.8B]

Figure 3. Annual rainfall totals for the country (left panel) and for Aden (right panel)



There may also have been shifts in rainfall distribution within years. Annual totals can conceal changes in seasonal distribution of rainfall. For example, a long-term decline in rainfall at Taiz largely reflects lower totals in the four months April to July, somewhat balanced by higher rainfall in outer months, with significant implications for agricultural production, especially of rainfed agriculture.

There have been periodic pronounced swings in the intensity of rainfall events. For example, exceptionally heavy rainfall in the normally low precipitation governorates of Hadramaout and al-Mahra on October 25th, 2008 claimed more than 100 lives and left more than 20,000 people without shelter.

D. What the IPCC and global climate models say about Yemen

Yemen is located in an area where Global Climate Models (GCMs) produce a wide range of results. This reflects uncertainties in both climate model structures and emissions scenarios. Based on an ensemble of 21 GCM simulations, the IPCC in its Fourth Assessment Report projects higher rates of warming over East Africa and the Arabian Peninsula than the global average[4]. It is considered 'very probable' that heat waves and heavy precipitation events will become more frequent throughout the region (IPCC, 2007) but the range of uncertainty related to future rainfall is large.

There is good agreement amongst the models on temperature rise predictions for Yemen. The IPCC report indicated higher than average rises in temperature for Yemen. More recent analyses done for the

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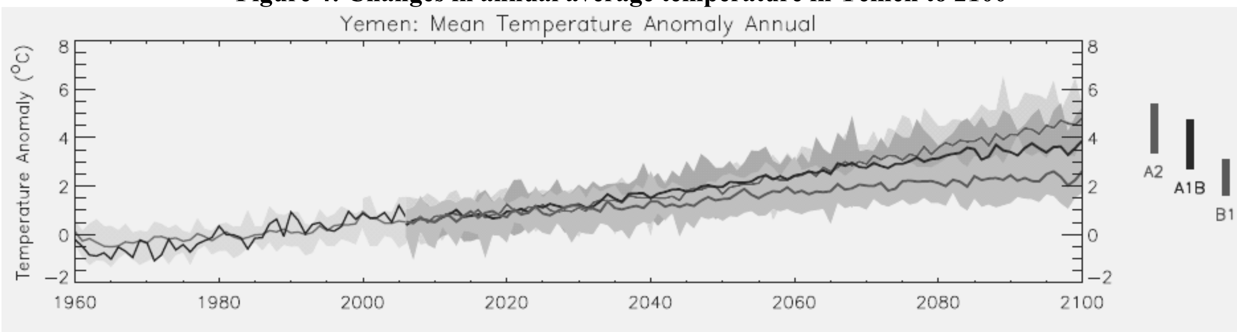
[3] According to AREA and CAMA, the estimated rainfall reductions in Sana'a since the 1960s were -9% to -43% respectively. Four stations show rainfall increases in the CAMA dataset, ranging between +3% at Aden and +27% at Al-Nogob. However, no station shows rainfall increases in both the CAMA and AREA records, underlining the sensitivity of detected trends to the influence of outliers, record start-date, length and source.

[4] The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (FAR) presented global climate scenarios with average warming in the range of 0.6°C to 4°C over the twenty first century, and rises in sea level of 0.18 to 0.59m (IPCC, 2007).

UNDP *Yemen Climate Change Country Profile*,[5] using an ensemble of 15 climate models and three emissions scenarios, confirm this prediction,. The results (Figure 4) presented rises in mean annual temperature of up to 5°C by 2100 (Source: McSweeney et al., 2008). [2.3]

Figure 4: Changes in annual average temperature in Yemen to 2100



Source: UNDP Yemen Climate Change Country Profile 2008

There is uncertainty about the trend of average annual and seasonal rainfall, but there will likely be an increase in variability and in heavy precipitation events. IPCC scenarios for rainfall are complex with only about half of the 21 Global Climate Models presenting increases in average annual rainfall for Southwest Arabia. Overall, the IPCC suggests, tentatively, a small rise in average rainfall, and an increase in variability and in heavy precipitation events. The Yemen National Adaptation Program of Action (NAPA) used further sources[6] and reports of actual trends in recent years. Two of the models quoted in the NAPA project significant increases in rainfall (of 10% and 21% in the spring months), whilst the third suggests a decrease of 13 percent. All three models suggest an increase in rainfall variability, which will effectively reduce useful average rainfall during the growing season. They also predict an increase in heavy precipitation events. This uncertainty over future rainfall patterns makes the development of scenarios for hydrology and the water sector a complex task. [2.3-4, 3.79]

E. Challenges for Yemen and the scope of this report

The particular challenges of climate change impacts for Yemen

Yemen is particularly vulnerable to climate change impacts because of its water dependence and current high levels of water stress. With per capita annual water resources of only 195 m^3, Yemen already faces extreme water scarcity[7]. Yet Yemen is a very water dependent country. The large agricultural sector uses over 90% of water, and there is strong unsatisfied demand from domestic and industrial users. The country is already vulnerable to intense storms that produce flash floods, interspersed with long dry periods and drought. Groundwater is being mined at an alarming rate—depleted at more than four times the recharge rate in some major aquifers. Possible climate change impacts, such as more violent and less predictable rainfall and a hotter and possibly drier climate would place Yemen's people and economy

[5] Interpolated, country-level summaries of seasonal rainfall totals and mean temperature have recently been prepared by the United Nations Development Programme (UNDP) for selected countries including Yemen. They are available from UNDP National Communication Support Programme (NCSP) and the UK Department for International Development (DFID) country-level climate summaries at: http://country-profiles.geog.ox.ac.uk/.

[6] Oregon State University, UK Met Office and the Max Plank Institute models

[7] According to the World Health Organization (WHO), a nation with annual per capita water resource of less than 1,000 m^3 is considered a high water scarce country.

under further stress. Assessing vulnerability to climate change and mainstreaming adaptation measures into an overall development strategy are therefore imperative.

The natural resource challenge is compounded by demographic pressure, weak governance and institutions, and a deteriorating economic situation. Since the last decades of the twentieth century, a fast rising and increasingly young population (half are under 15) has put intense pressure on resources and institutions. Although giant strides have been made since modern Yemen was born in the 1970s, governance and institutions remain frail, prey to political economy pressures and internal conflict driven by politics and tribal and sectarian stresses. Economic growth and development have been very fast in recent decades, aided by oil revenues and remittances. Now this growth path looks unsustainable, with oil revenues used for consumption, a low investment rate, and aid dependence. Groundwater mining is eating into natural capital. Poverty is on the rise, particularly in rural areas, driving accelerating rural-urban migration. The 2007 Poverty Assessment estimated about 35% of Yemenis to be below the poverty line in 2005/06, but a more recent study suggested a dramatic rise, to over 50% in some governorates.[8]

The economic and social outlook is not bright, and planning and international support are needed to help Yemen to adapt to the further stresses caused by climate change. Yemen faces decreasing financial and economic resilience as oil revenues dwindle, putting pressure on the exchange rate and on the exchequer. As water resources shrink, food imports will rise and become more costly with increasing global prices. Growing poverty, conflict and disaffection may result. Climate change will exacerbate the situation, and Yemen is ill-placed to adapt to further stresses. Far-sighted planning and international support will be essential.

Scope of the study

In the light of these challenges, Government commissioned the EPA to analyze vulnerability and to produce the adaptation program, the NAPA, which is presented in Table 1 below. In support of the NAPA, and in conjunction with EPA, the World Bank commissioned a series of studies of climate change in two phases: the first phase projected climate change scenarios for Yemen (Wilby 2008, Wilby 2009), and phase two assessed climate change impacts on the water and agricultural sectors, and outlined possible policy and program responses (HR Wallingford).

The present study is essentially a digest of the work done to date, and is intended as a contribution to Government's process of assessing vulnerability and adaptation options and to the formulation of a Strategic Program for Climate Resilience. The study addresses the following major questions:

- What changes in the Yemeni climate are expected in the light of global climate change?
- What are the possible impacts of climate change on the water balance?
- How might rainfed and irrigated agriculture be affected, and how might this affect the livelihood of farmers?
- What adaptive measures are available, and what should be the priorities for government policies, strategies and investments?

Other aspects of climate change impact are not dealt with in this study, for example: livestock and rangeland, coasts and reefs, biodiversity and species extinction, fisheries etc.

[8] Source: *Joint Task Force on Food Crisis in Yemen*

Table 1: National Adaptation Program of Action (NAPA)

Project #	Project name
1	Develop and implement integrated coastal zone management (ICZM)
2	Water conservation through reuse of treated waste and grey water
3	Awareness raising on adaptation to climate change
4	Establishment and maintenance of a climate change database
5	Planting mangroves and palms for adaptation to sea level rise
6	Programs to improve preparedness to cope with extreme weather events
7	Rainwater harvesting
8	Rehabilitation and maintenance of mountain terraces
9	Research on drought-, heat- and salinity-tolerant varieties
10	Sustainable land management to combat desertification and land degradation
11	Sustainable management of fisheries resources
12	Incorporation of climate change and adaptation into school education

Source: EPA NAPA

Chapter 2: Study Methodology and Limitations

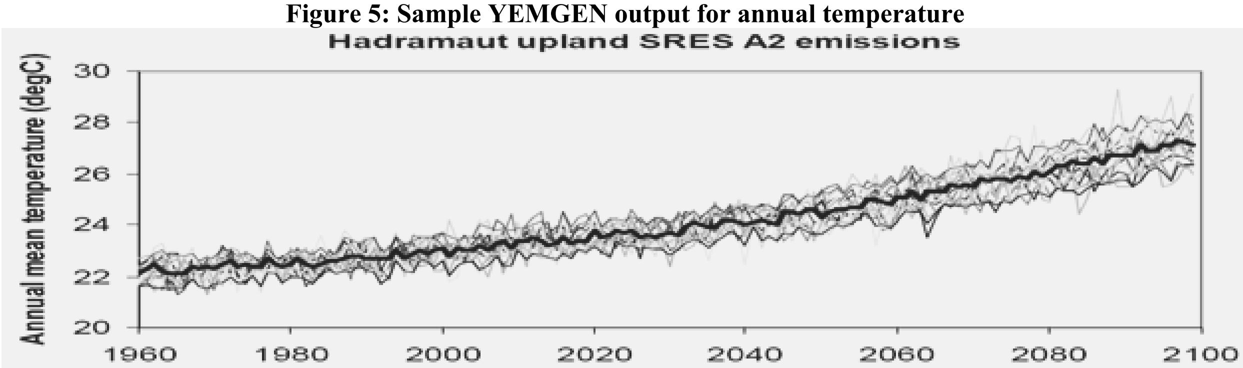
- Climate and water resources data in Yemen are too scant to confirm past climate and water resource trends, and modeling produces only illustrative results.

A. Study methodology

Downscaling

The methodology adopted for Phase 1 was to compile scenarios for Yemen over the twenty first century, 'downscaled' from an ensemble of global models and under a range of assumptions about future emissions. The spatial and temporal resolutions of most GCM outputs are too coarse for practical application. Hence there is a need to "downscale" large scale atmospheric conditions to the local scale, for example at the level of a hydrological unit such as a river basin. Phase I of this study used a statistical downscaling approach (SDSM) in order to downscale a suite of predictor variables (such as a mean sea level pressure, or atmospheric humidity) supplied by a GCM to estimate local predictands (such as daily maximum temperature and rainfall). The study used results from an ensemble of 15 GCMs[9] under three different emissions scenarios[10] [Wilby, 2009]. A weather generator—YEMGEN—was then developed in order to generate daily weather series for different areas of Yemen [1.11A, Wilby 2009] (see Annex 1). The YEMGEN tool makes use of the national rainfall and temperature observation network to generate daily time series at specific points. A sample output for annual temperature for one area "Hadramawt Upland" is shown in Figure 5 below. The example shown is based on one emissions scenario. Each of the colour lines represents one of the 15 GCMs, and the black lines represent the median, fifth and 95th percentiles of the annual values. [2.4, 2.5]

Figure 5: Sample YEMGEN output for annual temperature

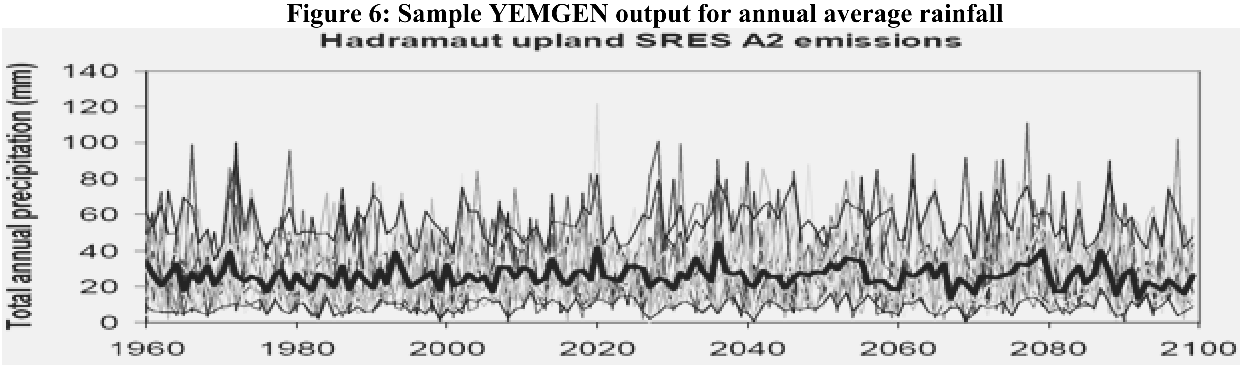


The median temperature projection suggests a warming of over 4°C by 2100. For this example, all downscaled model projections suggest a warming in annual mean temperature, but with a wide range of between +3 °C and + 6 °C 1960-2100. The median suggests a warming of over 4°C.[11]

[9] The 15 GCMs used were: BCCR, CCCMA, CNRM, CSIRO3, CSIRO35, GFDL2, GFDL21, GISS, INMCM, IPSL, MIUB, MPI, MRI, NCAR, and UKMO.
[10] 'Emissions scenarios' are standardized sets of assumptions about the rate at which emissions may change in coming years. The three scenarios employed were: A1B, A2 and B1.
[11] Note that the warming in this example is for a very arid area. Warming projections for other areas of Yemen were lower.

The median rainfall projection shows little overall change in rainfall between years. The precipitation scenarios for the same area (see Figure 6 below) show a very wide possible range amongst the 15 GCMs of both increases and decreases in annual average rainfall. However, the 'median' scenario shows very little overall change in annual precipitation.

Figure 6: Sample YEMGEN output for annual average rainfall



National and local predictability of climate is clearly low for Yemen. These two examples show how the lack of consensus in climate model projections for Yemeni climate at the level of the GCMs is replicated and intensified when GCMs are downscaled to the local level.

Three simplified scenarios and their application

For illustration, three simplified climate change scenarios were prepared. Based on the 15 climate models and three emissions scenarios, Phase II of this study developed three simplified scenarios of average annual and monthly temperature and precipitation changes for Yemen (see Box 2 below - the scenarios are presented in detail in Chapter 3 and Annex 1). These three scenarios were thought to be the best way of communicating the broad range of changes of climate expected for different time periods in the context of substantial lack of consensus between models and weak historical data availability.

Box 2: Three simplified scenarios

- A "hot and dry" scenario of higher warming of 2 to 4.5 °C, with aridity dramatically increased due to the combined effects of low rainfall and high ET.
- A "mid" scenario, with considerable warming of 1.6 to 3.1 °C over the twenty first century but no significant change in rainfall.
- A "warm and wet" scenario with lower warming of 1 to 1.6 °C and an increase in rainfall.

Source: HR Wallingford

These scenarios were applied at the national level and also applied to case studies at basin/ sub-basin levels. In addition to the valuable role of communicating a broad understanding of what Yemen can expect from climate change, the three scenarios were also used in Phase II of this study to test the sensitivity of water and agriculture sectors to climate change. The effects of climate change were assessed at the national level against the simplified scenarios, using 'downscaled' average annual and monthly temperature and precipitation changes, and case studies of particular areas were carried out using the generated daily rainfall and temperature data for that area.

Possible changes in the water balance were calculated. For the water sector, Phase II of this study used the predicted month on month changes in temperature and rainfall for the three simplified scenarios to estimate changes in the water balance (between water coming into the hydrological system as precipitation and/or irrigation, and what becomes of that precipitation such as ET, runoff to streams and rivers, or recharge to groundwater (see Box 3 below). For this exercise, Phase II first developed a national water balance model (see 'Hydrological Modelling' section below) and then used the three scenarios to estimate changes in annual runoff, ET and recharge.

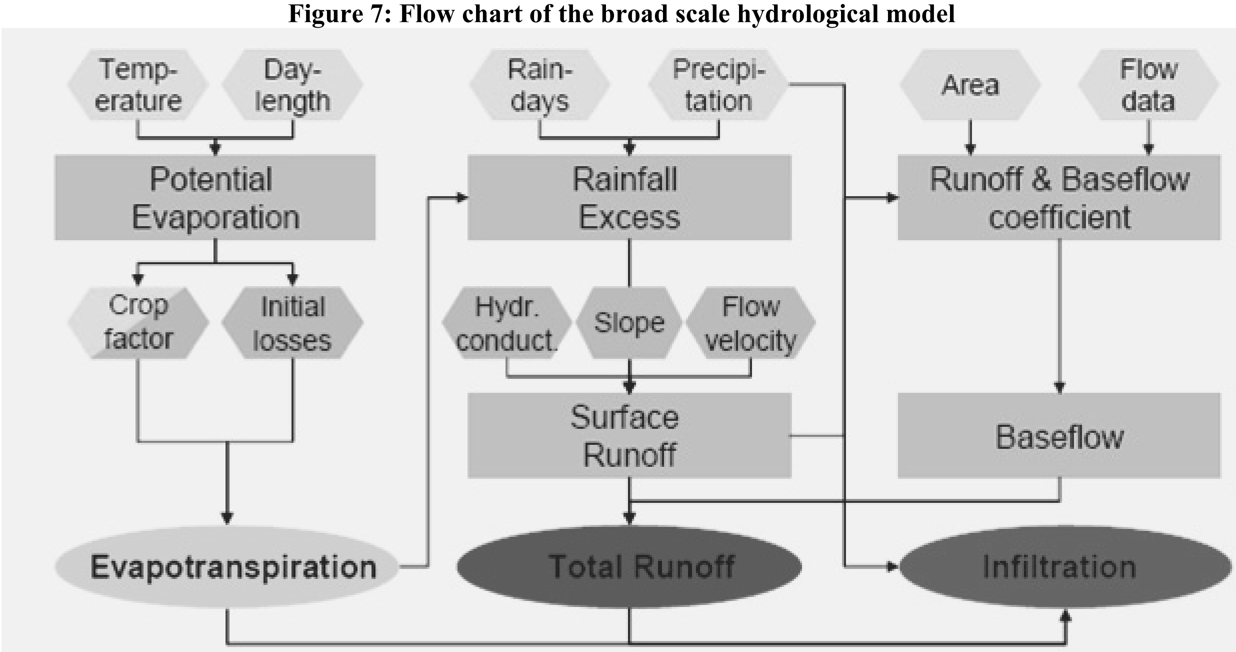
.....as well as the effect of changes in temperature and rainfall on the agriculture sector. For the agriculture sector, Phase II applied the three scenarios to the principal crops to determine how they would be affected by combined changes in temperature and precipitation (see 'Modelling Crop Responses to Climate Change' section below).

Hydrological Modeling

Phase II developed a broad-scale monthly hydrological model to estimate actual ET, runoff and groundwater recharge for the whole of Yemen. Figure 7 below provides an overview of the model, showing its key input variables (green), parameters (blue) and calculation modules (dark grey). The model is described more fully in Appendix 2 to the *Climate Change Impact Assessment* report.

For more detailed analysis in case study areas, a daily hydrological model was set up. This was to explore the potential impacts of climate change on the soil moisture balance and frequency of higher flows. These conceptual models were required to link changes in climate to various components of the water balance.

Figure 7: Flow chart of the broad scale hydrological model



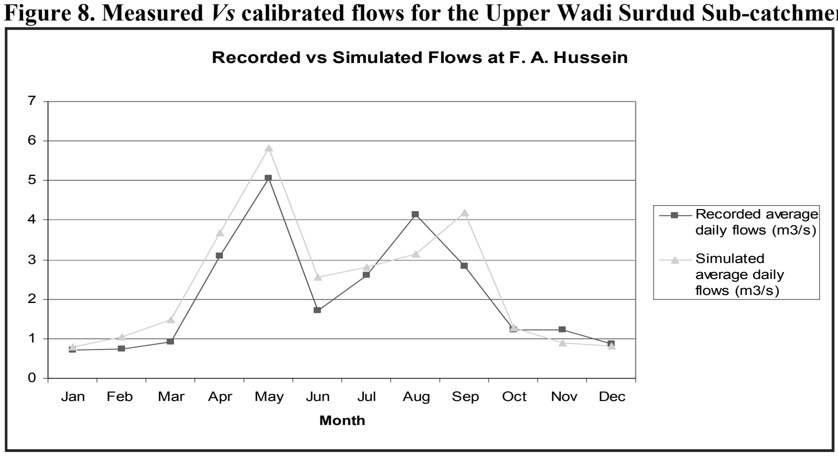
Both monthly and daily models broadly fit the observed hydrological characteristics. The broad-scale monthly model was tested against observed monthly runoff from selected basins. The model produced a satisfactory fit for estimating the annual water balance for different basins (see, for example, Table 2, Calibration results for Upper Surdud Sub-catchment). However, it was poor at reproducing the exact seasonal flow pattern within the year. Complete flow records were not available, and with such high natural variability in rainfall and annual runoff, precise calibration was not possible. Therefore model parameters were varied within sensible ranges to achieve a plausible water balance.

Table 2: Calibration results for the upper Surdud (highlands) sub-catchment

	Calibrated Model	**Measured Data**
Surface Runoff (mm/yr)	10.88	11.54
Baseflow Runoff (mm/yr)	17.75	18.82
Total Runoff (mm/yr)	28.64	30.37
Recharge (mm/yr)	42.95	no data

The more detailed catchment modelling using daily data provided a good fit to the observed data and provided more insight into potential changes in key hydrological indicators, such as spate flow frequency – see, for example, Figure 8 opposite showing recorded flows compared with simulated flows for the Upper Wadi Surdud Sub-catchment.

Figure 8. Measured *Vs* calibrated flows for the Upper Wadi Surdud Sub-catchment



Box 3: Hydrological modelling and the water balance

A hydrological model uses data on rainfall, temperature, land use/ land cover and soils to estimate how much of the precipitation will be lost through ET, how much will runoff into streams, and how much will percolate below the soil profile into groundwater. The significance of these components of the water balance is as follows:

Evaporation and transpiration: water that evaporates is lost without benefit, and it is a goal of water management to reduce the portion of the water balance lost to evaporation. In Yemen's hot climate, evaporation rates are very high: it is estimated that more than 90% of the rain that falls on the country evaporates within a few days of falling. Water that transpires through vegetation may be 'beneficial' i.e. it may be part of the growing cycle of useful crops, trees or pasture, or it may be non-beneficial transpiration through weeds or unproductive scrub.

Runoff: rainfall that runs off into streams and watercourses may be beneficial if it can be withdrawn for direct human use or for irrigation, or if it maintains the ecology of the basin. It is non-beneficial where flows are not harnessed and damaging floods occur, or when it causes erosion in the catchment or the stream bed. Water that runs off into 'sinks' or to the sea may not be beneficial unless it helps to preserve the environment in so doing. In Yemen, run-off is increased by the violent rainfall events, the sparse vegetation, and the limited permeability of most soils. Nonetheless only 5-10% of Yemen's rainfall ends up as run-off. Because of the violence and infrequency of the storm events, wadis are often dry for months and then carry huge spate flows for a few sporadic days a year.

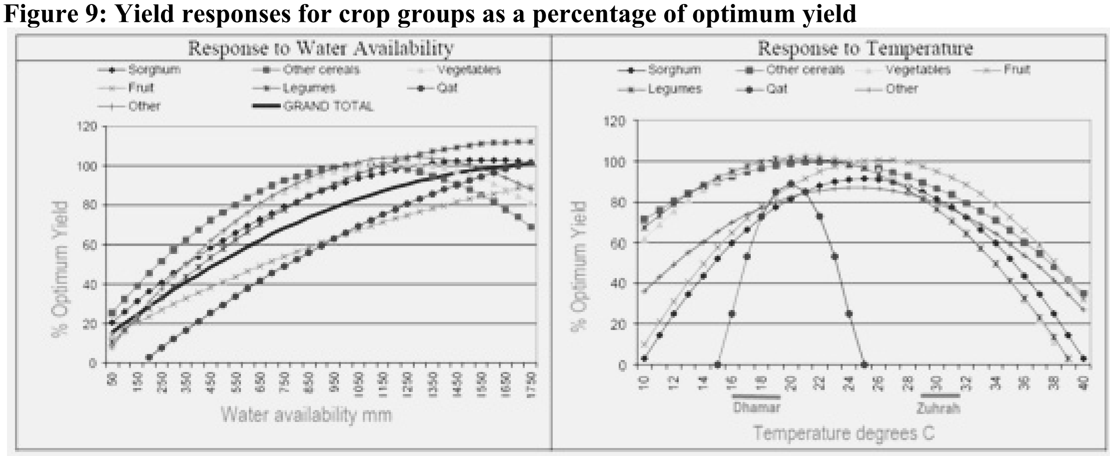
Recharge: rainfall that infiltrates below the soil horizon joins an aquifer, either local alluvial aquifers, or solid rock aquifers which tend to be deeper and more extensive. These deeper aquifers can hold huge reserves of water, sometimes for thousands of years. Aquifer water is beneficial if it emerges in springs that can be diverted or if it can be extracted through wells and put to use.

Source: Authors, WRAY 35

Modelling Crop Responses to Climate Change

Based on a national aggregate evaluation of crop yield response to water availability and to temperature, crop responses to climate change were modelled, using average crop response curves. The crop response curves employed were based on the crop water and temperature requirements tables for Yemen prepared by AREA in 1998, with assistance from FAO. The tables are based largely on international data, following standard Penman-Monteith techniques. However, they have been adjusted to take account of Yemeni conditions. The tables provide information for the effect of rainfall and temperature on yields. The analysis converted the crop requirement tables into best fit exponential curves which are used to estimate the yields and production for seven major crop groups. Using the curves to predict yield based on average water and temperature conditions in Yemen resulted in estimates of total crop production that were within 20 percent of actual production levels, except for sorghum which is 30 percent too high. The modeled crop production applies an adjustment factor to each crop group, to calibrate it to actual crop production. Figure 9 presents the crop response curves for water and temperature.

Figure 9: Yield responses for crop groups as a percentage of optimum yield



Source: HR Wallingford, based on data from AREA

The elasticity of yield response to water and temperature change was calculated as a quick reference to likely sensitivity to climate change. The response of crops to water and temperature can be measured by the water (WEY) and temperature (TEY) elasticity of crop yield, defined as the ratio of the change of yield to the change of water or temperature. These elasticities provide a valuable quick reference indicator of climate change impact. Most crop response curves show a pattern of diminishing returns to water and temperature up to an optimum and the elasticities thus decline to zero as water and temperature increase to the optimum. Table 3 shows the WEY and TEY for the main crops in Yemen. The first five columns present the data on AREA, production and yields from the Agricultural Statistics Yearbook 2007. The average temperature for each crop is calculated as the average temperature of governorates, weighted by the area of crop grown in the governorate. The implied water application is calculated from the crop response curves for each crop, as the amount of water that would need to be applied to produce the observed yields, given the average temperature.

Table 3: Responsiveness of crops to water and temperature (ratio of the change in yield to the change in water or temperature)

	Area	Prod		Yield		Average Temp	Implied water	WEY	TEY
	'000ha	'000t	%	t/ha	% Opt	C	mm		
Sorghum	519	500	9.9%	0.96	28%	23.7	141	0.47	0.28
Millet	133	99	1.9%	0.74	25%	26.2	127	0.68	-0.90
Maize	52	87	1.7%	1.67	33%	20.3	267	0.87	0.85
Wheat	141	218	4.3%	1.55	44%	18.7	287	0.35	-0.27
Potatoes	19	247	4.9%	12.88	64%	17.8	711	0.69	0.03
Tomato	17	230	4.5%	13.85	46%	21.4	388	0.81	0.13
Onion	13	191	3.8%	14.27	71%	23.3	855	0.82	-1.09
Watermelon	13	162	3.2%	12.85	43%	24.0	346	0.83	0.72
Bananas	10	120	2.4%	12.63	32%	26.5	1,008	2.31	-0.73
Mango	24	369	7.3%	15.31	51%	27.6	1,433	0.60	-0.67
Orange	8	108	2.1%	13.81	46%	22.1	1,617	0.53	0.53
Dates	14	54	1.1%	3.78	84%	26.4	1,729	0.68	0.26
Grapes	13	126	2.5%	9.74	39%	16.5	1,406	0.00	10.09
Kidney beans	24	63	1.2%	2.64	44%	26.5	526	0.61	-0.21
Lentils	12	9	0.2%	0.79	66%	16.9	981	0.86	0.27
Qat	141	156	3.1%	1.11	32%	19.4	275	0.70	0.30
Sorghum Feed	116	1522	30.0%	13.08	44%	25.7	671	0.93	-0.24
Alfalfa	25	284	5.6%	11.25	20%	21.6	166	0.56	0.15
Sesame	22	23	0.5%	1.07	71%	25.9	676	0.79	-0.13
Other	168	500	9.9%	2.97					
Total/average	1484	5070	100.0%	3.42	38%	21.3	576	0.68	0.14

Source: HR Wallingford, based on data from AREA and Agricultural Statistics Yearbook 2007

The analysis also modeled the impact on yields at the governorate level. The hydrology analysis provided key climate and water data for 31 main catchments, but agricultural data are available only by governorate. The analysis therefore converted the catchment climate and hydrology data to governorates and then calculates modeled crop production based on the average conditions for the governorates.

B. Methodological and data limitations

Methodological limitations

The large variations in GCMs mean that modeling results have to be treated with caution. GCMs produce a wide range of results – all present a warming trend for Yemen but disagree widely on precipitation (both in direction and magnitude of change). Therefore, care needs to be taken in how modelling results are interpreted and applied for adaptation assessments.

'Downscaling' from inconclusive GCMs in the context of imperfect local information risks multiplying errors. There is an augmented risk of error when a range of models, themselves uncertain, are 'downscaled' at the local level, especially in the context of highly imperfect local weather data and models. The three scenarios made use of a statistical downscaling technique providing daily time series but the wide range of possible precipitation changes remains a key feature – for example, for 2030-2039, the scenarios indicated a range of average changes in runoff of between -55% and +147%. Great care must be taken when interpreting the conclusions of all projections and assessments based on such

uncertainty, and a robust approach to decision taking is needed, with a broad tolerance and flexibility for change.

Other models might tell a different story, now or in the future. The methodology adopted in Phase II of this study considers 15 existing GCMs and three emissions scenarios. There are already other climate models, which if considered, might affect the results, and models are being developed or updated all the time. Clearly, downscaling and the development of scenarios might have to be revised and updated if and when significant new data or improved climate change models or regional downscaling techniques develop.[12]

Simplified scenarios are easy to grasp, but they have significant limitations. Simplified scenarios provide a robust central estimate of average annual changes but they have significant limitations. They provide changes for annual variables averaged over long time periods (30 years). They do not capture potential changes in rainfall intensity and seasonal shifts in climate within years, which are very important when one deals with, for example agriculture, especially rainfed agriculture, and flood related issues. Finally, the scenarios are driven by assumptions about how temperature and rainfall move together: 'warm and wet' or 'hot and dry', yet there is no empirical evidence that these two variables move in tandem. It is equally likely that lower rates of warming may be accompanied by reductions in rainfall ('warm and dry') or that an increase in temperature may be accompanied by higher rainfall ('hot and wet').

Scientific challenges of arid land hydrology—Yemen, especially the southern and western parts of the country, is characterized by rugged and mountainous topography that significantly dictates the distribution of rainfall and use of water. See also the digital terrain map on the next page.

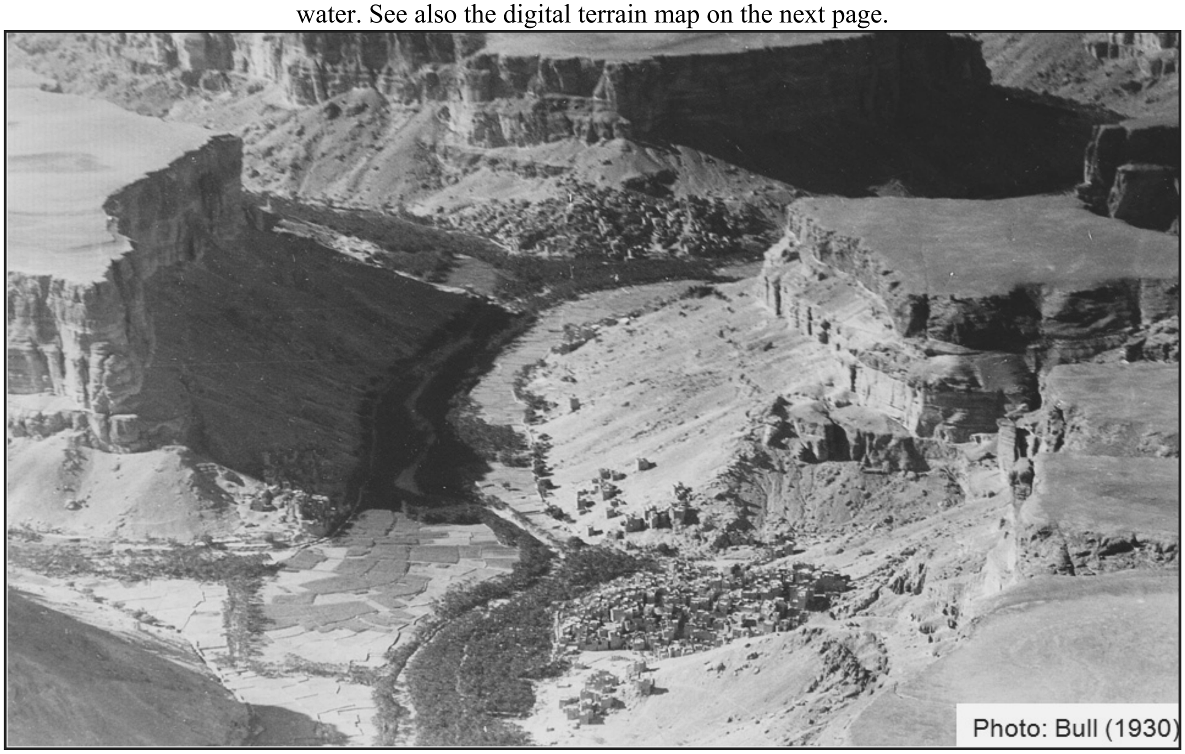
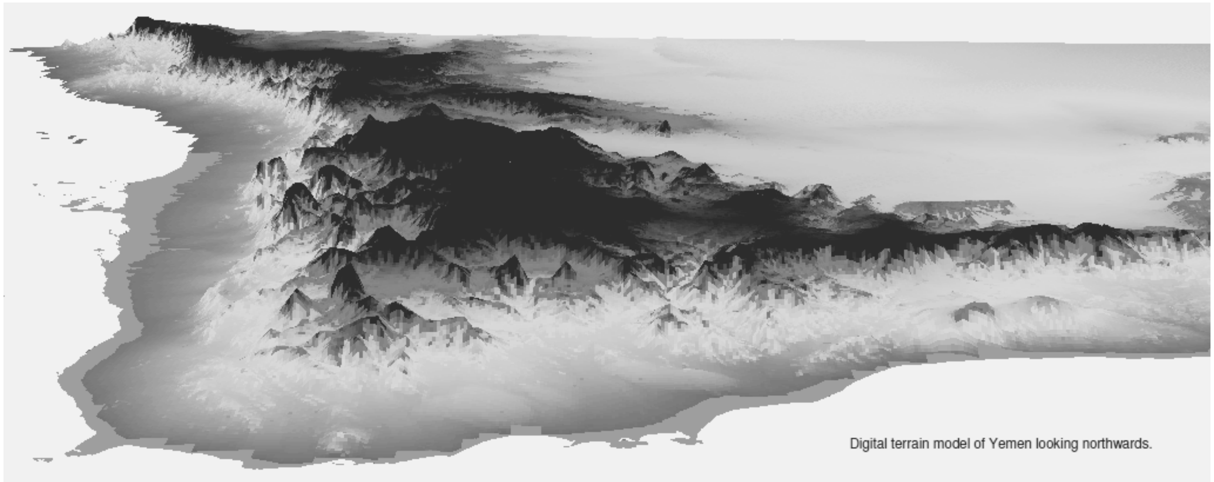


Photo: Bull (1930)

A pragmatic and empirical approach to water balance modeling is required. Not only is the data poor, but macro-water balance models are known to poorly represent semi-arid and arid-zone hydrology, in

[12] However, as will be discussed in Chapter 8 below, conducting additional climate modelling and downscaling is not recommended at present due to large uncertainties associated with GCM projections for the region and the poor availability of historical climate data.

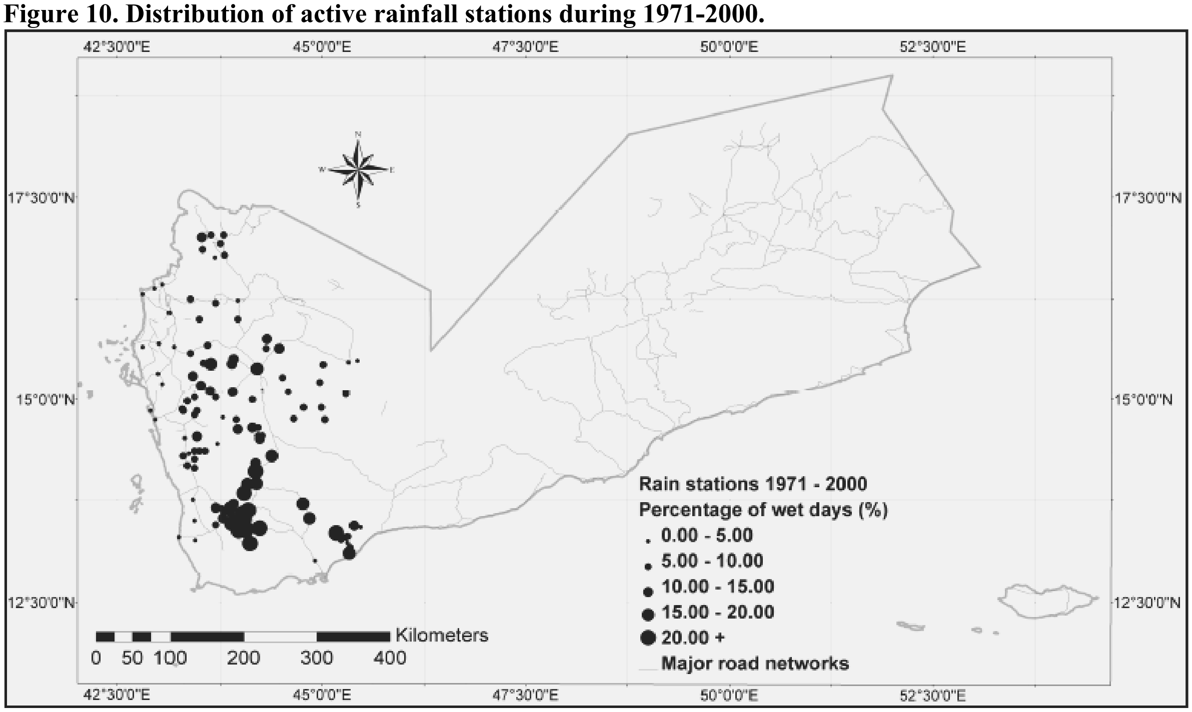
particular, groundwater recharge and episodic wadi flow such as spate. Climate change assessment in Yemen has therefore to take into account the large uncertainties introduced by groundwater recharge and surface water resource models.



Data limitations

Records of climate data in Yemen are largely short term, lack adequate spatial coverage and there are significant quality concerns. Long-term, systematic records of rainfall and temperature are very scarce in Yemen. Only seven stations have more than 20 years of data. Similarly, distribution of weather monitoring stations is sparse and concentrated in the western highlands of the country (see Figure 10 below). This lack of data severely hampers efforts to quantify long-term changes in climate and to assess renewable natural resources such as water. Without homogeneous rainfall and temperature records, it is hard to benchmark future climate variability and change, or the associated impacts.

Figure 10. Distribution of active rainfall stations during 1971-2000.



Symbol sizes are proportional to the percentage of days that are wet at each site.

There is also fragmentation of institutional responsibility for weather data, and little cooperation between agencies. A number of different agencies deal with the collection and interpretation of weather data: MAI, NWRA and CAMA. There is fragmented responsibility, and the various agencies do not cooperate well together.

Some useful weather data do exist, however, and performance is now improving, with a growing network. Useful data exist, largely for the western part of the country (see Figure 9), and the study was able to interpolate rainfall and temperature indices at sites without records. The data collection situation is now improving, with NWRA, MAI and CAMA expanding their monitoring systems, including in the east.

Water resources data in Yemen are also quite poor and erratic, and only useful to build a general picture of the resource balance although the situation is now improving. There is a critical shortage of systematic and long-term hydrological data collection in the country, including in very useful basins such as the Sana'a basin. Most of the data collection in Yemen—which is also true for most hydro-meteorological data—follows a campaign style/ project related data collection approach by study groups or donors interested in monitoring and evaluating the performance of the projects that they support. In addition to lack of data, lack of data analysis and its use for decision making is poor. Although very slowly and in uncoordinated way, NWRA is building a National Water Resources Information System (NWRIS), and some building blocks already exist. A well inventory has been conducted nationwide (60,200 wells have been inventoried), 326 automatic groundwater monitoring stations had been set up, and static groundwater levels and stream flows are being monitored in the most critical basins.

Agricultural data are also quite weak. The crop water and temperature requirements tables date from 1998, but they are based on older field work, and it is likely that there is a margin of error. Agricultural production, area and yield statistics are collected through a system that at its inception thirty years ago was reliable and well performing, but in recent years the quality and quantity of data from the field has declined, and agricultural statistics are widely seen as guesswork and extrapolation rather than reliable data based on statistically valid actual field measurements. As a result, modeling results can only be viewed as very general orders of magnitude.

Chapter 3: Climate Change and Variability in Yemen

- At the extremes, a 'hot and dry' scenario would increase aridity and reduce agricultural output, and a 'warm and wet' scenario could bring benefits to agriculture. Climate variability is likely to increase with likely negative impacts on agriculture, and more intense rainfall events could increase the risk of floods.

Climate change and climate variability

In this chapter, and throughout the report, the analysis and discussion distinguish between climate change and climate variability. Climate change is the emergence of measurable long term trends in temperature (warming and cooling), and in precipitation (total rainfall, and its timing, frequency and intensity). Climate variability is the possibility that temperature and rainfall will vary within and between years in an unpredictable way and that no pattern of change will emerge. Climate variability may occur independently of any discernible pattern of climate change. The intensity of rainfall events may vary wildly, leading to floods of unpredictable frequency and intensity. Or the spacing between rainfall events may vary in length, leading to protracted dry periods or over-saturation and increased flood risk. Or unpredicted heat waves or cold snaps may provoke unanticipated drought or crop damage. Variability is already a feature of Yemen's rainfall, including variability within and between years, and occasional wild swings in the intensity of rainfall events of the type that produced the disastrous flooding in Hadramawt and al-Mahra in October 2008 (see Chapter 1 above). Similarly, the variability of climate in space in Yemen is pronounced given its rugged terrain in the southern and western parts of the country (large elevation differences over short distances) and influence on the climate by the country's proximity to the sea on the west and south, and desert on the north and east.

The three scenarios

Three scenarios have been used, projected for the 2030s, 2050s, and 2080s. As mentioned in Chapter 2 above, three simplified scenarios of average annual temperature and precipitation changes were developed (see Table 4 below), based on the 15 GCMs and three emissions scenarios. The 'hot and dry' scenario took the worst combined changes in temperature and precipitation predicted by the models; the 'warm and wet' scenario took the best combined changes; and the 'mid' scenario lies between the two extremes. The three scenarios were projected for the 2030s, 2050s and 2080s periods.

The 'mid' scenario is a robust central estimate, and the outer scenarios provide a plausible boundary of possible climate futures. It is not possible to assign quantitative probabilities to these individual scenarios. However, the 'mid scenario provides a robust central estimate and the two outer scenarios provide a plausible range of possible climate futures. In qualitative terms, the likelihood of the mid scenario is "high", the outer scenarios are "medium" and outcomes outside of this range are of "low" likelihood.

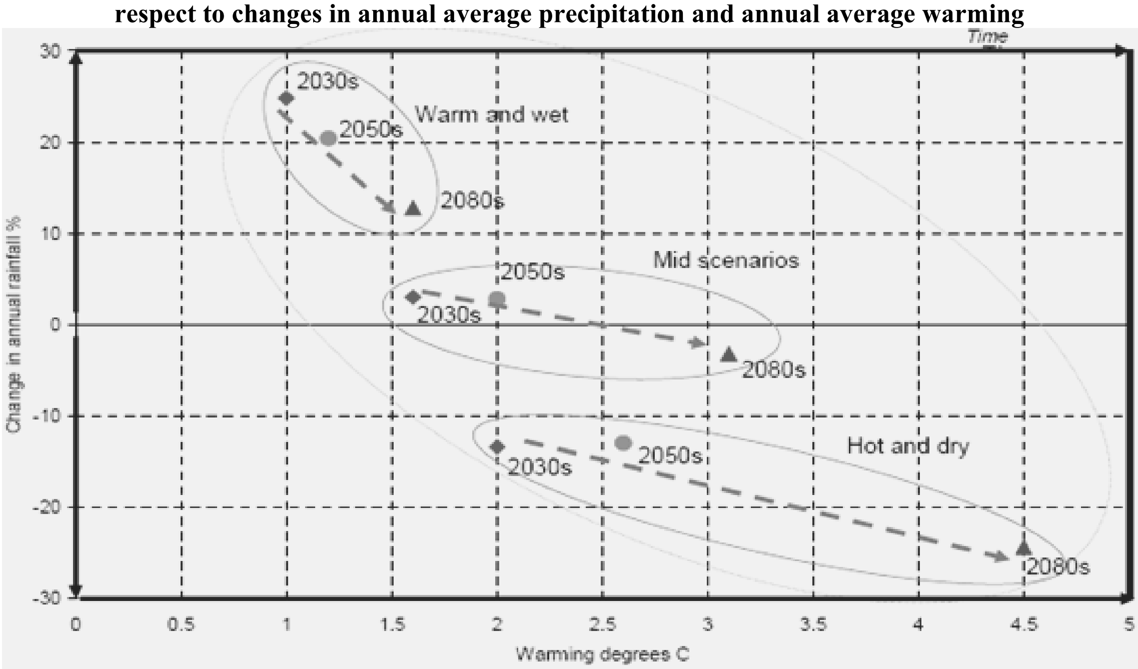
Table 4: Simplified climate scenarios summarising changes in average annual temperature and average annual rainfall (compared to the 1961-2000 baseline period)

			Tihama rainfall		Dhamar rainfall	Hadramaut rainfall	
Scenario	Yemen T increase °C	Yemen P changes %	Coastal plain Addahi-A	Highlands Al Haima	Dhamar Masna'ah	Valley Shibam	Upland
			2030s (2011 to 2040)				
Mid	1.6	3	6	1	2	2	4
Hot and dry	2	-13	-12	-9	-10	-16	-20
Warm and wet	1	25	25	15	14	25	45
			2050s (2041 to 2070)				
Mid	2	3	6	0	2	2	4
Hot and dry	2.6	-13	-3	-11	-8	-20	-23
Warm and wet	1.2	20	17	13	8	25	39
			2080s (2071 to 2100)				
Mid	3.1	-3	-3	-1	-3	-4	-5
Hot and dry	4.5	-24	-18	-15	-13	-30	-46
Warm and wet	1.6	13	13	6	7	13	25

Note: Based on YEMGEM output (Wilby, 2009). The data were interpolated for the 2030s and Yemen average change in precipitation added, although site specific data should be used where possible.

Figure 11 maps the three scenarios over time, showing both the uncertain rhythm of the expected ultimate decline in annual rainfall (gray hatched lines), and the wide range of predictions about the intensity of the warming effect (coloured symbols). The outer grey oval indicates that there is a larger range of possible changes over the twenty first century than are captured in the three scenarios.

Figure 11: Simplified climate scenarios for sensitivity analysis showing the location of each scenario with respect to changes in annual average precipitation and annual average warming



Source: HR Wallingford

Broad characterization of impacts of the three scenarios

Under the 'hot and dry' scenario, agriculture would suffer from increased aridity, the 'mid' scenario would bring a warmer climate, and the increased water availability of the 'warm and wet' scenario would probably bring benefits to agriculture. Possible impacts on water and agriculture are discussed below (Chapters 5 and 6). Broadly speaking, the impact of the three scenarios could be as follows:

In the *"hot and dry" scenario*, rainfall would decrease, and runoff and recharge would also decline. Temperatures may become too high for many existing crops (warming of 2 to 4.5 °C over the twenty first century), and aridity would increase dramatically due to the combined effects of low rainfall and high ET.

For the *"mid" scenario*, there is considerable warming of 1.6 to 3.1 °C over the twenty first century but no significant change in rainfall. These changes would have some effects on crop suitability and a small effect on the overall water balance through increases in ET.

For the *"warm and wet"* scenario, there is warming of 1 to 1.6 °C and an increase in rainfall. Runoff and recharge would increase. Agriculture would benefit in many areas from increased rainfall, surface water flows and groundwater availability.

Common factors in the predictions

There is agreement on the likelihood of warming, of an increase in variability of rainfall patterns within years, and of more frequent and intense rainfall - but not on changes in seasonal or annual rainfall totals. Although there is a wide range of possibilities shown by the GCMs and reflected in the downscaling and in the simplified scenarios, three common themes emerge that seem more than likely to come about:

- Yemen will be getting warmer, most likely at a faster rate than the global average (by between 1 degree and 4.5 °C by 2100.
- It is likely that there will be more variability of rainfall patterns within years. [2.vii]
- There will probably be an increased frequency of intense rainfall events, and therefore possibly an increased risk of floods.

By contrast, there is a wide range of predictions about winter, summer and total precipitation. This is largely due to differences amongst models on the future behavior of the ITCZ. The downscaled climate scenarios used for the study provide no evidence of significant inter-annual variation in rainfall. The range of doubt may narrow as empirical data accumulate.

Chapter 4: Water and Agriculture in Yemen

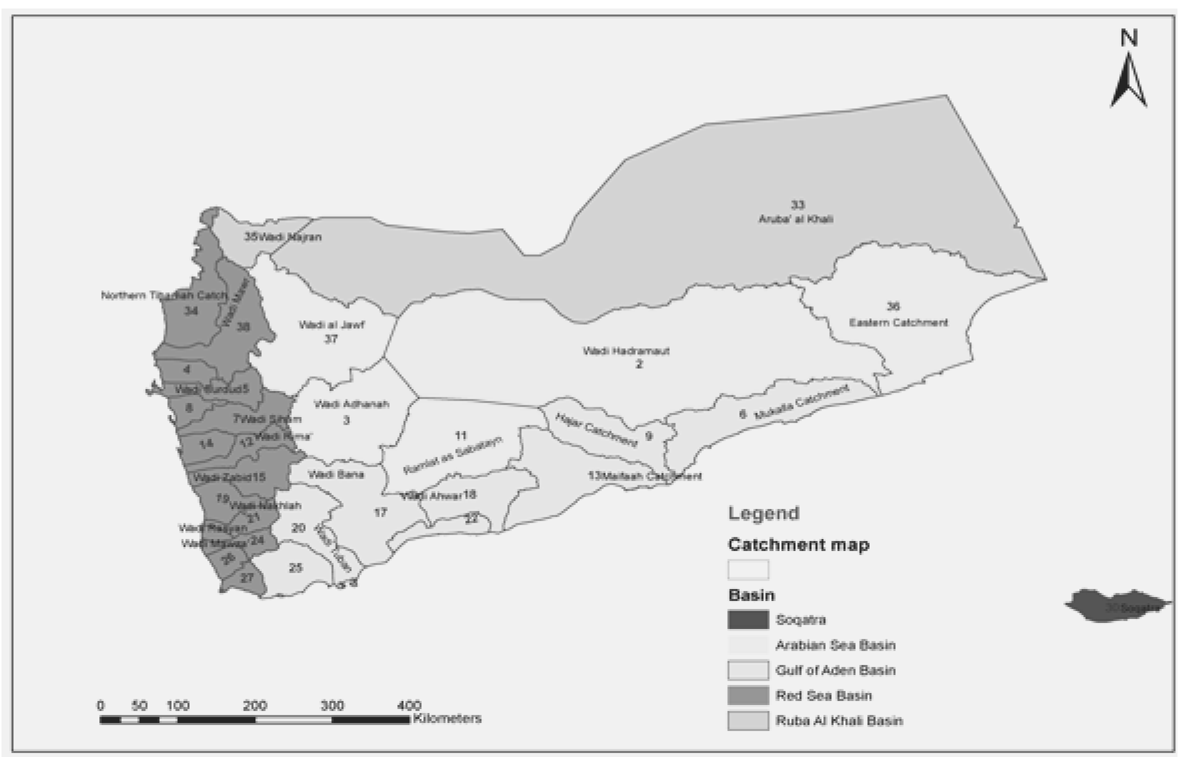
- Yemen is suffering growing water stress. Groundwater reserves are likely to be mostly depleted in about three decades, irrespective of climate change, reducing agricultural output by up to 40%.

A. *Water resources and uses*

The main surface water basins

Yemen is divided amongst four major basins. For the assessment of water balance, Yemen can be divided into a number of major basins draining the highlands westwards to the Red Sea, southwards to the Gulf of Aden, eastwards to the Arabian Sea and finally northwards in the Rub' Al Khali basin (see Figure 12). Annex 2 gives a detailed description of the four basins.

Figure 12: Major basins in Yemen: based on NWRA basin boundaries



Water Resources

Almost all of Yemen's <u>*rainfall*</u> *is rapidly lost to ET*. Although Yemen is the rainiest country in the Arabian Peninsula, most of the rain returns to the atmosphere within a few days, either through evaporation or through transpiration from plants. Some will penetrate the soil and be stored temporarily as soil moisture, but most of this rises again to the surface by capillary action and evaporates. Smaller portions may percolate deeper into the ground and join groundwater flows, or flow over the surface as runoff. Typically, less than one tenth of the approximately 37 BCM of rain that falls on Yemen is captured in streams and rivers, and in the larger catchments, the mean "runoff coefficient" is only 5%.

About 6% of rainfall runs off as surface water and flows into stream beds, often as violent spate torrents, and occasionally causing catastrophic floods. In times of heavy rain, runoff moves rapidly to the nearest branch of the drainage system and rushes downstream as a *spate flow* into ever larger wadi beds. As in all arid zones, wadi flows in Yemen tend to be ephemeral. Typically, the wadi beds are dry for most of the year, and floods come and go quite quickly. Some wadis may remain dry for several years, and then become the bearer of a huge flash flood. The flood peaks are often quick and torrential (causing disastrous *floods* as in Hadramout and al-Mahra in 2008—see Chapter 1), because rainfall events are violent, slopes are steep, and recharge in the catchment area is reduced by sparse vegetation and limited soil permeability. Much of the spate flow recharges the alluvial groundwater system thereby improving the groundwater stocks. Because of this rapid recharge in the stream beds, and because of diversion for farming, very little storm flow ever reaches the sea. Some of the water that infiltrates groundwater reappears above ground to contribute to surface flows in the wadi beds as *base flow* or as *springs.* All the major wadis draining to the west coast have permanent base flows in the foothills zone that may make up about 40% of total flow. Overall, about two BCM of water are captured in the surface water system each year, amounting to about 6% of total rainfall.

Alluvial and rock aquifers have large reserves of groundwater, and are recharged annually. Alluvial aquifers are the commonest and smallest in Yemen. They are formed from sand and gravel unconsolidated deposits and they receive spate flows and spring inflows. It is cheap and easy to extract water from the alluvial aquifers. The water table fluctuates rapidly, depending on seasonal inflows and discharges. Solid rock aquifers of sandstone and limestone tend to be deeper and much more extensive. Most productive are the deep sandstone aquifers, sedimentary rocks with porous characteristics that allow water to seep in. Yemen's aquifers are estimated to contain large reserves of about 35 BCM, including fossil water that is not recharged. Annual recharge is thought to be about 1.3 BCM (see Table 5 below).

In recent years, groundwater reserves have been mined on a vast scale, and many springs have dried up. It is the deep aquifers, tapped over the last four decades by over 100,000 tube wells, which have been the source of the groundwater boom that has driven the flourishing of the Yemeni rural economy. However, this groundwater boom has recently begun to turn to bust, with pumping depths plummeting to several hundred meters, and some reserves completely drained. As groundwater is part of an inter-connected hydrological system, the drop in groundwater levels had led to the drying up of most of Yemen's springs and the waning of the age-old agricultural systems that depended on them.

Water Uses

A variety of methods are used to harness water. Rainwater is used directly in rainfed agriculture. Because of the low rainfall, erratic distribution and high evaporation rates, most rainfed agriculture uses some form of water harvesting, such as 'runoff/ run on', small dams or terraces, or combines rain with supplementary well irrigation. Water flows in wadis are usually diverted for agriculture. Springs are harnessed for agriculture and household use. Water from the alluvial aquifers is tapped, largely for agriculture, by shallow wells. Water from the deeper rock aquifers is tapped, again largely for agriculture but with growing household use, from some several hundred meters deep.

Agriculture is estimated to use about 93% of Yemen's surface and groundwater resource. Intensive use of water has always been the mainstay of the rural economy, and since the development of commercial agriculture based on groundwater, agriculture has flourished as never before. Household and industrial use accounts for the balance of the use of Yemen's water.

Principal issues

Development has brought depletion of water reserves, inequity, and shortages. Traditionally, Yemen had evolved complex institutions for managing water sustainably and for resolving conflict. With the advent of rapid population growth and urbanization, market driven agriculture and above all the tubewell, demand outstripped supply, and Yemen has not been able to introduce new institutional mechanisms capable of regulating water use, protecting water rights or transferring water to its highest value use. As a result, as described above, water reserves are being mined at an alarming rate, water rights are changing inequitably, and households and cities are short of water. Poor farmers and poor households everywhere are the principal losers.

.....with negative socio-economic consequences. The socio-economic impacts of the current deteriorating water situation are likely to be a reduction in incomes and employment, unevenly spread and mainly hitting the poor. Increasing patterns of impoverishment, conflict and violence are already discernible.

Reforms have been underway for a decade but are impeded by vested interests and poor governance. Government is undertaking reforms to improve outcomes in the water sector. The 2003 water law establishes a modern system of water rights and regulation, and NWRA was set up in 1996 to conduct integrated water resources management. The incentive structure has been adjusted to move the cost of water towards its economic value, particularly through increases in energy prices, and government is subsidizing water conservation measures. Tests are underway to encourage responsible water management at the local level by communities in partnership with government. These and further reform measures to improve water use efficiency are discussed more fully in Section "B" below. However, reform measures have encountered opposition, particularly from powerful agricultural water users, and the government's ability to introduce regulation or affect the incentive structure to control water extraction and protect rights has been limited.

Water balance

The rapid changes in water abstraction and use have affected the water balance. Traditional water harvesting and soil conservation methods have been supplemented and/or replaced by increased groundwater abstraction from both shallow and deep aquifers so that the available water resource is already fully exploited or over-exploited in all populated areas.

Table 5: Illustrative schematic water balance for Yemen

Inflows	BCM	%	Outflows	BCM	%
Rainfall	37.0	97%	Groundwater recharge	1.3	3%
			Discharge to the sea	0.7	2%
Drawdown of groundwater reserves	1.2	3%	Evapotranspiration (ET)	36.2	95%
Total sources	**38.2**	**100%**	**Total uses**	**38.2**	**100%**

Source: Authors' estimates based on WRAY 35

The rate of groundwater extraction is currently twice the rate of aquifer recharge, and is increasing. Total groundwater recharge in 2003 was estimated by NWRA to be about 1.5BCM, based on the WRAY analysis. The hydrology modelling in Phase II of this study suggests that recharge is somewhat less (about

1.3 BCM).[13] Estimates of the number of boreholes and average borehole yield suggest that groundwater extraction is currently about 2.5 BCM a year. Table 4 above presents an illustrative water balance, showing a net drawdown of groundwater reserves of about 1.2 BCM annually. Phase II of this study suggested that the rate of overdraft may still be on the increase in a 'race to the bottom'.

The future of Yemen's aquifers (independent of climate change)

Independent of climate change, the most important impact on water resources will continue to be over-extraction of groundwater. Even without considering changes in climate, the rising demand and absence of regulation will continue to make deep groundwater abstraction viable, and the resulting over-abstraction will remain the most important factor affecting the water balance.

Groundwater reserves of about 35 BCM are likely to be depleted in the coming decades. It seems inevitable that extraction rates will continue at least at current levels and that groundwater levels will continue to fall. Boreholes will continue to be extended to deeper and deeper levels until the bottom of the aquifer is reached. Phase II of this study developed a possible scenario for the evolution of groundwater extraction over the next 40 years. Under this scenario, extraction continues at average borehole yield rates to the bottom of the usable aquifer in most places, at which point extraction then becomes limited by the rate of recharge.[14] The peak extraction happens in about 2016 and extraction then falls rapidly, so that by about 2025-2030, reserves are effectively exhausted and use would have dropped to the recharge rate (currently about 1.3 BCM annually, half of present levels of extraction). This scenario, which does not take account of any climate change effects, is presented more fully in Section "B" in Chapter 5.

B. Agriculture and agricultural water

Agriculture today

Agriculture remains the most important productive sector. Even after rapid changes since the 1970s, Yemen remains a predominantly rural country, where agriculture is still an important, although no longer dominant, sector. Agriculture still accounts for 33% of employment and 9% of GDP (2006 numbers).

Agriculture has changed enormously in recent years. The sector today is characterized by a strong market orientation, by diversification (see Table 6 below), and by the spread of irrigation, particularly from groundwater. Production of higher value cash crops has increased enormously, and Yemen is largely self-sufficient in fruit and vegetables. Qat cultivation has spread to cover one tenth of prime land. Cereals production has been unable to keep up with market demand, and Yemen is now heavily dependent on imported cereals. Linkages to industry are weak, and agriculture has an inward-looking orientation – exports are very small.

[13] The difference in these figures is due to different baseline periods as well as calculation methods.

[14] Given the weak knowledge about aquifer characteristics, it is not possible to say how long each aquifer will hold out. In some areas pumping depths are dropping at 6-8 meters a year, some localized aquifers are already depleted, and others have become too saline to exploit. In other areas, there may be deep reserves that are only economic to exploit if there is a large city in the vicinity – this may be the case of the Sana'a Basin, where possible large reserves below 500 meters are currently being investigated. There are also the vast 'desert' aquifers of the Mukalla sandstone formation and the Umm al-Rudhuma formation that also underlies Saudi Arabia and Oman, but these enormous reserves are generally deep and are far from population centers.

Table 6: Agro-ecological zones

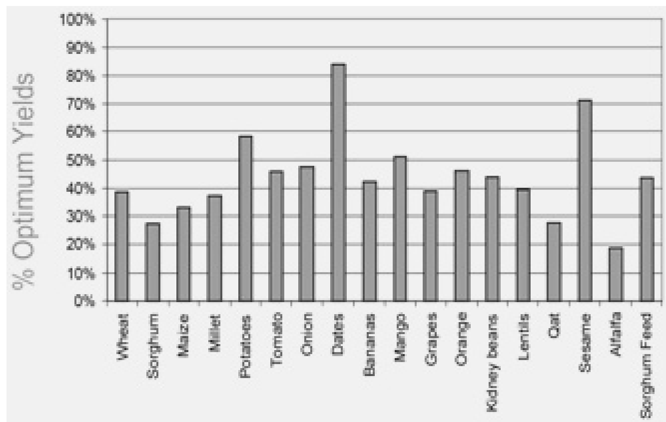
Agro-ecological zone	Main agricultural governorates	Principal crops
Coastal	Hodeida, Lahj, Abyan	Millet, sorghum, tomatoes, onion, bananas, oranges, cotton, sesame
Highlands	Sana'a, Hajjah, Sa'adah, Mahwit, Dhamar, Ibb, Taiz, al Beida	Maize, millet, sorghum, wheat, grapes, tomatoes, potatoes, onion, cow peas, qat, coffee, alfalfa
Eastern Plateau	Ma'reb, Hadramawt, al Jawf, Shabwa	Sorghum, wheat, dates, tomatoes, potatoes, onion, alfalfa

Source: AREA in 129 Annex 3:2

Problems of the agricultural sector

Productivity is poor, with absence of any recent productivity breakthrough and stagnation in the livestock economy. Levels of husbandry and productivity are not very advanced, and there has been no improvement in factor productivity for most crops in recent years. Yields remain well below technical potential (Figure 13), and below actual farmer yields in comparable environments in other countries.[15] Water management is weak, with irrigation efficiencies nationwide averaging only 40%.

Figure 13: Actual crop yields as a percentage of optimum



Source: AREA Crop Requirement Tables and MoA Agricultural Statistics Yearbook 2007

Producer services such as research, extension and credit have been in crisis for years, and efforts at reform have so far produced little improvement.

The limited natural resource base is under stress. The sustainability of current farming is not assured, with rapidly declining water tables, and watershed and range degradation upstream that provoke erosion and reduce groundwater recharge.

Rural incomes are stagnating. The rural-urban terms of trade have deteriorated, partly as a result of the government's structural adjustment program, as diesel prices move to border parity, and fruit and vegetable prices go down as import restrictions are lifted. The current increase in the price of imported cereals may improve incentives for a minority of farmers, but will increase costs for the majority of rural people who buy cereals. Rural areas are under the double pressure of shrinking water availability and

[15] Phase II of this study estimated that there may be productivity improvements available that would allow crop production to increase by 3% per year without increased water use. However, the realities of production under smallholder conditions, particularly the risk factor, significantly constrain the attainment of this technical potential.

rising population. If a more sustainable agriculture is to develop, as it must, this may mean lower incomes

Poverty and inequity are on the rise. Inequity is on the increase, as better off farmers exploit deeper groundwater, effectively privatizing the commons. Rural poverty has been rising fast as the poor have less equitable access to natural resources.

Nonetheless, the sector and the rural economy remain surprisingly buoyant, when compared to other countries in the region. Much of this can be attributed to the mining of groundwater, and to the explosion of qat production.

Agricultural water development and management

The expansion of irrigation has contributed to rapid growth of commercial agriculture. The total irrigated area doubled in the three decades from 1970: now over 40% of farmed land is irrigated. The rapid spread of new irrigation technology has had a huge effect on the cropping pattern – the area under cash crops has shot up from 3% of the total in 1970 to 14% today, and production of high value fruit and vegetables has increased by 20 times, from 40,000 tons annually in 1970 to 800,000 tons today.

Traditional water harvesting systems cannot compete with pump irrigation and have declined. Traditionally, Yemenis had many ingenious water harvesting techniques to husband their scant water, and these all had equally well-developed institutional systems to ensure their working. Water harvesting systems are declining as they face competition from pump irrigation, reduced profitability, environmental problems with the deterioration of the upper catchments, and land tenure problems, particularly land fragmentation**.**

Small dams have been promoted in recent years but contribute little to the water balance. Small dams have existed in Yemen since the days of the ancient South Arabian kingdoms as a means of improving water control, breaking the force of a spate flow, or enhancing recharge of groundwater.[16] For more than a decade, Government has been promoting small dams as part of the answer to the growing water resource constraint. This program has had limited impact on the water balance.

Springs, once important, have largely dried up. Spring irrigation has also been very important, each spring channeled and divided by canal systems as complex as the rights and rules that governed the sharing of the water. However, many of these springs have dried up with the motorized depletion of the aquifer. As a result, spring irrigation has dwindled and now covers only 2% of the farmed area.

Modern spate irrigation has been largely successful, but there are issues of unreliability, equity and management. Spate irrigation may be the oldest form of irrigation. Traditional diversion systems were well developed, based on communal efforts to erect water diversion structures and to share the diverted water. Development of modern spate schemes from the 1950s adapted traditional spate technology to a larger scale. Three problems have emerged with these modern spate schemes. First, although the introduction of permanent diversion structures increased the reliability of spate irrigation, it also changed water distribution patterns, creating inequity. Second, the economic returns are less assured than in

[16] The only existing large dam in the country is the Ma'rib Dam. Up to now, only 1,700 ha of area has been developed for irrigation, owing to disputes over land and water rights.

schemes fed by permanent river flows. Third, the capacity of the public sector to manage these schemes was eroded by the crisis in public budget and services in the 1990s.

Over the last decade, government has been implementing a program for spate improvement. The program is designed to (i) improve reliability and efficiency of the physical structures; (ii) increase income per drop through improvements to water use efficiency and adoption of better water management, higher value cropping patterns and improved crop husbandry; and (iii) improve the efficiency of operation and maintenance and scheme financial viability by promoting decentralized management by water user associations (WUAs). First reports indicate good results from the program, with high levels of farmer participation and production increases above expectations.

<u>Groundwater use for irrigation</u> developed rapidly under favorable conditions and now accounts for two thirds of the value of crop production. Until the 1960s, the use of groundwater for irrigation was confined to supplemental irrigation from shallow wells. During the last third of the twentieth century, the tube well and motor pumps revolutionized Yemeni irrigation. Groundwater irrigation developed rapidly, helped by a favorable incentive framework: cheap diesel, cheap credit, the absence of duties on equipment, an import ban on competing cash crops, active government support through projects, and the absence of any regulatory framework. Private capital was available from remittances, and the rapid growth of markets for irrigated crop production, particularly for qat, created strong demand and profitability. Full or supplemental groundwater irrigation now accounts for two thirds of the value of crop production, and despite ever increasing pumping depths, groundwater use remains currently financially profitable[17] in many areas and for many crops. Phase II of this study calculated that borehole irrigation is viable for selected cereals at depths of 200m, for vegetables at depths of about 250m, and for qat at about 300 m depth.

Although conveyance is sometimes by pipe over long distances, technology is generally simple, with little localized irrigation, low levels of know-how, and virtually no pressurized irrigation (drip, bubblier) or protected agriculture (plastic houses and tunnels).

Measures to try to improve efficiency and reduce over-extraction of groundwater have so far had limited impact. From the 1990s, the groundwater mining problem became evident, and Yemen began to take tentative steps to try to reverse the trend and to improve efficiency. Steps have comprised: (1) altering the incentive structure, largely by raising diesel prices; (2) promoting a package of technical improvements to conserve water at farm level and to improve irrigation efficiency; and (3) testing a decentralized partnership approach to water resource management. Although these are evidently the correct steps, there has been only limited impact, due to the generally weak legal and governance environment and the fragmented and weak public institutions faced with strong traditions of local autonomy and the lack of local rules and organizations adapted to management of deep groundwater. In effect, government has had little influence over the water-extraction decisions made by more than a hundred thousand independent-minded farmers.

Groundwater reserves will be exhausted in the foreseeable future, and climate change will at best only postpone the date by a few years. As discussed in Section 'A' above, Phase II of this study concluded

[17] There is a long and complex debate about whether the financial returns to farmers from water use reflect the full social returns to water use in Yemen. The analysis of climate change has little to add to this debate. In the hot and dry scenario the reduction in water use in agriculture will happen earlier and will be much sharper. But the principles of optimal policy response are the same as they are without climate change.

that in practice overexploitation of groundwater will continue until groundwater reserves are exhausted and extraction is limited to recharge, or should the incentive mechanism change over the next few years, the rate of groundwater depletion may slow down. Based on calculations under phase II of this study, climate change will affect the pace at which depletion occurs (see Chapter 5B below). On the other hand, based on current trend of groundwater exploitation, depletion of reserves by 2025-2030 could reduce agricultural production by more than 40%.

Supplementary irrigation is becoming a key feature of agricultural production, particularly for qat. Three quarters of Yemen's farmed land gets less than 600 mm of rain, and the uncertain, low or poorly spaced rainfall is a constraint to production and yield. Typically in such dry conditions, supplemental irrigation, also called conjunctive use, can expand the cultivated area or increase yield significantly during periods when soil moisture is inadequate. It is a useful technique as it is relatively low cost and uses little water. A survey found that supplementary irrigation is quite common, and it is a notable feature of qat farming. [Bamatraf, 1987]

The potential of the agricultural sector and agricultural water, and sources of growth

Agriculture still has a key role to play in the Yemeni economy. Given the demographic explosion in a still largely rural country, agriculture will have a key role to absorb labor and provide incomes for new entrants for the foreseeable future – at least if an uncontrolled and impoverishing rural exodus is to be avoided. There is a large, fast-growing domestic market, and demand is likely to continue to move "up market" to higher value foods as urbanization continues and incomes gradually rise. Demand from industry could also increase for cotton and fruit. Export niches also exist: original Mocha coffee, frankincense, myrrh, saffron etc.

There are many potential sources of future growth in agriculture. Although productivity has not improved much in recent years, many crops have good economic and technical potential for further growth, including cotton, grapes, papaya, coffee, and market garden crops. These crops have low domestic resource costs and high potential for productivity improvements by improving the efficiency of water use and crop husbandry. Potential genetic improvements also exist, and post-harvest, marketing and agro-processing activities can be improved to increase value addition along the value chain. Investment in these crops would be in line with Yemen's comparative advantage.

However, there are currently major problems of sustainability affecting horizontal expansion and of productivity affecting vertical expansion. Shortages of arable land and of agricultural water are the biggest constraints to expansion. In addition, adverse movements in the terms of trade and the poor performance of public services to the sector have also affected growth.

Keys to improving poor factor productivity include reforming agricultural services and promoting farmer associations. Given the dwindling prospects for full groundwater irrigation, focus should be on sustainable systems: rainfed agriculture with water harvesting and supplemental irrigation, and spate and other surface irrigation. In agricultural water use, needed measures include: (i) implementation of the regulatory framework in partnership with stakeholders at the basin and local level; (ii) further reform of the incentives structure to promote water use efficiency; (iii) promotion of WUAs; and (iv) reform of agricultural services and research and dissemination of technical packages for a more water-scarce agriculture.

What can government do to further develop agriculture and agricultural water management?

Three sets of actions are indicated for government:

- Macroeconomic solutions to remove incentives to water mining and inefficient water use and to strengthen institutional mechanisms to encourage water conservation and use efficiency. Similarly, unconventional thinking and policy measures, such as incentivizing the move of agriculture outside some critical basins where the comparative advantage of agriculture in the basin is less, should not be discouraged in Yemen. As water reserve in some critical basins—such as Sana'a basin—that are important for the country's economy are fast depleting, any conventional measure may not be able to save the water—it will just be a matter of time. On the other hand, alternative options of providing Sana'a with water (such as through desalination) is very costly, and even under future best scenario of efficient desalination technologies, the cost of pumping water over 250 km distance from the nearest coastline and against a pressure head of over 2,000 meter will continue to be costly. Under such circumstances, where the country's economy depends heavily on the potential of these basins to provide continued services, the best option would be to adopt a different policy that encourages low water productivity sectors to move outside of the basin to other basins where more water is available.

- Technical solutions to develop and disseminate the technology needed for improving value added, particularly returns to the scarcest resource water.

- Management solutions to give more responsibility and ownership for both resource management and service provision to farmers and farmer institutions, and to improve the quality and cost effectiveness of public services to agriculture.

PART II: ASSESSING THE EFFECTS OF CLIMATE CHANGE AND VARIABILITY

Chapter 5: Climate Change and Variability Impacts in the Water Sector

- Climate change and variability impacts on the water balance would vary according to outcomes and would be different for different areas. The biggest risks are further reduced water availability, particularly in lowland areas if the weather turns hotter and drier, and floods due to possible heavier rainfall.

A. *Impact on ET, runoff and recharge*

For Yemen as a whole

Changes in ET, runoff and recharge were projected to the 2080s under three scenarios. Phase II of the study used the monthly hydrological model (see Chapter 2) to estimate possible changes in runoff, recharge and ET for Yemen as a whole under the three scenarios: the 'mid', 'hot and dry' and 'warm and wet' scenarios. The scenarios were described in Chapter 3 above, together with the projected changes in average annual temperature and rainfall. The projections were made for three intervals: the 2030s, 2050s and 2080s. The results varied between major basins but the general picture is well represented by average figures for Yemen as a whole (see Table 7 below). The hydrological model projected only the marginal changes to basin water resources stemming from climate change and variability, and did not take into account the current rate of groundwater mining (see Chapter 4 above). The results reflect the trends in temperature and rainfall for each scenario, and the changes in runoff and recharge rates take account of expected increasing variability in rainfall patterns.

Adaptation strategies will vary according to local water availability. In basins where there are still adequate resources, such as parts of the southern uplands and of the wadis of the western escarpment, climate change strategies can be more flexible, as conjunctive water use will be available to compensate for any deficit in soil moisture. In basins nearing depletion, climate change will have the greatest impact, as they will more be prey to the vagaries of precipitation distribution. In terms of adaptation, for basins with aquifers that are nearing depletion, there are relatively fewer options available compared to basins where there is still enough water in the system as this allows for more flexible adaptation options. For example, for aquifers that are already depleted to 300-600-m deep, based on aquifer formation, it may take few years to decades for the water to replenish the aquifer system, and therefore, the marginal impact due to climate change over the impact of overexploitation of the aquifer water becomes less important.

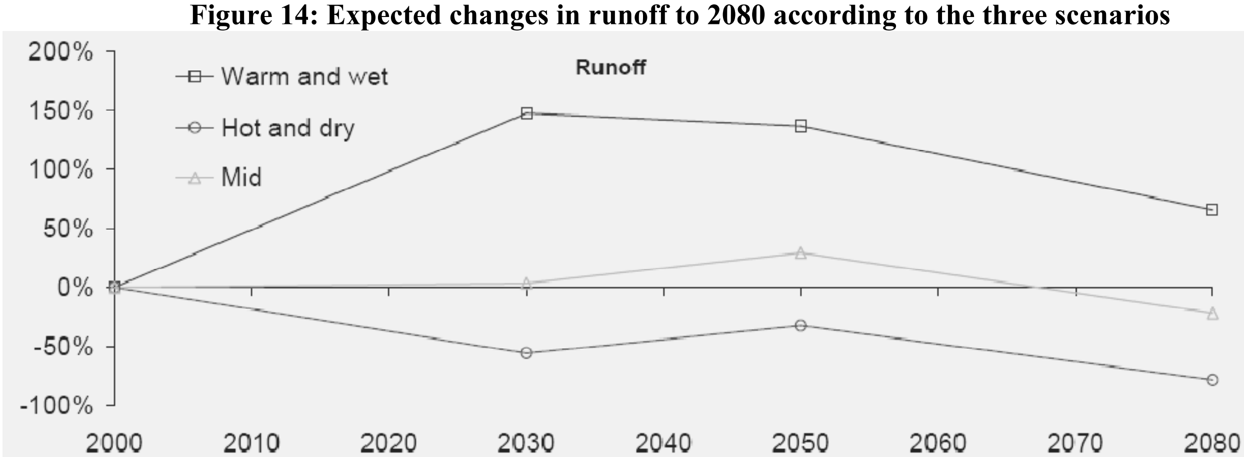
Table 7: Average changes in annual average runoff and recharge for different climate scenarios

Scenario	Year	Runoff	Recharge	ET	What to expect
Baseline	1990s	0%	0%	0%	
Mid	2030s	4%	4%	2%	large increase by the 2050s, then decline below current levels. A modest increase in recharge until about 2050, followed by a decline reaching about 12% by 2080. Little change in ET.
	2050s	30%	2%	2%	
	2080s	-22%	-12%	0%	
Hot & Dry	2030s	-55%	-31%	-6%	A large drop in runoff, of one half or more. Recharge rates decline by more than a half by 2080. ET declines. steadily as aridity increases.
	2050s	-32%	-32%	-6%	
	2080s	-78%	-55%	-11%	
Warm & Wet	2030s	147%	54%	13%	A doubling in runoff through most of the century, reducing somewhat in the second half. Recharge up by 50% by 2030, tapering off by 2080. ET well up, although dropping back a little after 2050.
	2050s	137%	41%	10%	
	2080s	66%	27%	9%	

Source: HR Wallingford

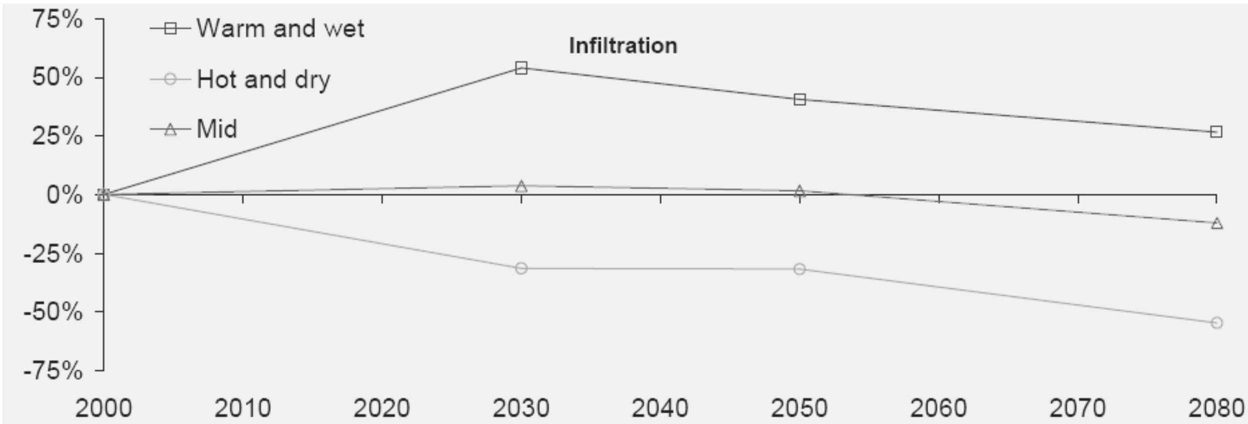
The 'mid' scenario shows modest variations in runoff, the other scenarios show, respectively, an improved and a deteriorating picture. The graph below (Figure 14) traces the expected changes in run off according to the three scenarios. The 'mid' scenario suggests there will be little change until the 2030s, and then an average increase in runoff of about one third in the 2050s, followed by a decline below current levels by the end of the century. The 'hot and dry scenario' suggests a drop in run-off of one half or more during the century, whilst the 'warm and wet' scenario shows a doubling in run-off through most of the century, reducing somewhat in the second half.

Figure 14: Expected changes in runoff to 2080 according to the three scenarios



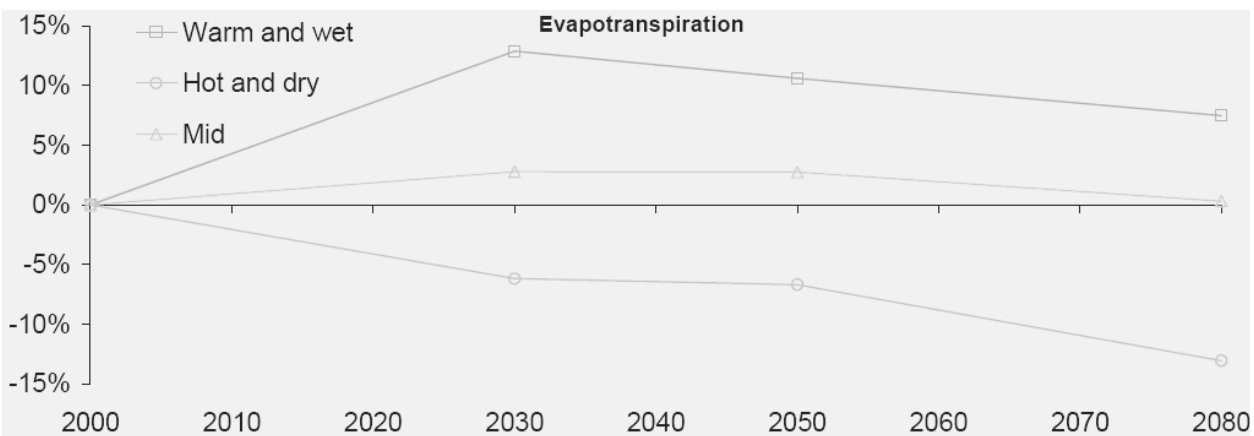
A similar spread of outcomes is projected for recharge. Expected changes in recharge are traced in the following graph (Figure 15), with the 'mid scenario' showing only a modest increase in recharge until about 2050, followed by a decline reaching about 12% by 2080. By contrast the 'warm and wet' scenario shows a considerable improvement in recharge (50% by 2030), tapering off to about one quarter above 2000 levels by 2080. Under the 'hot and dry' scenario, recharge rates are down by more than a half by 2080.

Figure 15: Expected changes in recharge to 2080 according to the three scenarios



Changes in ET will follow the anticipated changes in climate and hydrological factors. Figure 16 below shows projected changes in ET. Rising temperatures will tend to increase ET, but the main determinant will be humidity. Under the 'hot and dry' scenario, aridity will worsen and ET will be lower, and deteriorating in the second half of the century as temperatures rise and rainfall drops. Under the 'warm and wet' scenario, lower temperature increases and higher rainfall will make for a more humid climate and a rise in ET, although this will tail off towards the end of the century as rainfall increases moderate. There would be little change under the 'mid' scenario.

Figure 16: Expected changes in ET to 2080 according to the three scenarios



It will be clear from the above that there is no certainty about the expected direction or size of change in runoff, recharge or ET. The 'warm and wet' pattern would be on the whole good for Yemen as increased runoff and recharge would make more water potentially available as surface and ground water, and the resulting higher ET can be reflected in increased crop production. Risks of floods and erosion would, however, increase. The 'hot and dry' scenario would reduce water availability from both surface flows and groundwater by one half or more, with severe impact on an already water-stressed society. The lowered ET, reflecting lower water availability despite higher temperatures, would translate into reduced agricultural output. The 'mid' scenario offers an improving picture for both surface and groundwater until mid-century, followed by a slow decline: under this scenario Yemen would have a breathing space in which to adjust to a less water-dependent economy.

Whatever the other changes, the scenarios all confirm the likelihood of warming, and of more pronounced rainfall variability and intensity. As discussed above (Chapter 3), **t**here is agreement on the likelihood of warming, of an increase in variability of rainfall patterns within years, and of more frequent and intense rainfall. All areas are likely to experience warmer weather (by between 1°C and 4.5 °C by 2100), rainfall patterns are likely to be more variable within years, and there will probably be an increased frequency of intense rainfall events[18].

In addition, all scenarios suggest a deteriorating trend from mid-century, and planning should certainly take account of that. The 'warm and wet' and 'mid' scenarios agree that runoff and recharge will improve, or at least not deteriorate, for the decades until about mid-century, whereas all three scenarios show a deteriorating trend in the second half of the century. <u>This suggests that there may be a respite period until mid-century during which Yemen will have to plan for significant adjustment later on</u>.

Analysis by catchment and governorate

The area case studies underline the challenge for planners. For more detailed analysis in case study areas as described in Chapter 2 above, Phase II of the study set up a daily hydrological model to explore the potential impacts of climate change on the soil moisture balance and frequency of higher flows. Two examples of the catchment and governorate level analysis will suffice to show the value of the exercise – and the challenge for planners in interpreting and acting on the results.

In <u>Wadi Surdud</u>, measures to improve watershed management and the management of water resources are indicated – whether the climate changes or not. In Wadi Surdud (see Box 4), the prediction is that flows will vary little in frequency from the present[19], but the volume of flows may change – ranging from a decrease of 20% ('hot and dry') to an increase of 30% ('warm and wet'). Over-abstraction of the coastal aquifer will continue even in the wettest scenarios. Here the planner would probably best conclude that improving management of the watershed (to increase recharge and reduce erosion) together with socially equitable improvement of spate and groundwater management would be prudent policies. These solutions would apply whether the climate changed or not.

Box 4: Changing water balance and frequency of spates for Wadi Surdud

Wadi Surdud drains the highlands westwards to the Red Sea. The upper catchment receives higher rainfall sufficient to sustain rain-fed agriculture, which is supported by supplementary groundwater. The lower catchment is in the Tehama, an important agricultural area that relies on a combination of spate irrigation and groundwater abstraction from a coastal aquifer. Rainfall along the Red Sea coast is very low. Agricultural production increased following the development of modernized spate irrigation schemes based on permanent diversion structures in the 1980s.

Total groundwater abstraction in the lower catchment in the mid 1990s was much greater than the natural recharge, which derived from inflows from the upper catchment together with small amounts of local recharge. Application of the climate change scenarios for the 2030s, 2050s and 2080s to the daily hydrological models showed:

- A range of potential flow changes from a decrease of about 20% to an increase of about 30% for the dry

[18] Although this was generally projected by global models, the methodology used under this study (statistical downscaling methodology) has some limitations and has not confirmed this general statement.
[19] This result largely reflects the limitation of the approach used in this study to fully capture conditions related to extreme events—including the frequency and intensity of rainfall events.

and wet scenarios, respectively.

- No significant change in the average frequency of spate flows (see foot note 19 below), with more or less flow during spates in accordance with the application of wetter or drier scenarios.

- A large difference in the frequency of spates for individual downscaled scenarios demonstrating that this important variable would change with different patterns of daily rainfall.

- Continued over-abstraction of the coastal aquifer even in the wettest scenarios, making it clear that water efficiency and improved water resources management at the catchment scale are needed irrespective of any future climate scenario.

Source: HR Wallingford

In Wadi Hadramawt, adaptation strategies to deal with increased flood risk are indicated. In the Wadi Hadramawt basin (see Box 5), where damaging floods occurred in 2008, variability in the timing, frequency and intensity of rainfall is likely to be a significant risk, and spate and flood flows may increase in volume and frequency under both the 'mid' and 'warm and wet' scenarios. Under the 'hot and dry' scenario, flood flows would be smaller and rarer. Despite the smaller risk shown by the 'hot and dry scenario', the possibility of a repeat of the 2008 floods or of even more severe events suggests that planners should consider adaptation strategies.

Box 5: Potential impacts of climate change on flood frequency in Wadi Hadramaut

The Hadramaut is a large basin draining from west to east that receives very low rainfall. The western area of the basin is dominated by sand dunes and does not generate runoff. Populated areas, such as the city of Shibam, are located along the wadi in the centre of the basin, which receives occasional runoff from mountainous areas to the north and south. The area is an important agricultural area with water derived from spate flows (~9%) and groundwater sources. In October 2008, the area was affected by severe flooding that caused many fatalities, destroyed 450,000 palm trees, damaged farmland, killed livestock, destroyed houses, and contaminated water wells. Wetter conditions or more intense rainfall events due to climate change are likely to increase the frequency and severity of flooding.

The hydrology of sub-basins that generated flood flows in 2008 was reviewed as part of the study, using conceptual models and statistical models for estimating flood flows as a function of catchment characteristics and annual average rainfall. This analysis showed that:

• Under the 'mid' scenario, the mean annual flood could increase by 10% and higher flood flows could occur more frequently.

• Under the 'warm and wet' scenario, flood flows could increase substantially, by 40% in the 2030s, and large flood flows would occur, on average, twice as often. Thus the current once in 100 year flood would occur once in 50 years

• Under the 'hot and dry' scenario, flood flows would reduce by 20% in the 2030s, and become much rarer than in the past.

Despite the outcome of the 'hot and dry' scenario, the possibility of a repeat of the 2008 floods, or of even more severe events, highlights important adaptation strategies that should include:

- Rehabilitation of irrigation systems with reinforcement of flow structures and appropriate diversion structures for drainage of flood waters
- Prevention of development within the wadi bed and ensuring that vulnerable buildings are raised above flood levels or protected
- The development of appropriate flood forecasting and early warning systems with robust communication

strategy in order to prevent loss of life and property before/during flood events.

Source: HR Wallingford

The high level of uncertainty associated with climate change projections makes planning a difficult task. The catchment level case studies illustrate the planner's dilemma. There is considerable uncertainty over what is likely to happen, and the strategies would be different depending on the nature and size of the risk predicted. How a poor country like Yemen, with few financial and institutional resources, can best plan for climate change under such multiple uncertainties is a tough question that will be discussed in Chapters 7 and 8 below.

B. Impact on groundwater

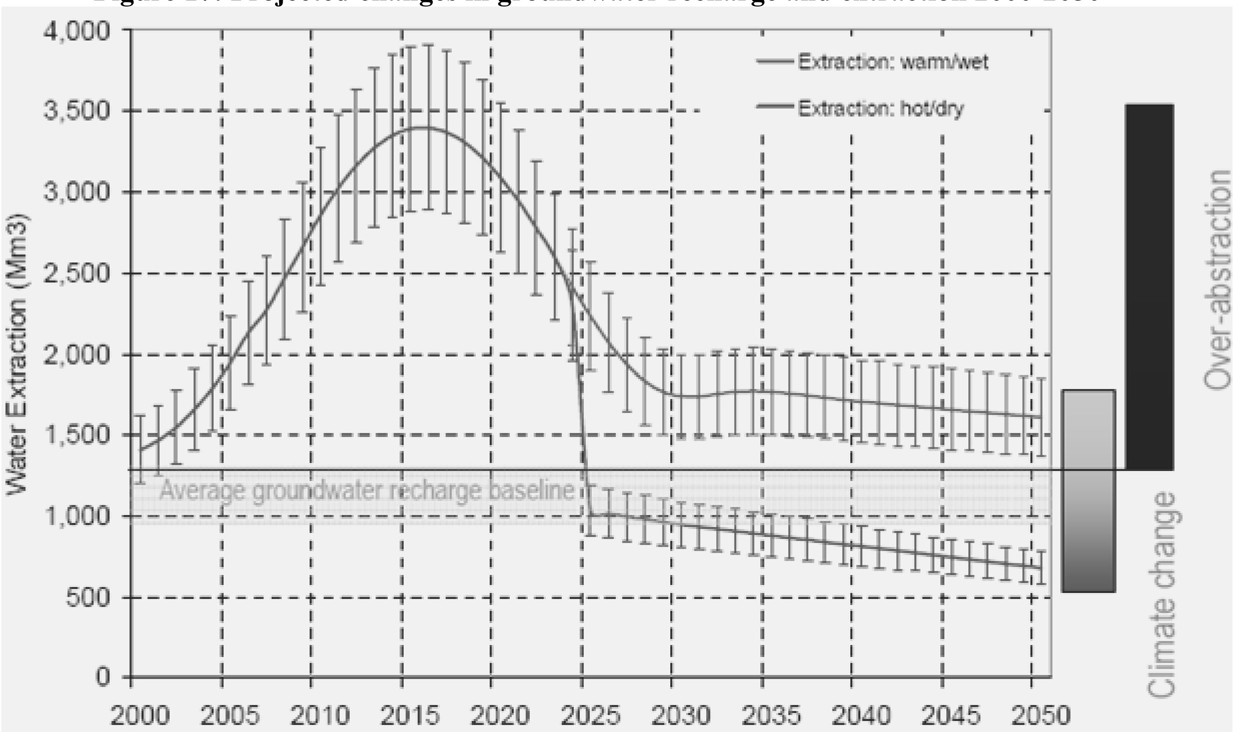
The outlook for groundwater independent of climate change

Once groundwater reserves of most critical aquifers are exhausted, by about 2025-2030, groundwater extraction will be limited to recharge levels, higher in the case of the 'warm and wet' scenario, lower in the case of the 'hot and dry' scenario. The prospects for groundwater abstraction and climate change impacts for Yemen as a whole are summarised in Figure 17 below.[20] The red line is common to all scenarios up to 2025: it assumes that climate change will have little impact and that by 2025 usable groundwater reserves will be exhausted and abstraction will equal recharge at most. After 2025, the green line shows the range of extraction levels that would be consistent with current rates of recharge plus the extra resource available from increased recharge under the 'warm and wet' scenario. The red line after 2025 traces the drop in recharge – and hence of abstractions - below current recharge levels. The 'mid' scenario is not shown: it can be assumed that recharge and abstractions after 2025 under the 'mid' scenario will follow the range of current average recharge. The components of change caused by climate change and by the fact that abstraction will gradually drop to replacement levels as reserves are exhausted are shown separately. The orange bar shows the range of change to recharge and abstraction that is expected from climate change. The blue bar shows the inevitable drop in abstractions that is expected as reserves are exhausted.

Higher recharge under the 'warm and wet' scenario may delay exhaustion of reserves for a few years, but under all scenarios groundwater extraction will drop well below present extraction levels. The reduced upper bound of extraction after 2025 reflects an increase in water availability due to climate change. However, even under the most optimistic climate scenarios, with wetter conditions, the exhaustion of reserves will simply be delayed by a few years (from 2025 to 2030). Once the crisis has occurred, the rate of natural recharge – and hence the quantity that can be abstracted – may vary if climate change affects the rate of natural recharge, but will in all cases still be well below current extraction level (maximum extraction under the most favourable scenario of 1.6 BCM after 2030).

[20] As pointed out in Chapter 4 above, the average groundwater depletion for Yemen may mask a range of local aquifer situations with variations around the average. This does not, however, alter the fact that in two to three decades, most of Yemen's farmers will no longer be able to draw on groundwater reserves as they have been doing so extensively over the last forty years.

Figure 17: Projected changes in groundwater recharge and extraction 2000-2050



Under the 'hot and dry' scenario, groundwater extraction could drop to one quarter of current levels by mid-century. Under the worst case climate change scenario, available water resources will continue to decline sharply after 2025 even below current recharge rates, possibly dropping as low as 0.7 BCM by 2050, with severe consequences for Yemeni society, economy and environment.

Chapter 6: Climate Change and Variability Impacts in Agriculture

- Farmers are likely to have to adjust to warmer temperatures and to manage risks from more unpredictable rainfall patterns and from heavier rains. Increasing temperatures could increase output if water is available.

A. Impacts under the three scenarios

Effect of changes in water and temperature on yields

Average crop responses to climate and hydrological change were assessed. Phase II of the study calculated average crop responsiveness to climate and hydrological changes, following the methodology set out in Chapter 2 above (see also Annex 3). The analysis was made according to the three scenarios for the 2030s, 2050s and 2080s, using the average changes in climate and hydrological factors summarized in Table 8.

Table 8: Average changes in climate and hydrological factors for different climate scenarios

Scenario	Year	Temp. rise	Rainfall	Runoff	Recharge	ET
Baseline	1990s					
Mid	2030s	1.6 oC	3%	4%	4%	2%
	2050s	2.0 oC	3%	30%	2%	2%
	2080s	3.1 oC	-3%	-22%	-12%	0%
Hot & Dry	2030s	2.0 oC	-13%	-55%	-31%	-6%
	2050s	2.6 oC	-13%	-32%	-32%	-6%
	2080s	4.5 oC	-24%	-78%	-55%	-11%
Warm & Wet	2030s	1.0 oC	25%	147%	54%	13%
	2050s	1.2 oC	20%	137%	41%	10%
	2080s	1.6 oC	13%	66%	27%	9%

Based on responses to water and to temperature, the marginal impact of climate change on crop production was estimated for the three scenarios. The response to water (the ratio of change of yield to change of water available to the crop root) was found to vary between 0.4 and 0.9 for most crops, with a national average (weighted by crop production) of 0.68. This suggests that a 20 % change in water supply would produce a change in total crop production of 13.6 %. The response to temperature (ratio of change of yield to change of temperature) is more varied and is negative for those crops growing at above optimum temperatures, on average. The weighted national average is 0.14, suggesting that an increase in temperature of 10% (e.g. from 20 to 22 °C) would increase crop production by 1.4%. The possible production impacts overall for each scenario are detailed in Tables 9 and 10 below. In summary:

- *Yields would deteriorate progressively under the 'hot and dry' scenario*. Under the 'hot and dry' scenario, the combination of higher temperatures with less rainfall, runoff and recharge would increase the aridity of growing conditions and have a negative impact on yields. Phase II of the study calculated, for example, that 20% less water and 4% higher temperatures would reduce crop production by 10.8%. By 2080, a combination of temperature rise and significant drop in rainfall could have reduced crop production by 27%.

- *.....but increase under the '<u>warm and wet</u>' scenario, although tapering off over the century*. By contrast, in the 'warm and wet' scenario, the modest temperature rises accompanied by a significant increase in rainfall, runoff and recharge would have a favorable impact on yields. Phase II of the study calculated that 20% more water and 2% higher temperature would increase crop production by 15.0%. In 2030, production might be 14% up, thanks to modest temperature increases and a rise in rainfall, although these effects will taper off during the century, and by 2080, production would be only slightly up, by 6%.

- *The '<u>mid</u>' scenario would have little impact, although deteriorating after 2050*. Under the 'mid' scenario, conditions for agriculture show little change, although the rising temperatures and the increase in water availability from runoff and recharge up to mid-century may have a mildly favorable impact on yields (perhaps a 1% increase). Thereafter, the higher temperatures and decline in water availability will have a negative impact: yields 6% down by 2080.

In all three scenarios, the impact on crop production worsens over the three periods on average. Even the 'warm and wet' scenario would see the initial boost to production fall away during the mid and later years of the century, although the outcome would still be positive in 2080. The reason is a predicted decline in <u>rainfall</u> from 2050 under all scenarios. The impact of <u>temperature rise</u> on crop production is complex and is positive for many crops in highland areas, but negative in lowland areas.

Table 9: Marginal impact of climate change scenarios on crop production

	Mid			Hot and Dry			Warm and Wet		
	2030	2050	2080	2030	2050	2080	2030	2050	2080
Temperature (^{0}C)	+1.6	+2.0	+3.1	+2.0	+2.6	+4.5	+1.0	+1.2	+1.6
Rainfall change	+3%	+3%	-3%	-13%	-13%	-24%	25%	20%	13%
Crop Production	1.0%	1.1%	-6.3%	-10.7%	-11.2%	-27.2%	14.1%	11.7%	6.5%

Other factors, especially the unavoidable drop in groundwater availability, will have a greater and more certain negative impact on production. The changes in crop production discussed here are marginal changes arising from climate change, on top of all other non-climate factors, including declining groundwater availability and any effects of underlying technology trends. As the results do not consider the impact of non-climate factors, they do not constitute projections of crop production.

Table 10: Possible impacts on agriculture under the three scenarios

Scenario	What to expect	Possible impact on agriculture
Mid	Gradual rise in <u>temperatures</u>, up 3.1 °C by 2080. Mild increase in <u>rainfall</u> until 2050, beyond which rainfall declines. Little change in <u>runoff</u> until the 2030s, followed by a large increase by the 2050s, then decline below current levels. A modest increase in <u>recharge</u> until about 2050, followed by a decline reaching about 12% by 2080. Little change in <u>ET</u>.	Under this scenario, conditions for agriculture show little change, although the rising temperatures and the increase in water availability from runoff and recharge up to mid-century may have a mildly favorable impact on yields. Thereafter, the higher temperatures and decline in water availability will have a negative impact.
Hot & Dry	Larger increase in <u>temperatures</u>, reaching 4.5 °C by 2080. Substantial drop in <u>rainfall</u>, down by 24% by 2080. A large drop in <u>runoff</u>, of one half or more. <u>Recharge</u> rates decline by more than a half by 2080. <u>ET</u> declines steadily as aridity increases.	The combination of higher temperatures with less rainfall, runoff and recharge will increase the aridity of growing conditions and have an increasingly negative impact on yields.
Warm &	Moderate rise in <u>temperatures</u>, up 1.6 °C by 2080. <u>Rainfall</u> up 25% by 2030, then tapering	The modest temperature rises accompanied by a significant increase in rainfall, runoff and recharge

Wet	off. A doubling off runoff through most of the century, reducing somewhat in the second half. Recharge up by 50% by 2030, tapering off by 2080. ET well up, although dropping back a little after 2030.	will have a favorable impact on yields, declining somewhat after 2030.

Summary analysis of impacts by governorate

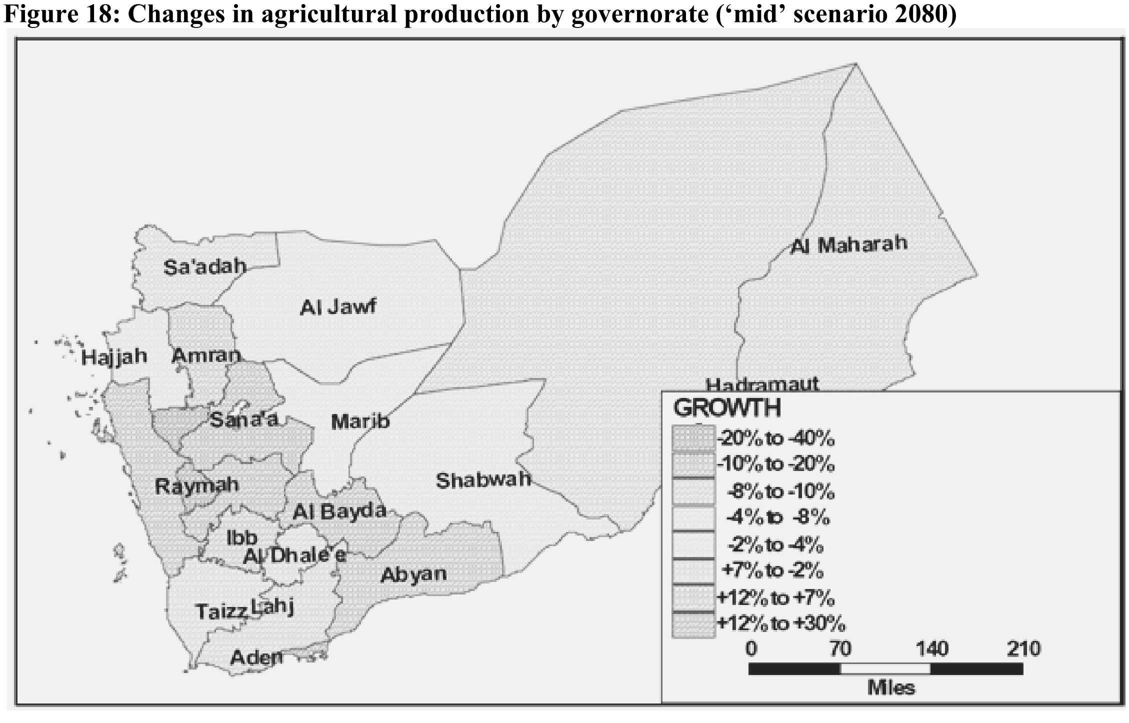
Governorate level analysis shows an even more varied picture, with the highlands generally benefitting from the warmer temperatures but lowland areas suffering where aridity increases.

Phase II of the study also calculated the expected response to climate change by governorate. Figure 18 below shows the geographical variation in change in agricultural production for the 'mid' scenario by 2080, under which national average temperatures would be up by 3.1%, rainfall would have dropped slightly (-3%), and runoff and recharge would also be down (22% and 12% respectively).

The analysis shows a mixed pattern, with production increases in the highlands (from Sa'adah to Taiz) benefitting from the somewhat warmer temperatures. Significant reductions would take place in some of the lower and hotter areas.

The pattern for this scenario is relatively clear, but the processes are complex and other scenarios show more mixed patterns, as a result of the net impact of both the hydrology projections (and especially the impact on groundwater) and the different relative impact of water at different temperatures.

Figure 18: Changes in agricultural production by governorate ('mid' scenario 2080)



Impacts by crop group

'Warm and wet' on the whole has beneficial impacts on crop groups, except for vegetables and legumes – and qat does well under all scenarios due to rising temperatures. Phase II of the study also calculated expected impacts of climate

change on different groups of crops. The results (Table 11) show wide variations for the three scenarios in 2080. Qat appears particularly sensitive, especially to changes in temperature, which have the potential to increase production substantially, because the crop is grown mainly in the highlands, where modest increases in temperature will generate increased yields. Surprisingly, sorghum appears to be more sensitive to climate change than other cereals. Legumes decline in all scenarios, as a result of the increase in temperature.

Table 11: Impacts on yields by crop group 2080

Crop	Mid	Hot & Dry	Warm & Wet
Sorghum	2%	-11%	15%
Other cereals	2%	-9%	13%
Vegetables	2%	1%	-2%
Fruit	-2%	-14%	8%
Legumes	-4%	-7%	-15%
Qat	71%	51%	77%
Other	-4%	-21%	14%

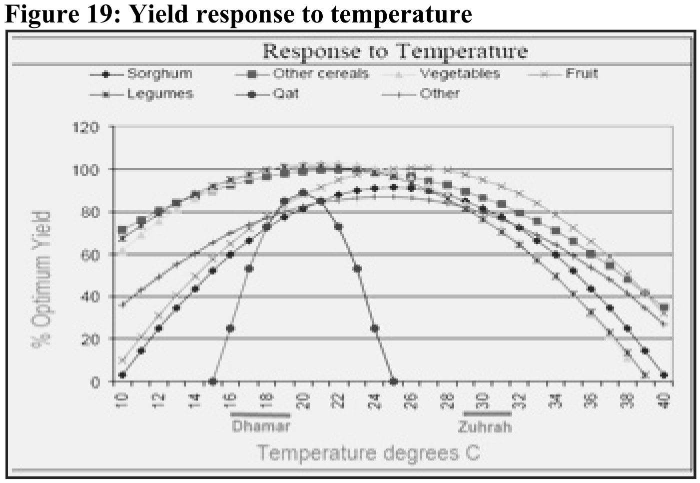
Source: HR Wallingford

B. Possible impacts of the most likely climate change and variability factors

Effect of higher temperatures

The most consistent projection throughout all scenarios is that temperatures will rise, by between 1°C and 4.5°C by 2100, and this could bring benefits to Yemeni agriculture. As pointed out above (Section A), the response to temperature varies between crops, and may be negative for crops like wheat which are less adapted to hot conditions. Figure 19 shows that most of the crops grown in Yemen achieve optimum yields between 18°C and 24°C and yields decline significantly above about 25°C. Certain crops, such as sorghum and tropical fruits, achieve optimum yields at higher temperatures, in the range 24°C- 28°C. Warming alone, independent of other factors, could be beneficial for most crops: as mentioned above, on a weighted national average basis an increase in temperature of 10% (e.g. from 20°C to 22°C) could increase crop production by 1.4%. There would be scope – and need – for switches in cropping patterns as warming proceeds.

Figure 19: Yield response to temperature



Effects of concentration of rain events

Rainfall may be more concentrated within years, reducing ET and – potentially – crop growth. An increase in the concentration of rain (i.e. a reduction in rainy days and an increase in the amount of rain each rainy day) has a number of different effects on the hydrology model but tends to lead to higher levels of runoff and recharge and lower levels of ET. Normally, reduced ET means lower plant growth and lower yields. According to the hydrology model, the impact of concentrating rainfall into 20% fewer rainy days varies considerably from one catchment to another, but the average reduction in ET is about 13%.

.....unless increased runoff and recharge are converted into crop water availability through irrigation. The increase in runoff under the example would be substantial, amounting to 77%, and the increase in recharge would also be substantial, at 15%. The reduction in ET and yield could be compensated if increased irrigation investment was made to utilise the increased runoff and recharge, and hence restore

higher levels of ET. Thus, although increased concentration of rain events means less productive rainfed agriculture, more water could be available for irrigation.

Effects of rainfall variability and length of growing season

Rainfed production could be negatively affected by less predictable rainfall. Evidence in Yemen suggests that the combination of rainfall predictability and length of the growing season is critical to crop yields, especially in rainfed agriculture. In the highlands of Yemen, the growing season is tightly constrained by the drop in temperatures during the autumn. If rains are late at the start of the season and planting is delayed, crops may fail to mature, with severe impact on yields. With the likely more unpredictable rainfall under climate change, rainfed production could be affected.

However, an increase in average temperatures under climate change may partly offset this impact by extending the growing season. This would make a major contribution to compensating for the less predictable dates of rainfall at the start of the growing season.

Effect of variation between years

Yemen's rainfall has always been variable between years, and farmers have coping strategies such as irrigation with groundwater. Yemen has a high degree of variability of rainfall between years which has a major impact on farm strategies, crop production and food security. The overall impact on Yemen as a whole is reduced by the fact that there is a good level of regional diversity in rainfall, so that all regions of the country do not suffer equally from dry years. Nonetheless, farmers have had to develop a range of coping strategies - one of the main drivers of increased and unsustainable groundwater use is to reduce the impact of this inter-annual variability.

Even if inter-annual variation is predicted to increase due to climate change impacts, existing strategies still remain relevant. From this preliminary analysis, the available evidence on climate indicates that inter-annual variability of rainfall will continue to be high, but shows no evidence that it will increase, which may be a reflection of the weakness of the methodology adopted in the study than the actual characterization of future climate. Recourse to groundwater will, of course, be more limited, and a more tactical approach will be required, but this is common to all possible futures, not just to climate change scenarios.

C. Economic impacts

Impacts on the macro economy and on poverty

The rural economy and the Yemeni economy overall are sensitive to changes in agricultural output and incomes caused by climate change. Agricultural incomes play a vital role in poverty reduction and in keeping the rural economy alive. As agriculture also plays a large role in Yemen's overall economy, there would be considerable multiplier effects throughout the economy from changes in agricultural output. This suggests that, although more detailed analysis would be required to understand the aggregate economic impact, the wider economy is relatively sensitive to changes in agriculture production caused by climate change.[21]

[21] To assess the full impact of climate change on the rural economy requires an equilibrium analysis. A Computable General Equilibrium (CGE) model developed by IFPRI demonstrates the sensitivity of the Yemeni economy to shocks, such as the global food and energy crisis and the financial crisis. A similar analysis undertaken by IFPRI in

Food imports will go up, and prices will also rise. Independently of climate change, food prices in Yemen will increase over the long term, reflecting higher world prices, declining oil exports and a weakening exchange rate. As population increases, the share of food consumption supplied by Yemeni farmers is likely to decline and imports will increase, pushing up prices and with likely further negative pressures on the exchange rate.

Yemeni agriculture is unlikely to be able to respond to higher prices with significant output increases, and a pessimistic climate change scenario would increase both rural and urban poverty. Higher prices would increase incentives to domestic food production, but the capacity of agriculture to respond is limited, particularly with declining groundwater availability. Subsistence sorghum production would increase, but the proportion of the poor having to buy food would be likely to rise. A pessimistic climatic change scenario with no adaptation action would exaggerate price rises and food insecurity and would push several million people below the poverty line.

Other Potential Impacts—on range and livestock, and fisheries

There would also be climate change impacts, not measured here, on Yemen's important livestock and fisheries economy. The livestock sector in Yemen is a very important part of agriculture and plays a critical role in food security strategies, especially as it provides a reserve that can be converted into cash in bad times. Substantial formal and informal exports to Saudi Arabia provide an important source of income. Climate change is likely to have a major impact on the productivity of extensive pasture and on nomadic livestock patterns. In particular, if there is a combination of warming and drying, there are risks that desiccation and overgrazing of the most extensive grazing areas will accelerate the trend towards desertification. If the carrying capacity of rangelands dwindles, there may be increasing pressure on irrigated fodder, which would place under threat the whole stratified market system for small ruminants, which is the most profitable part of the Yemeni livestock economy. Finally, changing temperatures are likely to reduce livestock productivity by increasing disease burdens. Analysis of the impact of climate change on this system was not included in the scope of work of the present study – it requires a dedicated study to reflect the complexity of the system (see Chapter 7B below). Similarly, the rise in the sea level and deterioration of the coastal ecosystem as a result will lead to a poor fisheries sector.

D. Key points for strategic responses

Overall, a number of key points can be drawn from the analysis which may help define strategic responses to be discussed in the next chapter:

- Agricultural production is <u>sensitive to climate change</u>, although the direction of change is unpredictable. Under the 'warm & wet' (optimistic) scenario, crop production could increase by more than 10%, whilst under the 'hot & dry' (pessimistic) scenario, production could go down by at least 10% (and even by a quarter towards the end of the century).

- There are <u>significant differences in the response of different crops</u> to changes in temperature and water availability, and these allow scope for farmer coping strategies.

Zambia (IFPRI 2009b), showed that a change in rainfall of 15% would lead to a change in crop production of between 3% and 6%, with GDP changing by between 1.4% and 2.0%.

- <u>Some areas of Yemen are more adversely affected than others</u>, pointing to areas of comparative advantage, and areas where adaptation measures are more likely to be needed.

- <u>Increasing temperature could assist crop production in some areas</u>, particularly the cooler highland areas where increased precipitation, run off and recharge make water more available, and where the growing season may be extended.

- By contrast, <u>where temperatures are significantly higher and precipitation significantly lower</u>, ET would increase but runoff and recharge would reduce and the net effect of higher temperatures on production would be negative.

- <u>Unpredictability is likely to increase</u>, suggesting that more tactical use of dwindling groundwater for supplementary irrigation could be a useful strategy to cope with dry spells.

However, the main constraint to agriculture will be reduction in groundwater availability caused by over-extraction. Note that the points listed above refer only to the possible impacts of climate change, and do not take account of the certain depletion of groundwater resources which, as mentioned above (Chapter 4B), could reduce production by more than 40% by 2030.

PART III: ADAPTING TO CLIMATE CHANGE AND VARIABILITY

Chapter 7: Adaptation to Climate Change and Variability in Yemen

- Climate change and variability will add to other natural resource challenges, to create a need for a wide range of adaptive measures. Most of these measures will be needed in any case, particularly in the context of dwindling groundwater.

A. Farmer responses to climate change and variability

Need for adaptation strategies

It is certain that in the coming years, farmers will have to adapt to growing water scarcity. Most of this scarcity is inevitable, as it is being induced by the current and apparently unstoppable rate of depletion of Yemen's remaining groundwater reserves. Climate change and variability may also affect this scarcity, and will also bring warmer temperatures and changes in rainfall patterns and intensity. Recharge and runoff rates will change. All these changes, whether climate-change induced or not, will pose challenges and opportunities to which farmers will have to adapt.

Farmers will seek out and adopt a range of adaptive measures, and public support and market development can help increase the range and facilitate implementation. This section examines a range of likely farmer responses to climate change and variability impacts. The range discussed is not exhaustive: it is intended to highlight most of the adaptive measures that are likely to be needed as climate change and other similar effects confront agriculture. The implications for public policy are then discussed in Section 'B'.

Farmer adaptations in agriculture

<u>The most likely single climate change feature is warmer temperature, which in the highlands at least could improve yields. Farmers may change their cropping calendar to take advantage of a longer growing season, and are likely to manage risks with more drought tolerant varieties and (where available) supplementary irrigation.</u>

Warmer temperatures may allow farmers to achieve optimum yields with their current cropping pattern, for example in the highlands, provided that water stress can be minimized. Warmer temperatures may allow a longer growing season, and farmers may <u>change their cropping calendar</u> with beneficial impact on yields. Average monthly temperatures in the highlands in the autumn normally fall by about 1.3ºC per month, so an increase in average temperatures of 2ºC could be expected to extend the growing season by about six weeks. Where water stress is a risk, farmers may seek to introduce <u>more drought tolerant varieties</u> or use <u>supplementary irrigation</u>. In lowland areas, if temperatures are significantly higher and precipitations are significantly lower, yields would be vulnerable. Farmers who have access to irrigation water may maintain their production, or they may have to switch their cropping pattern.

Increasing unpredictability of rainfall suggests farmers may adapt by using supplementary irrigation, growing drought tolerant or shorter cycle crops, or lengthening the growing season.

Unpredictable rainfall may translate into delayed planting, with negative impact on yields. As discussed above (Section 6B), if planting is delayed by more than a few weeks, crops may fail to mature. There may be crop failure or reduced yields. In addition, unpredictable rainfall may lead to drought spells during the growing season, contributing to yield losses.

Farmers are likely to use more supplementary irrigation and drought-tolerant or shorter cycle crops, or change their cropping calendar. The impact of delayed rains could be partly offset by using groundwater early in the season, by growing shorter cycle crops or varieties, or by taking advantage of warmer average temperatures to extend the growing season into the autumn, especially where supplementary irrigation is available. Where the rains are late, farmers may use supplementary groundwater irrigation during the planting period to prepare the land and ensure germination despite uncertainties in rainfall. They may also switch to fast growing crops, such as maize, that can be planted later. Where crops encounter stress in dry periods after planting, farmers may seek to plant drought-tolerant varieties. They may also take advantage of the expected increase in average temperatures to change their cropping calendar, extending the growing season. This would make a major contribution to compensating for the less predictable dates of rainfall at the start of the growing season (see Box 6).

Box 6: In Dhamar, possible changes in temperature and the timing of rainfall suggest adaptation strategies

In Dhamar at present, the temperature in September and October declines by about 1 °C per month. All scenarios suggest progressive warming, and as a result, the growing season in Dhamar could be extended by several months. This could mean that the growing season for most crops in Dhamar in the future would be limited more by the lack of rainfall from September onwards than by the decline in temperature.

At the same time, the expected increasing tendency to lower rainfall at the beginning of the growing season (i.e. in April and May) is likely to challenge farmers with respect to land preparation and seed germination.

Farmers are likely to adapt by using supplementary irrigation and by switching to late planting varieties to overcome uncertainties in rainfall and to extend the growing season by several weeks. There may also be potential for switching to fast growing crops, such as maize, that can be planted later.

Source: HR Wallingford

Concentration of rain events suggests farmers would seek more surface irrigation, water harvesting and supplementary groundwater irrigation

Concentration of rain events reduces water available in the soil and therefore reduces ET and plant growth – but it also increases runoff and surface water availability. As discussed above (Section 6B), the likely growing concentration of rain events is likely to reduce the productivity of rainfed agriculture but may increase the availability of water for irrigation.

Farmers are likely to seek to develop more surface irrigation and water harvesting infrastructure to capture the increased runoff, and more use of supplementary groundwater irrigation to bridge the gap between unpredictable rainfall events. The volumes of water involved in increased runoff and recharge are larger than those lost from crop ET. It is therefore possible that, if sufficient investment in surface irrigation and water harvesting infrastructure takes place, the impact of reduced crop ET from increased concentration of rain events could be more than offset by the increase in water from irrigation. The ability to use supplementary groundwater irrigation during dry periods would be particularly important.

Declining groundwater availability may cause farmers to return to traditional agricultural and water harvesting techniques

Yemeni agriculture adapted with extraordinary rapidity to the tubewell, and the groundwater boom of the last three decades has changed agriculture from largely subsistence farming to a market-oriented activity. As groundwater reserves run down, adaptation options will be essential whatever the climate change outcome. Improvements to the productivity and profitability of traditional rainfed and terrace cultivation and of water harvesting schemes may offer some possibilities, although the economics of traditional agriculture are negatively affected by high wage rates, the decline of collective action at the local level, and the low productivity of rainfed systems.

Changes in water availability and temperature may encourage farmers to switch to better adapted cropping patterns

If water availability and temperature during the growing season change, crop yields will change. Farmers may then switch to better adapted crops to help alleviate the effects of climate change. A first level of response could be to switch between crops with differing responses to climate change within an agro-ecologically homogeneous 'crop group' – for example, switching between faba beans and lentils within the legume crop group. Phase II of this study calculated that switching between crops within crop groups could reduce the impact of climate change by up to 25%. Alternatively, farmers might switch to a different crop group. Box 7 illustrates the possible yield and production response.

Box 7: Farmer coping strategies may include switching from one crop group to another[22]

The impact of switching between crop groups can be estimated by analysing the different response of the crop groups. In areas where water availability is 300 mm, a 1% change in water use generates a 0.51% change in sorghum yield, a 0.88% change in the yield of other cereals, 0.85% change in vegetable yields and 0.34% change in fruit yields.

Thus, in the 'warm and wet scenario', if water available to the crop roots increased by 20%, switching 10% of land from sorghum to other cereals or vegetables would increase crop production by 15%, whereas production would go up by only 9% if the farmer stayed in sorghum. If markets for cash crops are available, crop value would go up by much more, as the farmer could be moving into higher value crops.

In the 'hot and dry scenario', if water available to the crop roots fell by 20%, the opposite switch would reduce the fall in crop production from 13% to 8%, but the value would drop more, given the low value of sorghum.

Source: HR Wallingford

Declining water availability and unpredictable rainfall may sharpen the need for efficient groundwater and surface irrigation, especially supplementary irrigation.

A likely response to dwindling groundwater is for farmers to improve the productivity of water use through more efficient groundwater and surface irrigation, especially supplementary irrigation.

A conventional gravity-fed small scale irrigation system is typically 35-45% efficient. Depending on the layout of fields and the types of crops, about 15% of water is lost whilst being conveyed to the fields and

[22] The assumption here is that farmers make well informed and rational decisions about the crops they grow and the way in which they grow them (based on, among other considerations, the margins to be obtained, market volatility, risks to crop failure and the need for staple food). Therefore, farmers will respond by favoring those crops that have the most advantageous yield response to climate change (i.e. favoring responsive crops, if climate change is favorable and unresponsive crops, if it is not favorable).

another 20% is lost in application on the field. Removing these losses through piped conveyance and through drip, bubble and sprinkler irrigation can bring an irrigation system up to 70-80% efficiency.

Yemen has encouraged the use of plastic pipes (PVC and PE) for conveying water from the wellhead and for distribution within the farm. GSCP, for example, has successfully worked with farmers on the design and installation of both conveyance and distribution pipe networks. Box 8 illustrates the financial profitability of this for farmers, even without subsidy. Attempts to promote drip and bubbler and protected agriculture under plastic houses have been less successful.

Box 8: As groundwater becomes scarcer, modern irrigation is a profitable investment for farmers – even at market prices

In Yemen today, pipes for water conveyance cost about YR 160,000/ha ($800/ha) and increase water availability to plants by about 20%. Drip irrigation systems costs about YR 600,000/ha ($3,000/ha) and increase water availability by a further 35%. For wheat, average yields are about 1.5t/ha, and prices are YR130/kg. The crop response curves for wheat suggest that, at normal levels of water application, a 1% percent increase in water results in a 0.9% increase in wheat yields. The table below presents this analysis and shows that, if wheat is grown, the payback period for piped conveyance is about three years and for drip irrigation the payback is about six years. The analysis is highly sensitive to assumptions about the response of wheat yields to increased water availability.

Returns to irrigation and water efficiency in Yemen

	Unit	No investment	Piped conveyance	Piped + drip
Water use	mm	300	300	300
Efficiency		40%	55%	75%
Water to plant	mm	120	165	225
Wheat yield	t/ha	1.5	1.9	2.6
Incremental value	YR ‘000s		49	92
Investment cost	YR ‘000s		160	600
Payback period	Years		3.3	6.5

Source: HR Wallingford: 39

The poor outlook for agricultural water, not only due to climate change, may increase the willingness of stakeholders to adopt an integrated approach to water resources management at national, basin and local levels.

One advantage of climate change analysis is that it focuses attention on the fact that water is part of a complete hydrological cycle in which each element reacts with all others, and human intervention makes decisive changes. This underlines the need for an integrated approach to water resources management at national, basin and local levels.

B. Adaptation options for the water and agriculture sectors, and policy implications

This section examines the policy and program implications of the responses to climate change discussed in Section ‘A’ above. Farmer responses and the implications for policy and programs are summarized in Table 12 below, and the implications are then discussed in detail. Farmer responses are grouped in five ‘adaptation options’: (1) Investment in efficient irrigation systems, and use of groundwater for supplementary irrigation; (2) Investment in improved knowledge base related to climate and water resources issues; (3) strengthening traditional agricultural and water harvesting techniques; (4) adapting farming practices, including changing cropping patterns, growing shorter cycle or later maturing varieties, changing the cropping calendar etc; and (5) adoption of integrated management of the water resource at all levels, including looking at water also as an economic good.

Table 12: Adaptation options and suggested measures

Adaptation options	Suggested measures
1. Investment in efficient ***irrigation*** systems, and use of groundwater for ***supplementary irrigation***	▪ Piped conveyance and distribution ▪ Improved spate irrigation and pressurized irrigation (drip, bubbler) ▪ Improved irrigation management, including market-based approach to irrigation efficiency ▪ Drought bridging through supplementary irrigation ▪ Wastewater reuse ▪ Incorporating flood preparedness into surface irrigation management
2. Investment in improved knowledge base related to climate and water resources issues	▪ Improved network of hydro-meteorological station ▪ Improved data collection and analyses, including robust data sharing among various agencies ▪ Early warning system and seasonal forecasting with long lead time, plus robust dissemination strategy ▪ Development of state-of-the-art tools in order to guide decision making
3. Strengthening traditional ***agricultural and water harvesting techniques***, and sustaining the ***livestock*** economy	▪ Promoting water harvesting, fog harvesting ▪ Terrace rehabilitation ▪ Promoting improved livestock and rangeland systems
4. Adapting farming practices: changing ***cropping patterns***, growing shorter cycle or later maturing ***varieties***, changing the ***cropping calendar*** etc	▪ Varietal research (on short cycle or drought tolerant varieties, high value low water using crops etc.) ▪ Farming systems research
5. Adoption of ***integrated management of the water resource*** at all levels	▪ Develop capacity for planning and regulation on a partnership basis ▪ Water resource evaluation and monitoring ▪ Incentive structure to encourage efficient and sustainable use ▪ Licensing, registration, regulation ▪ Promote basin level planning and management ▪ Support WUAs as the lowest building block of water resource management ▪ Watershed management in key catchments

Adaptation option 1. Investment in efficient irrigation systems, and use of groundwater for supplementary irrigation

Improving irrigation efficiency is an essential response to the inevitable decline in groundwater availability. The current groundwater crisis in Yemen will continue to develop irrespective of climate change. This is a priority area for action in both water resource management and agriculture. Helping Yemeni agriculture to adapt to the current overexploitation of groundwater resources would reduce farmer vulnerability and increase the country's capacity to adapt to climate change. Farmers are likely to adapt to growing water scarcity by investing more in irrigation efficiency. The expansion of markets and rise in prices should improve farm incentives to make investments in irrigation efficiency viable. Modern irrigation could increase water efficiency from 40% to 75% (Box 8 above), which is nearly sufficient to offset the impact of lower groundwater extraction at a sustainable level and of climate change, if applied nationwide. Part of the adaptation would be by improving the efficiency of irrigation through modern techniques, notably (a) improving and expanding spate irrigation; (b) piped conveyance and distribution, and pressurized irrigation (drip, bubbler); (c) improved irrigation management, including drought bridging through supplementary irrigation; (d) market-based approaches to irrigation efficiency; and (e) wastewater reuse.

Improvements in irrigation efficiency have to be made within a framework of integrated water resource management. Essentially, improving irrigation efficiency may have reduced impact on groundwater sustainability if water is not managed by collective action at the local level, supported on a partnership basis by basin committees, NWRA and MAI. The measures described in this section have to be combined with the measures for water resources management described under Adaptation Option 5 (a) below.

1(a) Improving and expanding spate irrigation

Increased rainfall variability brings the opportunity for more beneficial use of surface water in agriculture, and also the challenge of enhancing flood protection. Increased variability of rainfall is one of the most significant features of projected climate change in Yemen under all scenarios. With higher levels of runoff during intense rainfall events, there will be opportunities to increase the volume of water diverted for surface irrigation, and this volume would be greater still under the 'warm and wet' scenario. Where runoff is greater, particularly as a result of more violent rainfall events, there is also an increased risk of the kind of flood witnessed in Hadramawt in 2008, and hence a need to upgrade infrastructure for flood protection and diversion. In addition, the current proportion of spate flows that is beneficially used in agriculture is very small - about 5% - and this could possibly be increased by better infrastructure and technology.

Improving the efficiency of spate irrigation and extending the areas where it is practiced could form an important element of Yemen's adaptation to climate change. Yemeni experience under IIP, together with international experience,[23] suggests that this should initially concentrate on improvement to existing schemes, rather than new schemes. Investment in surface irrigation could be justified whatever the climate change outcomes in view of the fact that all climate change scenarios foresee an increased frequency of intense rainfall events.

Further development of spate irrigation should ensure an efficient and equitable balance between water uses and users. Investment in spate irrigation is a high priority measure, particularly for the Tehama and the south coast. Planning at the basin scale is required to ensure that the water resource is managed optimally. This should include technical and economic optimization to ensure the correct balance between use in the highlands, recharge of the coastal aquifers, diversion for spate irrigation, and environmental flows, particularly to manage saline intrusion, an increasing threat under climate change. Water resources planning should also take account of equity aspects, ensuring that water resources are shared equitably, and that new arrangements do not cause uncompensated losses to existing users, which has been a problem with past spate improvement.[24]

1(b) Piped conveyance and distribution, and pressurized irrigation

Using pipes can reduce conveyance and distribution losses. A main objective of existing irrigation policy is to reduce losses between the well and the plant roots by piped conveyance and on-farm distribution, so as to be able to reduce groundwater extraction without reducing crop production. Investment in drip irrigation is foreseen for the future, but is a lower priority, given the lower economic returns.

This option is an imperative under any scenario. If climate change tends towards the 'hot and dry' scenario, reduced water availability will make efficient water use ever more essential. A 'warm and wet' tendency would make more annual recharge available that could be beneficially used as groundwater reserves are depleted. Under all scenarios, the increased variability of rainfall and the gradual warming will increase the priority of improved irrigation efficiency, as more irrigation will be required.

[23] Lawrence and Van Steenbergen 2005
[24] Note that this measure corresponds to NAPA Project # 2.3 (see Table 1).

The investment required over the next 15-20 years could be very large if agriculture is not to shrink dramatically. Phase II of this study speculated that installing conveyance pipes and drip irrigation in all irrigated land in Yemen would in theory allow Yemeni farmers to live from the annual recharge, and that the investment cost to the nation could be as much as $ 5 billion, spread over the 15-20 years before groundwater resources are exhausted (i.e. an annual investment of up to $250 million).[25]

1(c) Improved irrigation management, including drought bridging through supplementary irrigation

As a complement to investment in physical measures there is a range of management measures available to improve water use efficiency. These include: improved on-farm water management (e.g. methods of saving water during distribution to the plant roots, irrigation scheduling, etc); and crop management (e.g. choice of drought tolerant varieties, varying the cropping calendar, and zero tillage).

One vital measure is to generalize the use of intermittent irrigation as a supplement to rain or other water sources. As qat farmers have convincingly shown, a "just in time" application of supplementary irrigation makes all the difference. The climate change study suggests that priority should be given to measures that build on existing experience in the GSCP, concentrating more on using groundwater conjunctively with rainfed cultivation and with rainwater harvesting and soil conservation measures. Conjunctive use of spate and groundwater resources is also a priority, as highlighted in a recent study of Wadi Ahwar in the Gulf of Aden basin (de Vries and Ghawana, 2009).

1(d) Promoting a market-based approach to irrigation efficiency

The current state subsidy to irrigation may not be efficient. Up to now, the state has subsidized investment in water conserving irrigation, notably through GSCP, which invests around $5 million per year in irrigation efficiency. The logic of the subsidized public programs is to increase incentives and to spread the most efficient technology, ensuring access for poorer farmers who would not otherwise have the resources to invest. However, there is little evidence that this subsidy achieves its equity goal, and the existence of subsidized programs may crowd out private sector initiative (see Box 9 below).

Water use efficiency is likely to become a profitable investment as scarcity grows. Studies such as the 'Groundwater Incentives Study' suggest that investment in irrigation efficiency should be profitable in Yemen (see also Annex 4). There are no reliable estimates for the level of ongoing private investment in irrigation efficiency, but certainly, Yemeni farmers regularly invest in piped conveyance without subsidy. There is certainly scope to promote – or simply allow - the development of private markets.

One aspect of this is to level the playing field for private markets to develop. There is good experience internationally with development of commercial markets for irrigation efficiency equipment, including local manufacturing of irrigation equipment such as pipes and filters. In India, for example, the approach has released considerable energy, bringing costs down and generating considerable business activity (see Box 9 below). Some manufacturing of conveyance equipment is already taking place in Yemen and prices are reported to be cheaper than imports. Relatively small reductions in cost will make a substantial impact on the viability of improved irrigation and the speed with which is adopted. This justifies some public support, although it is important that this is done in a manner that encourages competition, growth

[25] The study speculated that increasing water efficiency nationwide to 55% through improved water conveyance would cost about YR 200 bn ($1 billion), and increasing to 75% efficiency through more expensive drip systems would cost a further YR 800 bn $4 billion). Note that this measure corresponds to NAPA Project # 2.1 (see Table 1).

and innovation. When established, the manufacturers of improved irrigation equipment will become a major force for promoting uptake.[26]

1(e) Wastewater reuse

There may be niche opportunities for wastewater reuse in agriculture. In water scarce countries, wastewater can represent a valuable resource. Although in Yemen volumes of treated wastewater are likely to remain small, there are, nonetheless, some niche opportunities for using wastewater in high value crops cultivated close to urban centres, and for encouraging urban households to cultivate small plots using their own wastewater. The year-round nature of this water supply would be particularly important to counter the impact of greater rainfall variability, especially for crops that are intolerant of dry spells.[27]

Box 9: Irrigation efficiency subsidies slow adoption of drip technology

Drip and sprinkler technologies have been aggressively promoted in India since the mid-1980s; yet, by 2002, the area using them was only 60,000 ha. A big part of the problem was subsidies that, instead of stimulating the adoption of these technologies, actually stifled the market. Subsidies had been directed at branded, quality-assured systems, but in the process had not allowed viable, market-based solutions to mature.

Subsidies were channelled through the big irrigation equipment companies. Their equipment typically cost $1,750/ha, which put it out of the reach of most farmers – except the few who could access the subsidy programs.

Fortunately a grey market of unbranded products began to offer drip systems at $350/ha. Then, one innovative manufacturer introduced a new product labelled 'Pepsi' – basically a disposable drip irrigation system consisting of a lateral with holes. At $90/ha, Pepsi cost a fraction of the price of all other systems.

Source: DID 2006 from van Steenbergen 2002

Adaptation option 2. You cannot manage what you do not know —Investment in improved knowledge base related to climate and water resources issues

Given the uncertainty associated with climate models for the region and poor historical records of climate related data, Yemen should develop a capacity for seasonal forecasting and early warning with a long lead time and a robust dissemination strategy to make the information readily available to users. Seasonal forecasting and early warning systems are improving rapidly in many countries. In Yemen, similar work could be undertaken. The system would have to operate in conjunction with measures for increased data collection and sharing (see below), in order to have access to suitable data for the calibration, validation and testing of any forecasting models. If successful, it could be valuable to link such work with wider work on farm advisory services and, in particular, plans for community management of water resources.

1(a) The collection and sharing of hydro-meteorological data and other socio-economic data (see Figure 20) needs to be improved and better coordinated. The climate observation network has improved significantly in recent years but data and information on spate flows, groundwater levels and rates of abstraction are poor, making any estimates of future water availability highly uncertain. It is essential to develop an improved observation network so that, over time, trends in temperature, rainfall, runoff, recharge and groundwater can be detected. Much greater effort is required in the development of catchment information systems in order that accurate water balances can be developed. A further constraint has been lack of access to the data that does exist, as a result of a weak institutional culture

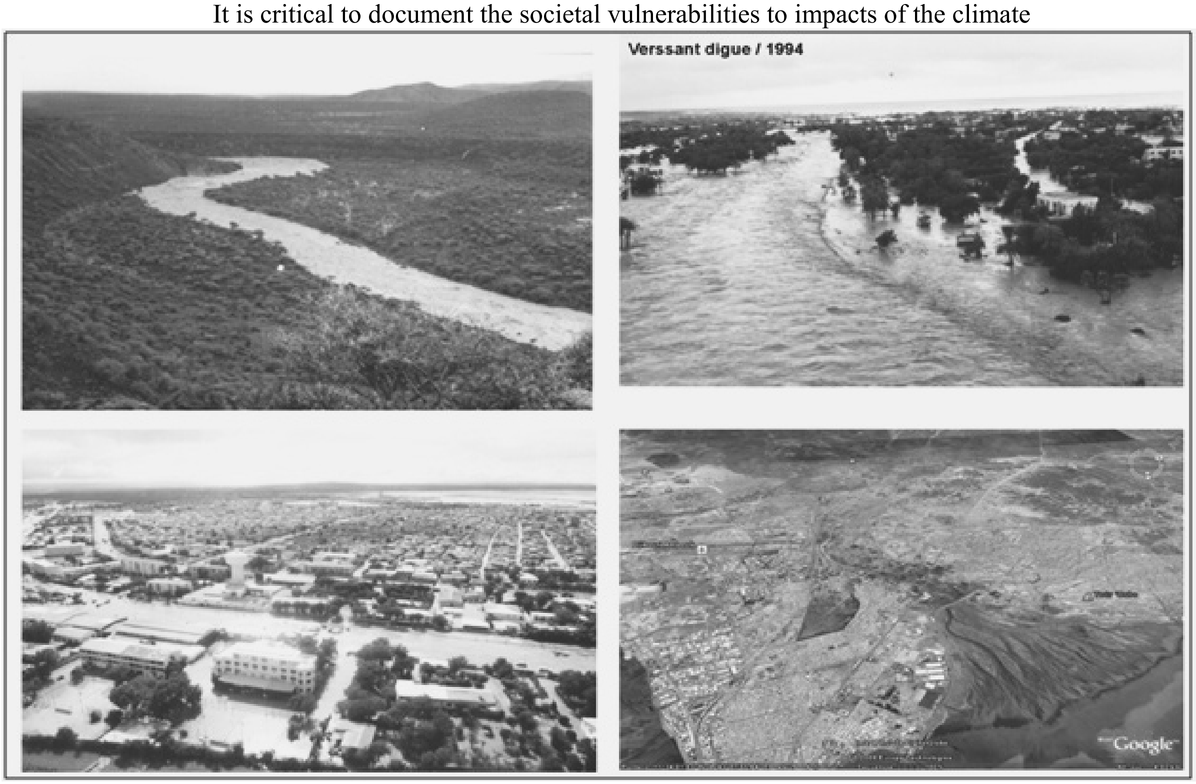
[26] Note that this measure corresponds to NAPA Project # 2.4 (see Table 1).
[27] Note that this measure corresponds to NAPA Project # 2.5 (see Table 1).

regarding sharing. Uncoordinated, multi-agency responsibility for meteorological and hydrological data collection and dissemination represents a significant impediment to national climate risk assessment and reporting. Institutional reforms are urgently required to improve access to data. Lessons could be learned from the success of the Central Statistical Office in promoting a more open attitude to data. Action to establish and maintain a database of climate change and adaptation is included in the NAPA (*Project # 4*, see Table 1).[28]

1(b) Strengthening capacity for early warning system and seasonal forecasting with long lead time— given the uncertainty associated with global and regional climate change models for the region where Yemen is part of, and with recent developments in weather forecasting using state-of-the art tools, Yemen is better off developing its capacity in seasonal forecasting and efficient early warning system to reach the user community. Development and use of tools to aid decision making is also another potential option of adaptation.

1(c) Improved public awareness and involvement will be an essential part of future adaptation programs in both urban and rural areas, and a robust dissemination strategy is essential. As the adaptation strategies for dealing with climate change in the water and agriculture sectors are likely to be very close to existing strategies for water management, the climate change message is an invaluable "entry point" to increasing awareness and engaging participation in integrated water resource management and agricultural water programs. The climate change message should, however, be 'mainstreamed' into the larger messages on IWRM, water saving, water use efficiency etc.

It is critical to document the societal vulnerabilities to impacts of the climate



[28] These measures will need to be coordinated with those under Yemen's National Disaster Risk Management Strategy prepared under GFDRR financing which is strengthening Yemen's institutional capacity for disaster risk assessment and risk reduction, and supporting a national civil works program to reduce the risks of flooding.

Adaptation option 3. Strengthening traditional agricultural and water harvesting techniques, and sustaining the livestock economy

If rainfed systems are to be a fall back as groundwater dwindles, then productivity needs to be improved. As the scope for irrigation dwindles, and demographic pressure on the rural economy increases, high productivity rainfed systems might be a recourse for farmers with limited alternatives. Government has been exploring options for reviving rainfed systems and improving their productivity, including through the ongoing IDA-funded Rainfed Agriculture and Livestock Project (RALP). Currently, as part of its evaluation of the potential impacts of climate change on sector policies, Government is reviewing adaptation options for rain-fed areas. Possible measures under this agenda include implementation of integrated watershed management such as (a) promoting water harvesting; (b) terrace rehabilitation; and (c) promoting improved livestock and rangeland systems.

3 (a) Maximizing the use of rainwater through water harvesting techniques

A variety of water harvesting technologies have long been practiced in Yemen. Water harvesting techniques have been practiced in Yemen since time immemorial (see Figure 21). The most common practice was 'run off run on', under which 'run off' rights were assigned from specific slopes to parcels of bottom land in a proportion – sometimes up to twenty times the area of bottomland – adequate to grow a crop on the 'run on' land. A second technique is the use of small check dams and retention structures which have been constructed in the highlands since earliest times. Recent promotion of such dams under the Agriculture and Fisheries Production and Promotion Fund (AFPPF) has been problematic, but small dams have played a successful part in improving water availability and promoting recharge in the Sana'a basin under SBWMP. Tanks and cisterns also have a very ancient pedigree and exist throughout the highlands. They are generally, however, used for human and animal drinking rather than for agriculture.

Revival of water harvesting could improve the productivity of rainfed cultivation. These traditional techniques of water harvesting have been neglected during the recent years of easy groundwater pumping. A program to revitalise these practices could include both technical support, including design and management improvements (see Rappold 2005), and some financial support to stimulate private and community investment. The objective would be to increase water availability in the soil profile or for local irrigation, and to increase recharge to groundwater. One form of water harvesting – fog harvesting – has been successfully piloted for domestic supply in the Hajjah area, and could be scaled up, as has been successfully carried out in similar climatic conditions in Latin America.

3 (b) Terrace rehabilitation

Terraces serve multiple productive and environmental functions--The traditional Yemeni terrace system allows the retention of enough water in the soil profile to grow a rainfed crop in low rainfall areas. It also reduces erosion due to unchecked runoff on steeper slopes, and improves recharge. Terraces also have an enormous landscape and amenity value. Under climate change, these functions could take on increasing importance.

.....but have been crowded out by cheap irrigation. For two decades, marginal terraces have been falling into disuse, as they could not compete economically with subsidized irrigated agriculture, despite their important role in a subsistence economy. Planners have long tried to devise a mechanism to help restore terrace systems to their old vitality, if only as part of larger watershed management schemes.

Traditional water harvesting methods in Yemen

Photo: Ahmed Al-Kalisi

With the dwindling of groundwater, terraces could be a recourse for farmers, although they would probably need technical and financial support. Some experience already exists with terrace rehabilitation in the RALP project, and an ongoing study under RALP is specifically addressing the revival of terrace agriculture in the context of climate change. Although a host of social, land tenure, technical and economic constraints have been identified, there may be scope to support revival of terraces, although with a cost of about 25 $/m of terrace rehabilitated, the investment costs for 1 ha of about $5,000 are very high. However, there is a public interest both in the environmental and the amenity functions of terraces that justifies at least partial subsidy.

3 (c) Livestock and rangeland systems

A policy and program response is needed to sustain Yemen's complex livestock and rangelands systems under climate change. As discussed in Chapter 6C above, the livestock issue lies outside the scope of the present study. It is clear, at least, that further study is required to determine how recent experience in livestock support programs can be adapted to deal with the issues.[29]

Adaptation option 4. Adapting farming practices

Adapting farming practices requires targeted research and dissemination. Adapting farming practices is the simplest and lowest cost adaptation measure, but it depends on the availability and dissemination of profitable and feasible technical solutions. The capacity of Yemen's research and extension is limited,

[29] Note that this measure corresponds to NAPA Project # 10.2 (see Table 1).

but recent experience under IDA-funded projects, including GSCP, IIP and RALP, has been constructive. Many of the adaptive measures discussed in this chapter would benefit from targeted research and dissemination. In addition, there is scope for improving services to farmers across the board, including improved access to agricultural inputs, extension, and integrated pest and nutrient management practices.

Research is needed on drought-tolerant, disease resistant and short-maturity crops and varieties. Increased drought tolerance will have a significant impact in some areas, where crops are being grown above their optimum temperatures. For example, wheat typically provides incomes that are between 10% and 50% higher than sorghum, depending on water availability. Extending the temperatures at which a healthy wheat crop can be grown by 1°C would allow perhaps 20,000 ha more wheat to be grown in place of sorghum, with an increase in crop value of as much as YR 500m. Breeding for tolerance to higher temperatures and short dry spells is thus going to be vital under all climate change scenarios. AREA is already engaged in this work and is exchanging experience with neighbouring countries. This work should receive accelerated support, in the light of climate change. Improving crop resistance to diseases that are prevalent at higher temperatures is also important area for research.[30] Although delays in planting due to unpredictable late rains at the start of the season may be compensated for by a longer growing season permitted by warming, there is also scope for research on short maturing crops and varieties.

One possibility is to investigate whether an entire new product chain could be adapted to Yemen's changing agro-ecological conditions and farming systems. There is some ongoing research into the possibility of expanding the cultivation of high value, low water crops, such as almonds. The development of an 'almond chain' would require not only that production fit into farming systems, but that development of services and markets for inputs and outputs all the way down the chain to final export be developed. Recent attempts, for example, to convert farmers from qat to coffee have shown the need for this kind of integrated approach, including extension services, inputs, micro-finance, downstream processing and market development etc. However, such innovations are likely to provide only limited 'niche' opportunities, and market development would be a challenge, particularly where the market is thin.[31]

Adaptation option 5. Adoption of integrated management of the water resource at all levels

Under scarcity, integrated natural resource management becomes increasingly important. As discussed in Section A above, growing scarcity underlines the need for an integrated approach to water resources management at national level, basin level, and local level. In addition, under climate change there is an increased need for integrating management of land resources with that of water. Priority measures under this agenda are therefore to (a) develop integrated water resource management; (b) promote watershed management approaches in key vulnerable catchments; and (c) pilot and scale up.

5 (a) Integrated water resource management (IWRM)

Yemen is trying an integrated approach to water resource management on a decentralized and partnership basis. Over the last ten years, Yemen has initiated an integrated approach to water resources management in line with the 'Dublin Principles'. This 'IWRM' approach is incorporated in the 2003 water law. Reflecting the virtual impossibility in Yemen of imposing regulation from the top on rural water users, the approach is grounded in decentralization, partnership and stakeholder participation at the national, basin and local levels.

[30] Note that this measure corresponds to NAPA Project # 9.1 (see Table 1).
[31] Note that this measure corresponds to NAPA Projects # 2.6 and 9.2 (see Table 1).

At the national level, the priorities are to develop the knowledge base and to adjust the incentive structure to encourage efficient and sustainable water use. Water management requires efforts to develop the knowledge base through water resources evaluations and studies to quantify the resource, build a picture of the water balance and monitor developments. One key topic where good data collection could drive the policy agenda is on qat. Most importantly, water management requires a conducive incentive framework. Although centralized management of water resources is quite difficult in the Yemeni context, Government can adjust or at least influence the incentive framework (in the broad sense of all factors affecting individual and community water management behavior). The Yemeni Government has the power – and some track record - to:

- directly influence farmer behavior through its control of the energy price, affect behavior through subsidies and public investment, and indirectly affect agricultural prices and incentives through trade policy.
- support the development of institutional frameworks such as water user associations and basin committees, that decentralize power to water users, and so motivate responsible behavior.
- conduct limited regulatory activities and develop measures to recognize and protect water rights, particularly when conducted in partnership with water users.
- align economic and financial values of water and facilitate transfer of water to its highest value uses through encouraging the development of equitable and sustainable water market exchanges

At the basin level, the priority is to develop basin management plans that are adapted to water resources, uses and challenges in each basin. Authority and resources to implement the plans can be delegated to basin committees and water user associations. Basin committees can include local agencies of agriculture and water supply, local authorities and stakeholder representatives.

At the local level, water user associations can be the lowest building block of IWRM. The essence is a partnership approach between NWRA, MAI and stakeholders, particularly farmers. Key issues are the quantification and characterization of local groundwater resources and 'rights' within comprehensive basin/watershed level water balance assessment, and the development of agreed management plans backed up by knowledge. The use of satellite imagery to monitor consumptive use could also be an invaluable tool. Box 10 gives an example of how WUAs might become the lowest building block of IWRM. Early results of the approach are modest, but under NWSSIP, WSSP and some agricultural programs it is gaining impetus. The successful bottom up approach to groundwater management in Uttar Pradesh in India provides an example of how this partnership approach might develop in Yemen. Extension of the approach to all parts of Yemen and at a basin scale is a high priority under any climate change scenario.[32]

Box 10: The Community Water Management Project (CWMP)

The objective of this pilot project was to test a replicable model for sustainable self-management of groundwater by water user associations (WUAs) that represent all water users in a discrete hydrological area. The project helped set up nine WUAs in three areas and gave them institutional support and capacity building so that they acquired skills in WUA management. The heart of the project was then for the WUAs and the project to work with NWRA and GSCP to define the water balance and to prepare and execute a **water management plan** targeting a specific "hydraulic goal" – effectively how the WUA would work towards reducing pumping to more sustainable levels whilst sustaining or improving incomes. Investment support from GSCP was made available so that water saving investments could be implemented under the water management plan. The project is complete and lessons are available. Continuation, capitalization and scaling up are needed.

[32] Note that this measure corresponds to NAPA Project # 2.2 (see Table 1).

Source: Authors

5 (b) Watershed management approaches in key vulnerable catchments

In catchments affected by water shortages and by erosion and poverty, a full watershed management approach may be appropriate. A key tool in managing water resources in poor areas with severe land and water resource depletion problems is the watershed management approach, which integrates management and use of land, vegetation and water in a catchment with the objective of protecting or conserving the hydrologic services which the watershed provides and of reducing or avoiding negative downstream or groundwater impacts (see Box 11). Attempts have been made in the past to introduce combined soil and water conservation approaches in Yemen, but there has been no program that has scaled this up to the level of an entire vulnerable catchment. A priority is to introduce watershed management approaches in catchments where there are notable water shortages, erosion and poverty.[33]

Box 11: Integrated participatory watershed management as part of the solution to climate change

Degradation of watersheds worldwide in recent decades has brought the long term reduction of the quantity and quality of land and water resources. Changes in watersheds may result from a range of natural and anthropogenic factors, including natural soil erosion, changes in farming systems, over-abstraction of water, over-grazing, deforestation and pollution. The combination of environmental costs and socio-economic impacts has prompted investment in watershed management in many developing countries. *Watershed management* is the integrated use of land, vegetation and water in a geographically discrete drainage area to protect or conserve the hydrologic services which the watershed provides and of reducing or avoiding negative downstream or groundwater impacts.

Key watershed characteristics driving management approaches are the need for integrated land and water management, the causal link between upstream land and water use and downstream impacts and externalities, the nexus in upland areas between resource depletion and poverty, and the multiplicity of stakeholders. Watershed management approaches need to be adapted to the local situation and to changes in resource use and climate.

From the 1990s, an *integrated and participatory watershed management approach* was adopted. While engineering solutions were not excluded where appropriate, the emphasis was placed more on farming systems and on participatory and demand driven approaches implemented at the decentralized level. Impulse was given to this new departure by the renewed emphasis on rural poverty reduction in development programs.

Source: Watershed Management Approaches, Policies and Operations: Lessons For Scaling-Up. 2008. World Bank

[33] Note that this measure corresponds to NAPA Project # 10 (see Table 1).

Chapter 8: Conclusions and Recommendations

- Yemen should invest in a 'knowledge response' to climate variability and change, particularly in forecasting and early warning, together with improved data collection and sharing, and public awareness and stakeholder involvement, and in assessing a range of resilience measures and technologies.
- The suggested adaptation measures are already part of Yemen's National Water Strategy and Water Sector Support Program, and of the National Adaptation Program of Action (NAPA). Investment and implementation of these programs needs to be strengthened and accelerated.

A. Elements of a strategic response to climate variability and change in water and agriculture

This chapter summarizes how Yemen can pursue a strategic approach in partnership between government, the Yemeni people and international partners to integrate preparedness and adaptation for climate change and variability in water and agriculture into the overall development effort. The approach follows the lines set out in Yemen's NAPA and is intended to contribute to the development of the water and agriculture components of Yemen's Strategic Program for Climate Resilience.

Yemen will need to develop both a 'knowledge response' and adaptation measures to the risks and opportunities of climate variability and change in water and agriculture. This report has underlined the high degree of uncertainty regarding the future of Yemen's climate, but has also highlighted that certain adaptation options in water and agriculture would be appropriate whatever the emerging climate patterns (including if the changes turn out favorable for some, such as the 'warm and wet' scenario). These options coincide with the existing strategic priorities for the water and agriculture sectors. Under these circumstances, a two-part approach is recommended:

i. A <u>strong knowledge response</u>, to develop more knowledge to reduce uncertainty over averages, to get a better grasp of probability distributions related to climate effects and of the technical aspects and economic returns to the portfolio of resilience measures in water and agriculture, and to advance knowledge of the technologies that could reduce the cost of these responses.

ii. <u>Accelerated implementation of existing programs in the water and agriculture sectors</u>, strengthening investment and implementation measures already underway to manage risk and water scarcity (and to exploit opportunities) in water and agriculture.

The risks are not all 'downside' risks. There are possibilities that Yemen might gain from some aspects of climate change, particularly if some parts of the country benefit from the 'warm and wet' scenario. This 'opportunity' needs to be factored into the knowledge response and into implementation measures.

(i) A knowledge response to climate change and variability in water and agriculture

Given the uncertainty over climate models, a program of forecasting and early warning, together with improved data collection and sharing, public awareness and stakeholder involvement, are the key preparedness measures best adapted to Yemen's situation. Given the uncertainty associated with climate models for the region and poor historical records of climate related data, Yemen should develop a capacity for seasonal forecasting and early warning with a long lead time and a robust dissemination strategy to make the information readily available to users. Seasonal forecasting and early warning systems are improving rapidly in many countries. In Yemen, similar work could be undertaken in conjunction with the National Remote Sensing Centre, which has facilities for receiving satellite products. The system would have to operate in conjunction with measures for increased data collection and sharing (see below), in order to have access to suitable data for the calibration, validation and testing of any forecasting models. If successful, it could be valuable to link such work with wider work on farm advisory services and, in particular, plans for community management of water resources.

The collection and sharing of hydro-meteorological data needs to be improved and coordinated. The climate observation network has improved significantly in recent years but data and information on spate flows, groundwater levels and rates of abstraction are poor, making any estimates of future water availability highly uncertain. It is essential to develop an improved observation network so that, over time, trends in temperature, rainfall, runoff, recharge and groundwater can be detected. Much greater effort is required in the development of catchment information systems in order that accurate water balances can be developed. A further constraint has been lack of access to the data that does exist, as a result of a weak institutional culture regarding sharing. Uncoordinated, multi-agency responsibility for meteorological and hydrological data collection and dissemination represents a significant impediment to national climate risk assessment and reporting. Institutional reforms are urgently required to improve access to data. Lessons could be learned from the success of the Central Statistical Office in promoting a more open attitude to data. Action to establish and maintain a database of climate change and adaptation is included in the NAPA (*Project # 4*, see Table 1).[34]

Improved public awareness and involvement will be an essential part of future adaptation programs in both urban and rural areas, and a robust dissemination strategy is essential. As the adaptation strategies for dealing with climate change in the water and agriculture sectors are likely to be very close to existing strategies for water management, the climate change message is an invaluable "entry point" to increasing awareness and engaging participation in integrated water resource management and agricultural water programs. The climate change message should, however, be 'mainstreamed' into the larger messages on IWRM, water saving, water use efficiency etc.

This knowledge response is integral to the preparations underway for Yemen's Pilot Program for Climate Resilience (PPCR). The likely elements of the PPCR that relate to water and agriculture are discussed in Box 12.

[34] These measures will need to be coordinated with those under Yemen's National Disaster Risk Management Strategy prepared under GFDRR financing which is strengthening Yemen's institutional capacity for disaster risk assessment and risk reduction, and supporting a national civil works program to reduce the risks of flooding.

Box 12: Elements of Yemen's Pilot Program for Climate Resilience (PPCR) relating to water and agriculture

Water

- Upgrading the network of hydro-meteorological monitoring stations; collating relevant physiographic, agricultural, social and economic datasets to enhance understanding of the system and decision-making processes in the sector.
- Enhancing capabilities to develop and use appropriate tools (hydrological models, weather forecasting with a long lead time, including seasonal forecasting, early warning system, decision support system) and latest technologies, such as GIS, remote sensing, MIS/DSS.
- Investing in a public awareness campaign regarding the scarcity of water, and in community water management, for example through water user groups.
- Building institutional and technical capacity in the MWE, including NWRA, the water utilities and GARWSP to better integrate climate change concerns into water strategies and policies.
- Ensuring close cooperation among various agencies with interests in the water sector, including MAI, MWE, NWRA, EPA, the water utilities, GARWSP, and CAMA.
- Updating knowledge on different basins to determine safe yields and storage capacities of aquifers and surface water sources.
- Assessing engineering mechanisms for managing risk from variability and change in water, including integrating climate resilience into the design of new infrastructure for irrigation and flood control, and using bioengineering-based options to protect embankments and irrigation infrastructure.

Agriculture

- Planning for adapting the measures in the National Water Strategy (NWSSIP) and the National Irrigation Program (NIP) to reflect climate change and variability risks and opportunities.
- Making an inventory of existing coping mechanisms developed by local communities in efforts to adapt to climate change and variability and scale up their implementation.
- Capacity building and awareness raising across all departments at the Ministry of Agriculture and sub-national levels.
- Strengthening data collection (e.g. agricultural productivity, land use, soil type) and analysis for both planning and research purposes.

Source: PPCR First Joint Mission Aide Memoire November 2009

(ii) Accelerating key measures already programmed in water and agriculture

Chapter 7 assessed likely farmer responses to climate variability and change in Yemen and underlined the need for adaptive strategies that will need to be implemented over the coming decades to cope with the potential impacts on production, incomes and the rural economy as a whole, and on water availability for settlements. Although there would be significant differences between agro-climatic zones and different basins[35], five main adaptation options have been highlighted:

1. Investment in **efficient *irrigation* systems**, and use of groundwater for *supplementary irrigation,* including putting in place appropriate incentive mechanisms and enforcing regulations and policies that encourage efficient utilization of water.
2. Investment in improved **knowledge base** related to climate and water resources issues
3. Support to traditional **agricultural and water harvesting techniques**, and sustaining the **livestock** economy
4. Adapting farming practices: changing **cropping patterns**, growing shorter cycle, drought tolerant or later maturing **varieties**, changing the **cropping calendar,** etc
5. Adoption of **integrated management of the water resource** at all levels from the bottom up, including looking at water also as an economic good.

Climate variability and change add an extra dimension of risk (and opportunity) to existing natural resource challenges, and the five options are already on Yemen's agenda for water and agriculture. As discussed above (Chapter 3), climate change adds a dimension of risk – and possibly opportunity - to the already daunting challenge Yemen faces in natural resource management, particularly intense rainfall events, drought and dwindling water resources. The five options thus address not only climate variability and change vulnerabilities but also the broader issues of water management and agriculture on which climate variability and change principally impact. The suggested adaptations are already on Yemen's agenda and will need to be implemented in any case. Essentially, Yemen's climate change and variability adaptation program in water and agriculture consists in doing more – and better – what has already been started.

The five adaptation options can be mainstreamed within both NWSSIP and NAPA. Climate change adaptation measures need to be mainstreamed into the broader measures already in preparation or under implementation for dealing with the challenge of adjusting to a more water scarce economy. Here Yemen has the advantage of two excellent strategic documents: the National Water Sector Strategy and Investment Program (NWSSIP), updated in 2009, and the NAPA. All of the adaptation options discussed in Chapter 7 fit within one or other of these programs, and most of them fit within both, as Table 13 below shows.

Table 13: Matching possible adaptation options and measures with existing national strategies and programs

Adaptation options	Suggested measures	NWSSIP Update	NAPA Project #
1. Investment in efficient ***irrigation*** systems, and use of groundwater for ***supplementary irrigation***	▪ Piped conveyance and distribution	2.1.1	2.1
	▪ Improved spate irrigation and pressurized irrigation (drip, bubbler)	2.1.1 3.1.2	2.1 -
	▪ Improved irrigation management, including market-based approach to irrigation efficiency	2.1.1	-
	▪ Drought bridging through supplementary irrigation	-	2.4
	▪ Wastewater reuse		
	▪ Incorporating flood preparedness into surface irrigation management		
2. Investment in improved knowledge base related to climate and water resources	▪ Improved network of hydro-meteorological station	3.1.2	2.3
	▪ Improved data collection and analyses	-	6

[35] Most adaptation options are site specific based on current water resources availability and use trend, and potential for renewable water resources in each basin.

issues	▪ Early warning system and seasonal forecasting with long lead time, plus robust dissemination strategy ▪ Development of state-of-the-art tools in order to guide decision making	2.1.1*	2.5
3. Strengthening traditional ***agricultural and water harvesting techniques***, and sustaining the ***livestock*** economy	▪ Promoting water harvesting, fog harvesting ▪ Terrace rehabilitation ▪ Promoting improved livestock and rangeland systems	2.1.4 4.1.1 -	7.1 8.2 10.2
4. Adapting farming practices: changing ***cropping patterns***, growing shorter cycle or later maturing ***varieties***, changing the ***cropping calendar*** etc	▪ Varietal research (on short cycle or drought tolerant varieties, high value low water using crops etc.) ▪ Farming systems research	3.1.1 3.1.1	9.1 2.6, 9.2
5. Adoption of ***integrated management of the water resource*** at all levels	▪ Develop capacity for planning and regulation on a partnership basis ▪ Water resource evaluation and monitoring ▪ Incentive structure to encourage efficient and sustainable use ▪ Licensing, registration, regulation ▪ Promote basin level planning and management ▪ Support WUAs as the lowest building block of water resource management ▪ Watershed management in key catchments	1.1.1* 1.1.2*, 1.2.1* 1.2.3* 1.1.5*, 3.2.2* 1.1.7* 3.1.4 4.1	 2.2 10

*NWSSIP references are to the Irrigation Program except items marked * which form part of the IWRM Program.*

The adaptation options can be implemented through existing organizations and programs. There are ongoing programs or projects for four of the five adaptation options recommended (see Table 14 below). Activities in two of these categories are supported by the multi-donor Water Sector Support program (WSSP), which is a flexible vehicle through which further financing can easily be channeled. In addition, MAI is in the process of bringing all of its activities in support of irrigation within a single National Irrigation Program (NIP). The principal gaps where further program activities or financing are required are in (4) *Adapting farmer practices*, where AREA is responsible for the research agenda; and (5) for the *Watershed management* component. Both of these activities are included in NWSSIP, but at present there is no strong program or external finance.

Table 14: The fit of recommended adaptation options with ongoing programs and external financing

Adaptation option	Government agency	Ongoing programs or projects	External Financing
1. Investment in efficient ***irrigation*** systems, and use of groundwater for ***supplementary irrigation***	MAI	GSCP, National Irrigation Program	WSSP
2. Investment in improved knowledge base related to climate and water resources issues	MAI, TDA	IIP, National Irrigation Program	WSSP
3. Return to traditional ***agricultural and water harvesting techniques***, and sustaining the ***livestock*** economy	MAI	RALP	IDA AFPPF
4. Adapting farming practices: changing ***cropping patterns***, growing shorter cycle or later maturing ***varieties***, changing the ***cropping calendar*** etc	AREA	NWSSIP	
5. Adoption of ***integrated management of the water resource*** at all levels	NWRA, with basin committees and WUAs (IWRM) MAI (watershed management)	NWSSIP NWSSIP	WSSP

B. Making it happen

The chart below illustrates a possible indicative implementation timeline and sequencing, for illustration only. In order to move from analysis to action, it is recommended that government agree with civil society and international donor partners to review and decide on the preparedness and adaptation options and measures discussed in the study as follows:

1. Review the case for adopting the proposed knowledge response (adaptation option 1), take a decision, seek funding and implement (lead responsibility: EPA/NWRA/CAMA)

2. Review the proposed expansion of action on *surface and groundwater* (adaptation option 2) and its fit within the ongoing GSCP/IIP/NIP, take a decision, and seek extra funding within NWSSIP/WSSP (lead responsibility: MAI/ NWRA) —this needs to be accompanied by appropriate incentive policies for efficient water resources management and use such as removing the incentives that encourage over-exploitation of the groundwater and replacing them with those that ensure water saving.

3. Review the proposed expansion of action on *rainfed agriculture, water harvesting and livestock* (adaptation option 3) and its fit within the ongoing RALP, take a decision, and seek extra funding within NWSSIP/WSSP (lead responsibility: MAI)

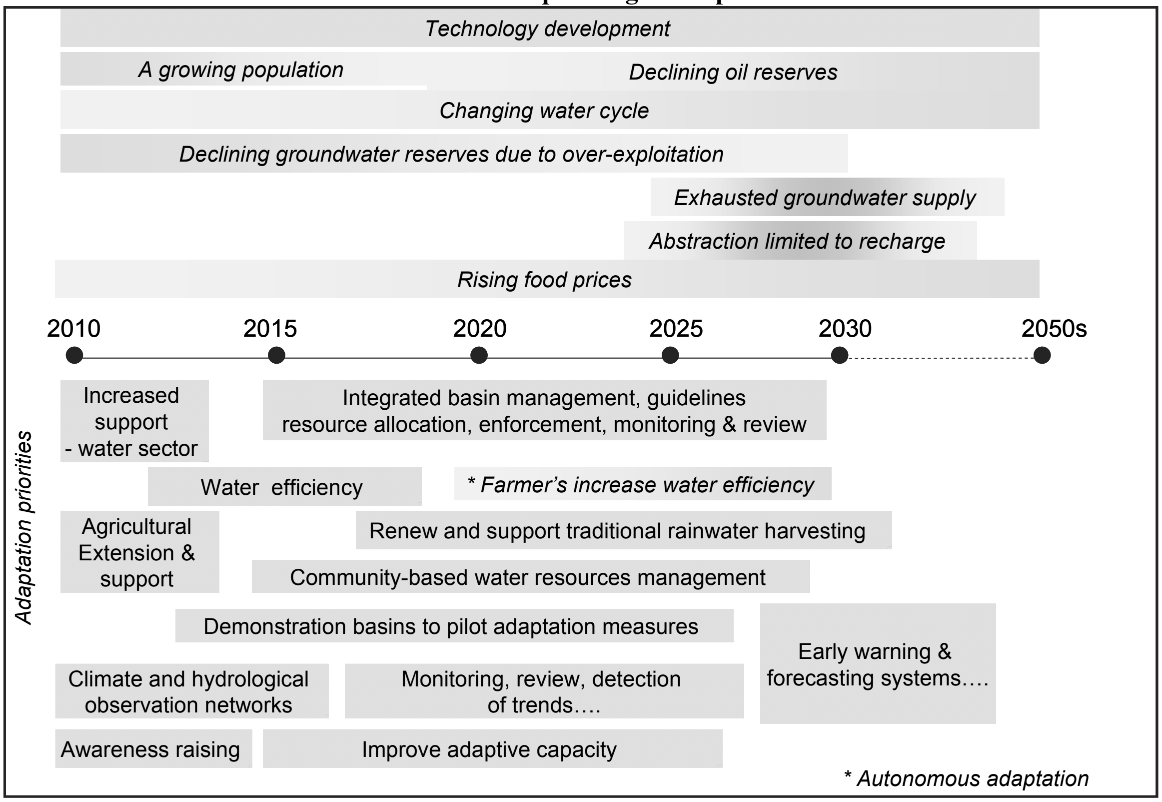
4. Review the proposed expansion of action on *varietal and farming systems research and other relevant adaptive research* (adaptation option 4), take a decision, and seek funding, preferably within NWSSIP/WSSP (lead responsibility: AREA/MAI)

5. Review the proposed expansion of action on *integrated water resource management* (adaptation option 5), including *watershed management* and its possible fit with RALP, take a decision, and seek extra funding within NWSSIP/WSSP (lead responsibility: NWRA for national and basin levels, MAI with NWRA for local level and WUAs)

6. Unconventional thinking and policy for the agriculture agenda should not be discouraged in Yemen in order to avoid disaster level water scarcity and sustain economic development in critical basins of the country, including Sana'a basin. Some of these unconventional policies include incentivizing moving out sectors that do not have comparative advantage from such critical basins. Review the proposed action plan with all relevant stakeholders and take a decision (lead responsibility: MOPIC/MAI/MWE/MOF)

Financing from the PPCR under the Strategic Climate Fund (SCF) might be channeled to EPA (for the preparedness measures) and through WSSP and other relevant programs for the adaptation options.

An illustrative timeline and sequencing for implementation



Source: HR Wallingford

C. Value added from this study

The study has identified key likelihoods and risks, and proposed key adaptation and preparedness responses. This study has, for the first time, brought together projections on climate change for Yemen for the twenty first century. Based on these scenarios, the study has gauged the possible effects of climate change on water and agriculture and identified likely farmer responses and the corresponding adaptation options for policy makers. Although the uncertainty is considerable, the study has identified core likelihoods – of warming, of growing variability of rainfall, and of more frequent intense rainfall – and has recommended how response to climate change risk can be mainstreamed into Yemen's policies and strategies for dealing with natural resource challenges as a whole. The study has also recommended key preparedness measures. The analysis and recommendations are likely to be of value to Yemeni decision makers for two sets of reasons:

a) *The long term horizon of the study allows policy makers to prioritize and sequence responses as part of the overall development effort for poverty reduction*. For a country faced by many problems, the study highlights the natural resource challenges and the possible impacts on poverty. The projections through the twenty first century give a long term perspective that is unusual for policy makers but which is essential in the case of such slowly evolving risks as climate change. This long term perspective allows early identification of trends and the prioritization and sequencing of responses.

b) *The study also demonstrates how response to climate change and variability risks can be mainstreamed into what Yemen has already initiated in terms of reform and adaptation in the* *water and agriculture sectors*. Here the study adds emphasis and underlines needs for strengthening certain parts of the program, and shows where incremental funding would best be directed. Finally, the study sets out a series of action steps that propose a way of moving from vision to action.

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Annex 1—Climate Change Models and Downscaling

Climate change models

The following table provides a summary of climate model output that is now available for downscaling in Yemen for the 2050s and 2090s time-slices. (1.21)

Climate model output assembled for statistical downscaling in Yemen

GCM	SRES emissions scenario		
	A1B	A2	B1
CCC	√	√	√
CNRM	√	√	√
CSIRO5	√	√	
ECHAM5	√	√	
GFDL	√	√	√
GISS	√	√	√
IPSL	√	√	
MIUB	√	√	√
MRI	√	√	

Downscaling

GCM scenarios need to be "downscaled" to the level of planning units such as basins – but the value of downscaled scenarios for planning has not yet been proven.

Many varieties of statistical and dynamical downscaling methods have emerged to translate the large-scale atmospheric conditions represented by GCMs into local-scale climate data, often at river basin scales, or even to the resolution of individual meteorological stations.

Given the large choice of available downscaling techniques, it is important to select the most appropriate tool for the intended application, whilst taking into account local constraints of data availability, quality, time, resources, human capacity and supporting infrastructure. A recent review of downscaling arranged the techniques into three categories of low, intermediate and high resource requirements.[36] The methods are summarized in Table – below: *Options for constructing regional climate change scenarios*.

In the table, the options are listed in order of increasing complexity and resource demand. Methods incurring only modest demands include sensitivity analyses, climate change factors, analogues, and trend extrapolation. Intermediate intensity methods include pattern-scaling, weather generators and statistical downscaling. Finally, the most demanding methods are dynamical downscaling and decadal climate forecasting using coupled Atmosphere-Ocean (AO/) GCMs. The table also includes a summary judgement about feasibility for climate change impact assessment in Yemen.

***Recommended options for climate scenario development for Yemen*—based on foregoing analyses,** for the time being, a modified weather generator downscaling techniques is the best option for constructing

[36] Wilby, R.L., Troni, J., Biot, Y., Tedd, L., Hewitson, B.C., Smith, D.G. and Sutton, R.T. 2009. A review of climate risk information for adaptation and development planning. *International Journal of Climatology*, 10.1002/joc.1839.

climate change scenarios for Yemen under the dual constraints of limited data availability and uncertainty.

Until an ensemble of RCM scenarios becomes available for East Africa and the Arabian Peninsula or the network of meteorological stations provides improved coverage, the best option is to estimate weather generator parameters at gauged and ungauged locations for the present climate and to adjust these parameters for climate change by the 2050s and 2080s. Pattern-scaling techniques could be used to generate scenarios for earlier or intervening periods.

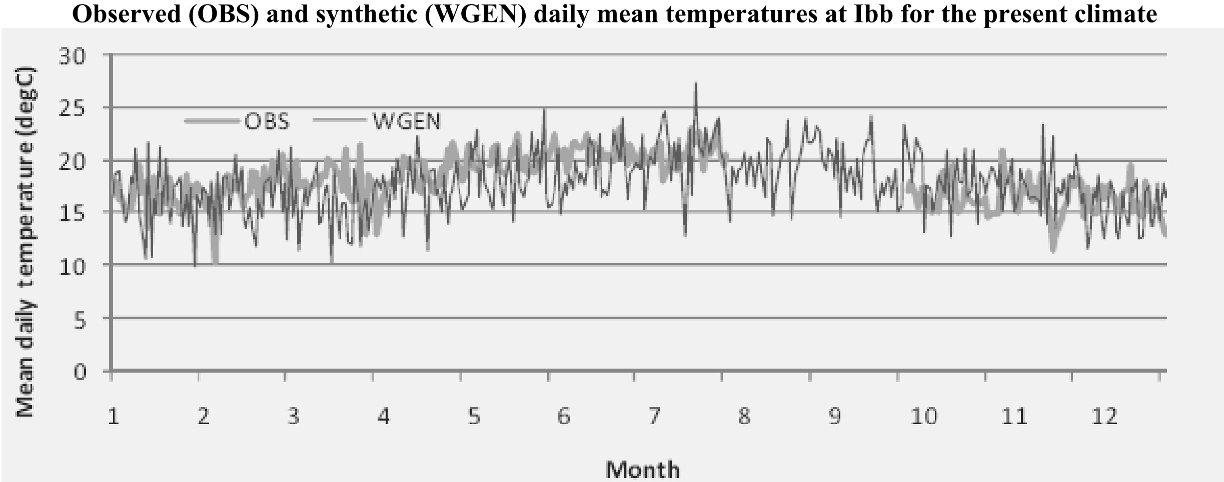
The advantage of the weather generator approach (see Box below) is that it is already in widespread use for simulating the present climate. It presents only modest computational demands and uses tools freely available. The approach preserves relationships between weather variables. The disadvantages (see table below) are manageable in the Yemeni context.

Using weather generators to develop national climate change scenarios for Yemen

Weather generators offer a practical means for downscaling daily weather variables to multiple stations (and ungauged locations) and for characterising the uncertainty arising from different climate model and emission runs.

Weather generators are models that replicate the statistical attributes of meteorological station records (such as the mean and variance) but do not reproduce actual sequences of observed events (see figure).

Observed (OBS) and synthetic (WGEN) daily mean temperatures at Ibb for the present climate



At the heart of most weather generators is a Markov model that emulates transitions between wet- and dry-spells or -days. The optimum statistical distribution for representing daily rainfall totals varies from place to place, but the gamma, exponential, and fourth root are most popular. Secondary variables such as maximum and minimum temperatures, solar radiation and wind speed are conditioned by wet-day occurrence and inter-variable dependencies. The whole process is driven by random number generation to determine whether a day is wet or dry, if wet how wet, how warm, how windy, and so on. Weather generators are modified for climate change assessment by either relating key parameters such as wet-day probabilities to other, slowly-varying indices of atmospheric circulation, or by recalibrating the weather generator using synthetic weather series adjusted by the change factor method.

Source: 1:19

Use statistical downscaling to develop case studies for strategically significant sectors and/or regions

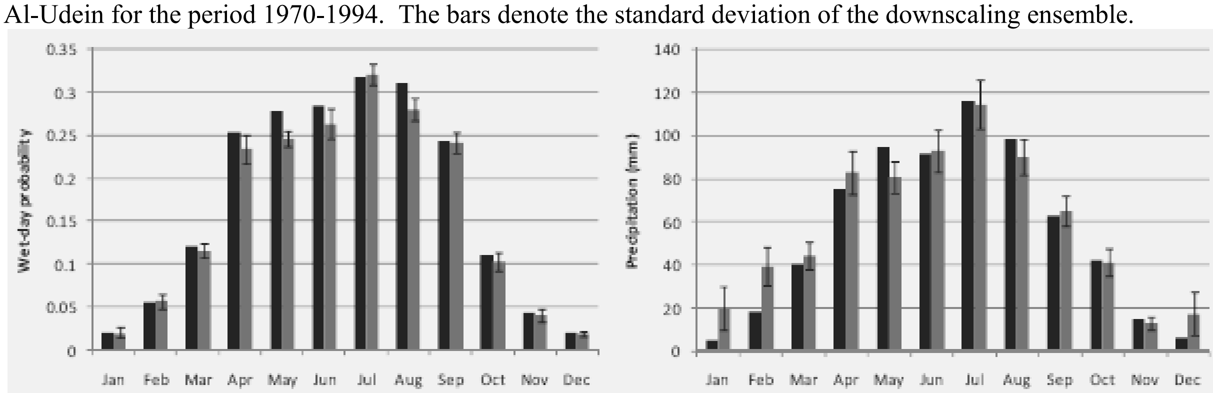
Having first identified strategically significant sectors and/or regions, regional climate change scenarios could be developed by statistical downscaling methods (see box below), using the full matrix of GCM and emissions (see table above) at short-listed sites with sufficient data for calibration and verification (See Wilby 2009 Annexes 1 and 3 for list of stations where adequate rainfall; and temperature records are maintained). Where there are insufficient data, and a scenario is required for planning purposes, the weather generator method might be applied.

Using statistical downscaling to develop sectoral or regional case studies for Yemen

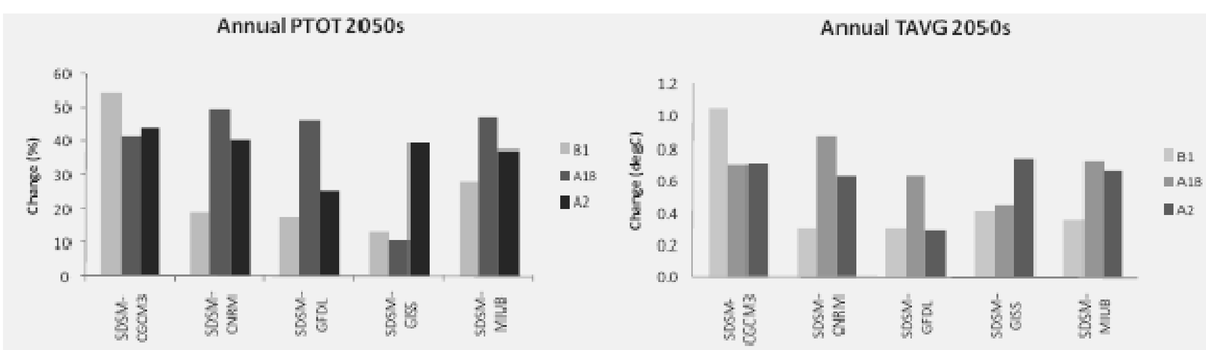
Statistical downscaling can provide daily weather series for detailed climate change impact assessment at river basin scale or below. The method is only possible where there are high-quality observations for model calibration and validation.

Methods range in complexity but the general principle is the same: to use a suite of predictor variables (such as a mean sea level pressure, or atmospheric humidity) supplied by a GCM to estimate local predictands (such as daily maximum temperature or rainfall total). Methods differ mainly in terms of the form of the transfer function relating the large- to local-scale atmospheric response, and inter-comparison studies consistently show that there are no universally optimal sets of predictors or forms of relationship – each must be assessed on a case by case basis.

Preliminary analyses for sites in Yemen suggest that it is possible to produce convincing downscaling results for the present climate even where rainfall data are incomplete. The figure below shows observed (black bars) and downscaled (red bars) monthly wet-day probabilities (left panel) and monthly mean rainfall totals (right panel) at Al-Udein for the period 1970-1994. The bars denote the standard deviation of the downscaling ensemble.



Provided that predictor variables are available, statistical downscaling can be an efficient tool for exploring uncertainties in climate change scenarios due to the host GCM and emissions scenario (see figure below), or for producing fully transient daily scenarios up to 2100. The figure shows changes in annual mean rainfall totals (left) and mean daily temperature (right) at Al-Udein downscaled from five GCMs (CGCM3, CNRM, GFDL, GISS, MIUB) and three SRES emissions scenarios (B1, A1B, A2) by SDSM*lite* for the 2050s.



PTOT = TAVG =

Options for constructing regional climate change scenarios

Method	Advantages	Disadvantages	Feasibility for Yemen
Climate Sensitivity Analysis	1. Easy to apply; 2. Requires no future climate change information; 3. Shows most important variables/ system thresholds; 4. Allows comparison between studies.	1. Provides no insight into the likelihood of associated impacts unless benchmarked to other scenarios; 2. Impact model uncertainty seldom reported or unknown.	Sensitivity testing should be applied as a matter of course to rapidly identify possible non-linear impact responses and/or the amount of climate change that would exceed capacities to adapt.
Change Factors	1. Easy to apply; 2. Can handle probabilistic climate model output	1. Perturbs only baseline mean and variance 2. Limited availability of scenarios for 2020s.	Change factors are readily available and help characterise climate model/emissions uncertainty, but given their coarse resolution are best used to inform the range of conditions used for sensitivity testing
Climate Analogues	1. Easy to apply; 2. Requires no future climate change information; 3. Reveals multi-sector impacts/vulnerability to past conditions or extreme events, e.g. flood or drought episode.	1. Assumes that the same socio-economic or environmental responses recur under similar climate conditions 2. Requires data on confounding factors such as population growth, technological advance, conflict.	Temporal analogues can help raise awareness of risks and vulnerabilities but it is suspected that there will be insufficient high quality socio-economic data on past climate impacts.
Trend Extrap-olation	1. Easy to apply; 2. Reflects local conditions; 3. Uses recent patterns of climate variability and change; 4. Instrumented series can be extended through environmental reconstruction; 5. Tools freely available.	1. Typically assumes linear change; 2. Trends (sign and magnitude) are sensitive to the choice/length of record; 3. Assumes underlying climatology of a region is unchanged; 4. Needs high quality observational data for calibration; 5. Confounding factors can cause false trends.	Trend extrapolation can be highly problematic even for the near term but could be used alongside climate model projections to inform views on the "direction of travel".
Pattern scaling	1. Modest computational demand; 2. Allows analysis of GCM and emissions uncertainty; 3. Shows regional and transient patterns of climate change; 4. Tools freely available.	1. Assumes climate change pattern for 2080s maps to earlier periods; 2. Assumes linear relationship with global mean temperatures; 3. Coarse spatial resolution.	Pattern-scaling could be used to interpolate downscaled scenarios for earlier or intervening periods such as the 2020s that might not otherwise be available from time-slice experiments (see below)
Weather Generators	1. Modest computational demand; 2. Provides daily or sub-daily meteorological variables; 3. Preserves relationships between weather variables; 4. Already in widespread use for simulating present climate; 5. Tools freely available.	1. Needs high quality observational data for calibration and verification 2. Assumes a constant relationship between large-scale circulation patterns and local weather 3. Scenarios are sensitive to choice of predictors and quality of GCM output 4. Scenarios are typically time-slice rather than transient.	Weather generators offer a practical means for downscaling daily weather variables to multiple stations (and ungauged locations) and for characterising the uncertainty arising from different climate model and emission runs.
Empirical or Statistical Down-scaling	1. Modest computational demand; 2. Provides transient daily variables; 3. Reflects local conditions; 4. Can provide scenarios for exotic variables (e.g., urban heat island, air quality); 5. Tools freely available.	1. Requires high quality observational data for calibration and verification; 2. Assumes a constant relationship between large-scale circulation patterns and local weather; 3. Scenarios are sensitive to choice of forcing factors and host GCM; 4. Choice of host GCM constrained by archived outputs.	Statistical downscaling is only possible where there are high-quality observations for model calibration and validation, but these methods can provide daily weather series for detailed climate change impact assessment at river basin scale or below.
Dynamical Down-scaling or Regional Climate Models	1. Maps regional climate scenarios at 10-50km resolution; 2. Reflects underlying land-surface controls and feedbacks; 3. Preserves relationships between weather variables; 4. Ensemble experiments are becoming available for uncertainty analysis.	1. Computational and technical demand high; 2. Scenarios are sensitive to choice of host GCM; 3. Requires high quality observational data for model verification; 4. Scenarios are typically time-slice rather than transient; 5. Limited availability of scenarios for 2020s.	Regional climate model experiments are not yet available for Yemen and, in any event, such models tend to over-estimate rainfall totals over high terrain.
Decadal climate forecast	1. Forecasts of global mean and regional temperature changes for the 2020s; 2. Reflects dominant earth system processes and feedbacks affecting global climate; 3. Ensemble experiments are becoming available for uncertainty analysis.	1. Computational and technical demand high (supercomputing); 2. Scenarios are sensitive to initial conditions (sea surface temperatures) and external factors (such as volcanic eruptions); 3. Scenarios are sensitive to choice of host GCM; 4. Coarse spatial resolution	Despite significant technical advances in decadal forecasting capability, these products will be of limited value to policy-makers and planners until there is greater consensus about regional precipitation anomalies.

Where downscaling is not possible, use sensitivity testing of existing models to conduct vulnerability assessments

Where downscaling is not technically feasible due to a lack of data or low predictability of weather generator parameters from geographic metrics, emphasis should be on discerning impact and adaptation thresholds using sensitivity testing of available sector models. Change factors derived from international archives (such as the IPCC or UNDP country-level ensembles) could be used to bound the range of plausible climate scenarios.

However, given the weak data availability and the uncertainty over appropriate regional models, adaptation decisions should be robust regarding the climate change trajectory.

Annex 2—Yemen's four main surface water basins

The Red Sea Basin: A number of large wadis drain the steep western escarpment and lose most of their water in the permeable sediments of the coastal Tehama. All wadis have catchment areas larger than 1,000 km2 - Wadi Mawr is the largest (approximately 8,000 km2). Rainfall in the highlands in spring and summer generates significant run off in the upper and middle catchment. Flood peaks are high as rainfall in the catchment area is high and slopes are steep. In the coastal plain, some of the wadi flow is diverted for spate irrigation and lost to ET, some percolates below the soil profile into the aquifer and recharges groundwater, and some reaches the sea, generally by groundwater outflow. The flows of several wadis have been monitored for short periods, shedding some light on the rainfall-runoff relationships in these wadis. This is Yemen's most important basin, contributing 36% of total run off.

Gulf of Aden Basin: The main wadis, all of which have catchments over 1,000 km2, drain south from the southern highlands. The large spate flows are extensively diverted in the broad coastal plain, but a larger share of flows still reaches the sea than in the Red Sea systems. In recent years, spate flows have dwindled due to continuing diversion upstream.

Arabian Sea Basin: In ancient times, this large complex basin area supported Yemen's great trading kingdoms. Its topography would allow water to flow from the eastern slopes of the highlands, down through the Ramlat as Sabatayn to Wadi Hadramawt, and out towards the sea via Wadi Masila. However, as rainfall rates are low and much of the soils of the basin allow for rapid recharge, the "basin" is more a series of discontinuous segments. Runoff volumes can be large, as witnessed during the flooding of 2008 in Wadi Hadramawt, which caused a large number of fatalities and substantial economic damage to property and agriculture in the region.

Rub al Khali Basin: The northern and north-eastern slopes of the highlands drain into the sands of the Empty Quarter where infiltrates into groundwater.

The Mountain Basins: Scattered through the highlands, a series of plains surrounded by mountains constitute self-contained basins, with little or no surface water draining outside the basin: Sa'adah, Huh/al Harf, Amran/Raydah, Sana'a, Dhamar, Rad'a. The recharge of groundwater in these small basins is limited, but they are centers of high population concentration and hence of heavy water use. [*Adapted from WRAY 35, and from 2]*

Annex 3—Methodology for assessing impacts on agriculture

Governorate analysis

The estimate of crop response to climate change is based on the crop requirement tables used by AREA. To simplify the analysis, composite responsive curves are estimated for each of seven crop groups (sorghum, other cereals, vegetables, fruit, legumes, qat and cash crops). These composite curves span all crops within each group, allowing for some substitution within the groups (e.g. by replacing potatoes with tomatoes if rainfall increases, or vice-versa). The crop response curves are applied to current cropping patterns and the results are summarised below.

This national average crop responsiveness provides a useful measure against which to compare the results of more detailed analysis which breaks down the water balance and considers the effect of different yields and temperature conditions in different locations. The hydrology analysis provides key climate and water data for 31 main catchments. However, there is no agricultural data available for catchments and available images of vegetation cover do not provide evidence to assist in the conversion of governorate crop data to catchments. Therefore, the analysis converts the catchment climate and hydrology data to governorates and then calculates modelled crop production based on the average conditions for the governorates.

This allows for accurate analysis because the different climate, hydrology, cropping patterns and yield conditions in each governorate can be analysed separately. In particular, it allows an estimate to be made of the allocation of water to different crops, based on their current use of water, as estimated from the crop response curves, given current yields and temperatures in each governorate and summarise the impact on crop production (by weight) of the five climate change scenarios.

The changes in temperature, rainfall and crop production are presented as changes from a baseline scenario in which the climate is similar to current conditions. The changes are marginal changes associated only with climate change and do not take into account the possibility that crop production will: a) fall as groundwater extraction reduces to sustainable levels; and b) rise as a result of underlying trends in technology improvement, including increased irrigation efficiency.

Summary analysis of impacts by governorate

On these assumptions, estimates were made of crop production by governorate according to the three scenarios for 2030, 2050, and 2080 [2.iii.f]

For each scenario, estimates are made of crop production for three dates: 2030, 2050 and 2080. Each scenario and date has changes of rainfall and temperature for each month. The number of rainy days (and hence intensity of rainfall) does not change appreciably. The hydrology model adds estimates of recharge and runoff for 31 catchments, taking into account the geomorphology of the catchments. The catchment data is then analysed on the basis of the impact on agriculture on respective governorates.

Annex 4—Savings of water and diesel per ha as a result of improved irrigation systems

Items	Groundwater to open channel	Piped conveyance	Drip, bubbler systems
Water consumption (m^3/ha)	9 500	7 631	5 775
Net water saving (m^3/ha)	0	1 869	3 725
% water saving	-	20	40
Diesel consumption (l/ha)	1 360	1 083	816
Diesel saving (l/ha)	-	272	544
Cost of diesel (YR/ha)	47 700	38 080	28 560
Cost saving (YR/ha)	-	9520	19 040
Pumping time to irrigate (hrs/ha)	300	240	180
Pumping time saved (hrs/ha)	-	60	120

Source: Ministry of Agriculture and Irrigation, 2007. Second Joint Annual Review (JAR-II) of NWSSIP Year 2006 Irrigation Group. Sana'a, Republic of Yemen, 11pp. [from 1.26]