Appendix A

Climate Change Study

Red Sea Dead Sea Water Conveyance Feasibility Study

Climate Change Study

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1. Introduction

1.1. Purpose

This report details the results of a study of the potential implications of climate change for the proposed construction of the Red Sea Dead Sea Conveyor, hereafter referred to as the RSDSC or "the project". Under the "Base Case", the purpose of the RSDSC would be to transfer water from the Red Sea to the Dead Sea in order to raise the level of the Dead Sea and stabilise it at a level to be determined. Under the "Base Case Plus", stabilisation of the Dead Sea would be complemented by hydro power generation, desalination and the transmission of potable water to Jordan, Israel and the Palestinian Authority[1] with the long term stabilised Dead Sea level being somewhere within the range of 410m to 420m below global mean sea level (gmsl).

Based on current specifications, the RSDSC would draw a minimum of 1000 million cubic metres per year (MCM/yr) for the Base Case and a maximum of 2000 MCM/yr for the Base Case Plus from the Red Sea. Under the Base Case Plus, 310 MCM/yr of this water would be desalinated at the beginning of operation of the RSDSC in 2020, rising to 850 MCM/yr by 2060. For the purposes of the current RSDSC Feasibility Study, it is assumed that the majority of the resulting potable water in 2020 (220 MCM/yr) would be allocated Jordan, with the remainder allocated to Israel (60 MCM/yr) and the Palestinian Authority (30 MCM/yr)[1]. However, allocation of potable water between the Beneficiary Parties has not yet been agreed, and these figures do not necessarily represent the final water sharing arrangement.

The Climate Change Study (CCS) presented here is part of the wider RSDSC Feasibility Study (FS). The FS has been commissioned by the International Bank for Reconstruction and Development, and is being undertaken by Tractebel Engineering, operating under its commercial name of Coyne & Bellier. The CCS has been commissioned by Coyne & Bellier, and has been conducted by Dr Nick Brooks (the sub-consultant), independent climate change consultant and Visiting Research Fellow at the Tyndall Centre for Climate Change Research at the University of East Anglia, UK.

The remit of the CSS is to review the potential implications of climate change for the project based on a review of the existing literature and consultations with relevant experts from the region. The CSS is not required to undertake new research. The ultimate objectives of the CSS are to

- Assess the potential impacts of climate change on the project
- Assess how the environmental impacts of the project might be mediated by climate change
- Make recommendations about how climate change risks to, and associated with, the project may be mitigated.

These assessments are informed by existing global climate model (GCM) and regional climate model (RCM) simulations and other available data, which are used to provide general characterisations of potential future climatic conditions and, as far as is possible, assessment of the relative likelihoods of different future climate scenarios.

A specification of the CSS is to assess the potential implications of climate change for the project in three key locations (the sub-regions) and also for desalination and transmission, resulting in four sub-studies. The sub-studies, and the associated parameters/phenomena of interest as specified in the terms of reference for the CCS, are summarized below.

Red Sea, focusing on Gulf of Aqaba (Sub-Study A): precipitation, humidity, air temperature, prevailing wind strength and direction, water temperature, circulation, sea-level rise (rate and magnitude), vulnerability of marine ecosystems to climate change and project impacts.
Arava Valley/Wadi Araba (Sub-Study B): precipitation, humidity, air temperature, prevailing wind strength and direction, potential evapo-transpiration, climate moisture index, runoff coefficient, extreme rainfall events, storm frequencies, soil structure, ecosystems, groundwater.
Dead Sea (Sub-Study C): precipitation, humidity, air temperature, prevailing wind strength and direction, potential evapo-transpiration, climate moisture index, runoff coefficient, micro-climates of Dead Sea and surrounding water bodies, climatic and hydrological parameters used in the Dead Sea water mass balance model.
Desalination and Transmission (Sub-Study D): air temperature, relative humidity, prevailing wind strength and direction, precipitation, potential evapo-transpiration, climate moisture index, runoff coefficient, soil salinization.

Quantitative descriptions of potential climate change impacts on the above parameters and phenomena are provided where practical. However, given the general lack of availability of data from quantitative models representing the sub-regional scales associated with the sub-studies, much of the characterisation of future conditions necessarily takes the form of more general, “speculative” commentaries, informed as far as possible by scientific studies, but also by expert judgment.

1.2. Approach and methodology

This study is based on a desk review combined with a visit to the region during which consultations were held with key experts in relevant fields. The review is therefore based purely on a review of the existing literature and the expert judgment of those consulted during the regional visit. No new research has been conducted. Forty experts were contacted within the region. Of the twelve that responded, eleven were consulted in person, and one via email. A list of experts contacted and consulted is provided in Annex II.

The aim of this study is to provide broad characterisations of potential future climatic conditions as relevant to the feasibility, design, operation and impacts of the proposed RSDSC. Given the lack of detailed information and the uncertainties associated with climate change and its impacts in the study area and its sub-regions (see below), the study seeks to provide guidance on how uncertain climate change risks might be reduced, avoided, and understood better (for example via studies carried out at the inception and design stages should the project be approved).

The study is split into two parts. Part I provides a broad discussion of current climatic conditions, climatic variability, and projected/potential future changes in climate. The treatment of potential future climate change focuses on key climate-related variables such as temperature, precipitation, relative humidity and sea-level. Part I also includes a discussion of the implications of climate change for water resources in the region, focusing on the three partners in the FS, namely Israel, Jordan and the Palestinian Authority. Part II consists of four sub-studies addressing climate change and its implications for the proposed RSDSC in each of the three sub-regions (the Gulf of Aqaba, the Wadi Araba/Arava Valley, and the Dead Sea), as well as the implications of climate change for desalination and transmission.

For each of the geographical sub-studies, a description of the context (e.g. geographical, climatic, oceanographic, environmental) is followed by a discussion of observed and projected changes in climate and related phenomena, the impacts of emerging and projected climatic changes in the sub-region (for a no-project case), the implications of climate change for the proposed RSDSC in the sub-region, and a set of recommendations.

1.3. Constraints

The review is severely constrained by the lack of information regarding climate variability and change in the region. While a number of studies of current climatic variability and potential future climate change have been carried out of the wider eastern Mediterranean – western Asian region, there have been no studies of how climate change might affect the limited area within which the proposed RSDSC would be constructed or its sub-regions, namely the northern Gulf of Aqaba, the Wadi Araba/Arava Valley, and the Dead Sea basin. While studies of potential future climate change have been conducted for northern Israel and the Jordan Valley, the area covered by these studies does not extend into the RSDSC study area. Furthermore, it is extremely problematic to extrapolate projected changes in climate from one region to an adjacent region, or from the regional scale to the small spatial scales that are of interest within the context of the Feasibility Study.

The above constraints mean that it is impossible to provide detailed scenarios describing future climatic conditions at the spatial scales of interest to the FS, or even to provide ranges of possible future conditions with quantitative assessments of probability. Discussions of climate change must therefore be restricted to broad characterisations of potential or likely future climatic conditions, with very general qualitative assessments of the likelihood of different climatic outcomes for the study area. Given the paucity of data and high-resolution studies of climate change and its impacts at the scales of interest, there is little or nothing meaningful that can be said about the future evolution of certain parameters in some or all of the sub-regions (for example wind strength and direction).

Thirty days were allocated for the CCS, sufficient time for a detailed review of the literature pertaining to climate variability, climate change, and other relevant issues in the region, and for consultations with a number of key experts within the region. However, the time and resources allocated to the study precluded any new research, or detailed assessments of climatological processes linking climate change at the global, regional and local scales (e.g. investigations of teleconnections influencing certain dynamical processes associated with rainfall and extremes). Regional consultations were also constrained by time and the availability of experts, and the need to conduct all consultations within a single 10-day period.

PART I: THE CLIMATIC CONTEXT

2. Current climatic conditions in the region

2.1. Geographic context

The study area is situated between the latitudes of 29° and 32° N, in the Afro-Asiatic or Saharo-Arabian sub-tropical desert belt, and falls within the Mediterranean, or eastern Mediterranean (EM), region as defined in a number of studies of climate change and its impacts. The more localized region in which the study area is situated exhibits great spatial and temporal climatic variation, with climatic regimes ranging from Mediterranean to hyper-arid. Topography plays a key role in the spatial variability of climate, with the low-elevations of the Dead Sea basin contrasting with the high elevations of adjacent highland regions. For example, on the eastern side of the Jordan Valley and Wadi Araba, upland areas rise to well over 1000 m, with Shoubak (east of the Wadi Araba) situated at an elevation of 1365 m above sea-level, and the northern Jordanian highlands east of the Dead Sea basin rising up to 1150 m[2]. These high elevation regions receive several hundred mm of rainfall every year, whereas rainfall along the Wadi Araba is measured in tens of mm. Mean maximum temperatures in the highland areas of Jordan are some 10° C cooler than those in the adjacent Jordan Valley[2]. Climatic parameters such as temperature and rainfall therefore exhibit steep spatial gradients.

2.2. Precipitation regimes

Precipitation exhibits great spatial and temporal variability in the study area and adjacent areas, as indicated by mean annual rainfall amounts in Jordan (Table 1), in which the RSDSC would be situated. Three broad rainfall zones or regimes may be defined for Jordan, with the highest rainfall (400-600 mm/yr) occurring in the northwest of the country in upland areas and the far north of the Jordan Valley, lower mean annual rainfall of 250-350 mm occurring in central Jordan and the southern uplands, and the lowest rainfall (less than 170 mm/yr) occurring in the lowland regions of the east and south of the country[2]. This last zone may be separated into steppe (140-170 mm/yr) and desert (less than 100 mm/yr), with the lowest rainfall occurring in the most southerly regions. The RSDSC would transit through the lowest rainfall zone, in which rainfall ranges from around 30 mm/yr at Aqaba in the south to around 75 mm/yr in the vicinity of Ghor Safi in the north[2]. Nonetheless, rainfall in adjacent regions influences runoff regimes that are important for the Dead Sea (although most runoff in the Dead Sea basin is currently diverted before reaching the Dead Sea) and the Wadi Araba. It should be noted that estimates of mean annual rainfall vary for the Wadi Araba and Dead Sea basin, due to different studies using data from different stations and averaged over different time periods, and due to the high temporal and spatial variability in rainfall which means that mean rainfall may vary considerably depending on which stations and averaging periods are used.

Rainfall within the study area and the wider region is negligible during the summer months, when the large-scale atmospheric circulation is dominated by subsidence associated with sub-tropical anticylonic systems. The vast majority of rainfall occurs in winter, with some rainfall in spring and autumn. In Jordan, the proportions of rainfall falling in winter, spring and autumn respectively are 63%, 23% and 14% for the northern uplands, 63%, 24% and 12% for the central area and southern uplands, and 54%, 25% and 21% for the lowland, steppe and desert areas[2].

Winter rainfall in the study area is predominantly associated with the passage of Mediterranean cyclones over the EM and into the Middle East, and with the intrusion of high pressure systems and polar air masses into the region. Heavy rainfall events are generally associated with the southward displacement of the polar front jet and its interaction with the high-level (upper tropospheric) tropical jet stream[3].

Table 1. Measured mean annual rainfall at various locations in Jordan, based on data for periods ranging from 33 to 78 years duration up to 2000 from Freiwan and Kadioglu (2008).[4]

	Rainfall (mm)	Region/description
NW Region: northern uplands, western Amman, Irbid, northern Jordan Valley (400-600 mm/yr)		
Ras Muneef	572	Uplands
Ajloun, Balqa	> 550	Uplands
Northern highlands	> 400	Uplands
Baqura	394	Uplands (northern Jordan Valley)
Central Region: central Jordan and southern uplands (250-350 mm/yr)		
Raba/Kerak	339	Uplands
Shoubak	294	Uplands
Tafeeleh	238	Uplands
Lowlands consisting of steppe (140-170 mm/yr) and desert (<100 mm/yr)		
Mafraq	158	Steppe
Wadi Dhalail	148	Steppe
Ghore Safi	74	Desert (Dead Sea area)
Jafr	33	Desert
Aqaba	32	Desert
Mudawara	12	Desert

Rainfall is also associated with certain configurations of the Red Sea Trough (RST), a region of low-pressure that extends north from the Red Sea towards the eastern Mediterranean at lower atmospheric levels. The RST is part of a wider region of low pressure extending over northern Africa and the western and southern regions of Asia, migrating northwards and eastwards through spring and summer[5]. The RST is most prevalent in spring and autumn, dominating the eastern Mediterranean region in October and disappearing in summer. The RST is generally associated with hot, dry conditions over the eastern Mediterranean and adjacent areas of the Middle East. However, it is associated with heavy showers and convective storms when it coincides with low pressure at higher levels extending southwards from the Mediterranean towards the Nile[6]. This combination of conditions, known as an active Red Sea Trough, was associated with 21%, 25% and 37% of the rain days in northern, central and southern Israel for the period 1985-1995[5]. The majority of floods in the Negev Desert between 1965 and 1994 were associated either with an active RST, or with a well developed Mediterranean anticyclone accompanied by a pronounced low pressure trough at higher atmospheric levels over Syria (a Syrian low)[7]. Rainfall associated with an active RST is particularly important for the study area, and explains the greater proportion of rainfall in the drier areas of Jordan (which include the study) falling in autumn[2], when the RST is most active.

2.3. Evaporation and groundwater recharge

The vast majority of precipitation in the region is lost through evapotranspiration. Abu-Taleb (2000) estimated that on average, around 85% of precipitation was lost through evaporation over the entire area of Jordan for the period 1960-87, with 8000 million cubic metres (MCM) of precipitation (P) and 7200 MCM of evapotranspiration (ET) in 1986, and 6800 MCM of P and 6120 MCM of ET in 1987[8]. Kunstmann et al. (2005) estimated that, in the Upper Jordan Valley catchment, around 55% of mean precipitation is converted to ET, with some 19% entering the Jordan through direct runoff and 26% being transformed into base river flow via infiltration[9].

Groundwater recharge estimates in arid zones have been described as "notoriously difficult"[10]. The above ratio of ET to P may be interpreted as providing a very crude indication of the upper limit of recharge, with rainfall not subject to subsequent evapotranspiration entering rivers or groundwater reservoirs. Mohsen (2007)[11] provides an estimate of groundwater recharge equivalent to around 4% of precipitation averaged over Jordan as a whole, with surface water amounting to some 11% of precipitation (together equivalent to the 15% of precipitation not lost to ET as estimated by Abu-Taleb as indicated above).

Dottridge and Abu Jaber (1999) examine the issue of recharge for the Azraq basin in Jordan, in which "a large proportion of the annual average rainfall of only 50-150mm is lost by direct evaporation or runs off to evaporate from the qa'as [silty-clay playa surfaces]"[10]. According to Noble (1998: 4), for the Azraq Basin, "*modern direct recharge is a reality*, with a mean annual recharge of 16.5±1.7 MCM/yr for rainfall stations above 980m and 21±4 MCM/yr for the Azraq and Safawi areas, giving a total of 37±5 MCM/yr for the northern part of the Azraq Basin."[12] Wadi boreholes indicate recharge spikes 2-10 days after runoff events, indicating that modern *indirect* recharge in the form of wadi runoff transmission also plays a role in replenishing groundwater[12]. Dottridge and Abu Jaber (1999) provide similar estimates for recharge rates in the Azraq Basin, but argue that, as the unsaturated zone of the Azraq basin is up to some 400m thick, it could take centuries for infiltrated rainfall to travel to the water table[10]. Noble (1998) reports that ^{14}C data indicate an age of 12,000 to 25,000 years for water in the centre of the Azraq basin[12]. The situation therefore appears complex, with modern recharge supplementing reserves of older water, including "fossil" water, and with recharge rates and processes being highly spatially variable. This situation may be viewed as a reflection of the wider situation throughout the region, particularly in the more arid areas, with the proportion of renewable groundwater (associated with modern recharge) to fossil water varying with location.

3. Observed regional climatic trends

3.1. Changes in temperature

Studies of observed changes in temperature in the study area and wider region are relatively few, and tend to focus on particular seasons. Trenberth et al. (2007: 250-251) present global temperature change maps which indicate an increase in annual mean temperatures equivalent to between 0º and 0.5º C per century over the Eastern Mediterranean between 1901 and 2005, and equivalent to 0.5º-0.7º C per decade for the period 1979-2005, with greater warming in spring and summer than in autumn and winter[13].

A study conducted in by Saaroni et al. In 2003 found that summer temperatures over the Eastern Mediterranean region (focused on northern Israel) increased over the latter half of the 20th century and into the 21st century, with warming accelerating towards the end of the 20th century[14]. Warming was greater in July than August, resulting in an earlier peak in summer temperatures, with July replacing August as the warmest month. Temperatures became more variable over short timescales, with an increase in the frequency of both "hot" and "cool" days (as compared to days with temperatures closer to the average for the time of year). The overall warming was due to a combination of the magnitude of warming, the frequency of hot days, and higher temperatures on "ordinary" days. These effects dominated over the impact of more frequent cool days on overall mean temperatures. Weaker northwesterly winds are also thought to have contributed to the observed warming, through a reduction in the advection of cool air.

Alpert et al. (2008) present a map of summer (June-August) temperature trends based on reanalysis data for the period 1948-2003, and expressed in ºC/century. The study area is situated in a region in which summer temperatures increased at a rate equivalent to 1.6°-2.4° C per century, and is located slightly closer to the 1.6º C warming isotherm than to the 2.4º C isotherm[15]. Summer warming over the entire Mediterranean region varied from 1.5º-4º C per century over the same period[15].

3.1.1 Observed changes in temperature in Jordan

All 19 Jordanian stations described in Jordan's Second National Communication (SNC) to the United Nations Framework Convention on Climate Change (UNFCCC) exhibit an increase in mean temperature[2]. This warming was statistically significant at the 99% confidence level at 10 stations, and at the 95% level at one station. Maximum temperatures increased at 16 stations, with significant increases at the 99% and 95% levels at six and three stations respectively. Minimum temperatures increased at all but one station, significant at the 99% level at 14 stations.

3.1.2 Observed changes in temperature in Israel

A recent study by Kafle and Bruins (2009)[16] examined annual temperature changes between 1970 and 2002 at twelve widely separated locations in Israel. Warming was significant at all stations, at the 97.5% confidence level or higher. At coastal stations the greatest warming was recorded at Tel Aviv, where a long-term warming trend resulted in annual mean temperatures for the last four years of the time series being some 1º C warmer than those a the beginning of the series (although the urban heat island effect was not addressed). Annual temperature fluctuations reflected global patterns, with low annual mean temperatures in 1991-92, following the eruption of Mount Pinatubo, and the warmest year in the series being 1998-99 (with years defined from 1 September – 31 August), more-or-less coincident with the maximum in global mean surface temperature measured in 1998. Equivalent linear trends in temperature for the period 1970-2002 at the twelve stations ranged from 0.0215º to 0.0509º C per year.

3.1.3. Observed changes in temperature in the Palestinian Territories

Little information is available on observed temperature trends from stations in the Palestinian Territories, with most studies focusing on these areas relying on wider regional datasets. However, an increase in temperature has been reported for the Gaza strip, with an increase in minimum temperatures making the dominant contribution to a warming of 0.4º C over the period 1976-1995[17].

3.2. Changes in precipitation

As discussed in more detail in the relevant sub-studies in Part II of this Climate Change Study, the trend in precipitation over the study area and the areas immediately adjacent to it appears to have been negative. However, studies of historical changes in precipitation in the wider Eastern Mediterranean region indicate a complex pattern of change, with increases in precipitation in some locations and declines in precipitation elsewhere. Changes in precipitation in the areas represented by the Beneficiary Parties of the proposed RSDSC are discussed in more detail below.

In the wider region, the Palmer Drought Severity Index indicates a shift towards drier conditions in the parts of the Eastern Mediterranean for which data are available, north of the study area (no data are available over the study area itself)[13]. The proportion of precipitation falling in heavy rainfall events appears to have increased according to global data representing climatic variability presented in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC)[18]. However, data from other studies provide a mixed picture of changes in precipitation intensity, as discussed below.

3.2.1. Observed changes in precipitation in Jordan

Of the 19 meteorological stations described in Jordan's SNC, 13 exhibited downward trends in annual precipitation over the latter half of the 20th century, with declines ranging from 5-20%[2]. However, the declines were only significant at Shoubak (99% confidence level) and Azraq (95% confidence level). Many of the stations exhibiting declining rainfall also saw an increase in the number of rain days, indicating weaker rainfall events (e.g. Wadi Duhleil, Irbid and al-Rabba).

A small minority of stations, such as Ruwaished (in the arid eastern region) and Ras Muneef in the northwest, exhibited an increase in rainfall of 5-10%. Some of these stations experienced a decline in the number of rain days, indicating that a greater proportion of annual rainfall fell in fewer, more intense events, an opposite trend to that associated with some of the stations exhibiting an increase in rainfall.

3.2.2. Observed changes in precipitation in Israel

Observed trends in rainfall in Israel vary with location, with a decline in rainfall at some stations and increased rainfall at others. A study published in 1996 by Steinberger and Gazit Yaari[19] indicated a general pattern of reduced annual rainfall in northern Israel (from approximately the latitude of Tel Aviv northwards) over the period 1961-1990, with declines of up to 30% at some stations. Over the same period annual rainfall increased at the majority of stations in the coastal plain south of Tel Aviv and at stations in the north-central Negev, but remained unchanged or declined in the vicinity of the Dead Sea and the Arava Valley/Wadi Araba. Monthly rainfall increased in October and decreased in December and January across Israel.

Kafle and Bruins (2009)[16] provide a more detailed picture of rainfall changes between 1970 and 2001. Along the coastal plain, rainfall declined at Negba, the most southerly site, and increased Ein HaHoresh, Tel Aviv and Hazor Ashdod. However, the increases in rainfall at these three sites were not statistically significant. Along the coast, rainfall was greatest during the cool year of 1991-92, and least during the hot year of 1998-99.

In the more inland easterly regions, mean annual precipitation for the period 1970-2002 declined from 530 to 480 mm at Kefar Blum (upper Jordan Valley), 695 to 665 mm at Har Kena'an (upper Galilee), and from 35 to 20 mm at Eilat[16]. The driest year was 1998-99 at two of the four stations in the inland easterly regions (Kefar Blum and Sede Boqer).

In the northern Negev, mean annual precipitation declined over the period 1970-2002 from 230 to 180 mm at Beer Sheva, 140 to 115 mm at Arad, and 58 to 28 mm at the Sedom Pans south of the Dead Sea[16]. However, at the most westerly site in the northern Negev, precipitation increased from 190 to 230 mm. Of all the twelve stations examined for the period 1970-200 by Kafle and Bruins, changes in precipitation were statistically significant only at Sedom. The driest year at all four stations in the northern Negev was 1998-99, although the wettest year varied across stations.

The overall pattern therefore appears to be one in which rainfall has tended to increase in an area including the coastal plain south of Tel Aviv and extending into the western and central Negev, with negative rainfall trends elsewhere, principally in northern Israel and the parts of southern Israel furthest from the Mediterranean coast, namely the southern and eastern Negev and the vicinity of the Dead Sea. A forthcoming study[20] reinforces the picture of declining rainfall in the eastern Negev, describing significant declines in rainfall and changes in the seasonal distribution of rainfall in the Arava Valley (Wadi Araba) in recent decades. These changes are described in more detail in Sub-Study B below.

Givati and Rosenfield (2007)[21] conclude that the most probably cause of the decline in rainfall in northern Israel is an increase in the atmospheric concentration of sub-micron aerosol particles derived from anthropogenic sources, which hamper the formation of water droplets of sufficient size to generate rain or snow, "reducing precipitation from short-lived clouds such as form in moist air that crosses topographic barriers." Whether this explanation can be extended to other areas in which declines in rainfall have been observed is currently uncertain.

3.2.3. Observed changes in precipitation in the Palestinian Territories

Rainfall data for the Palestinian Territories are generally not readily available. While long-term trends cannot be identified at present, figures from the Palestinian Ministry of Agriculture, cited in Mason et al. (2009)[22], indicate that, during 2008-9, rainfall in the West Bank and the Gaza Strip was 22% and 12% below the historic average respectively. While these deficits may be within the envelope of historical interannual variability, it is likely that changes in the Palestinian Territories reflect those in neighbouring Israel, where rainfall data for the period 1970-2002 indicate a general decline except in the central regions nearer to the coast (see above).

3.3. Changes in other climatic parameters

3.3.1. Changes in relative humidity, evaporation and sunshine duration in Jordan

Jordan's SNC summarises trends in relative humidity, evaporation and sunshine duration. Evaporation has declined since the 1960s/70s at 14 out of the 15 stations for which data are available, the exception being Wadi Dhulail, where the change was positive but effectively negligible, and not statistically significant. The decline in evaporation was significant at the 99% confidence level for 11 stations.

Relative humidity has increased at 15 stations since the late 1970s and declined at four stations, with declines being significant at the 95% and 99% confidence levels for two and six stations respectively, and none of the increases being significant at these confidence levels. Data for both relative humidity and evaporation are available for six of the stations exhibiting a significant increase in the former. At five of these stations (Ghor Safi, Irbid, Aqaba, Ruwaished, Safawi), higher relative humidity is associated with lower evaporation, with trends in both being statistically significant. At the remaining station (Ras Muneef), a significant increase in relative humidity is associated with a small, statistically insignificant increase in evaporation.

Hours of sunshine declined by between 2% and 8% at all 16 stations for which data were available (with significant trends at 10 stations), except at Queen Alia International Airport, where there was a small but insignificant increase. Four of the five stations (Ghor Safi, Aqaba, Ruwaised, Safawi) with significant positive trends in relative humidity and negative trends in evaporation exhibited significant declines in hours of sunshine. At Irbid, trends were in the same direction, although the decline in sunshine duration was not significant. While the data for all stations indicate considerable variation in climatic trends, they do suggest a tendency over parts of Jordan for reduced sunshine (likely to be the result of increase cloud cover and/or greater atmospheric concentrations of dust particles and/or other aerosols) to be associated with a decline in evaporation and a reduction in relative humidity. Significantly, the two stations at the southern and northern ends of the proposed RSDSC route exhibit these coherent trends.

3.3.2. Changes in solar irradiance in Israel

A number of studies published in the 1990s described a decrease in the amount of solar radiation reaching the Earth's surface over Israel since the 1950s[23,24,25]. Measurements at three stations in the coastal plain indicated an average decline of 1.4 Wm^{-2} per year between 1956 and 1987, and an analysis of 130 station-years across Israel showed an average overall decrease in irradiance of 20%. The decline was greater in winter than summer, greater in the northern Jordan Valley than the southern Negev, and greater under overcast conditions than under clear-sky conditions. Overall, cloud cover was found to have declined slightly over the same period, and the decline in irradiance could not be explained in terms of changes in extent or duration of cloud cover. The favoured explanation for the observed decline in irradiance was an increase in atmospheric aerosol loadings from anthropogenic sources such as motor vehicles, resulting in the scattering and absorption of solar radiation and an increase in the reflectivity and absorbtivitiy of clouds[25].

3.3.3. Changes in aridity index in Israel

Kafle and Bruins (2009) examined trends in the aridity index (P/PET: ratio of precipitation to potential evapotranspiration) for the period 1970-2002 in Israel. They found negative trends in P/PET at nine out of twelve stations, with positive trends at two stations (Ein HaHoresh and Hazor-Ashdod) on the Mediterranean coast and at Besor Farm, the most westerly station in the northern Negev, adjacent to the Gaza Strip and close to the coast. The only statistically significant trends were negative, at Eilat, Beer Sheva and Sedom Pans. The overall pattern (regardless of considerations of statistical significance) was one of increased aridity inland, away from the coastal plain. At Tel Aviv P/PET decreased despite an increase in precipitation, due to a high level of warming.

3.4. Changes in extremes

The observed increase in the number of “cool” and “hot” days in the eastern Mediterranean region indicates a trend of increasing variability and extremity, particularly with respect to heat extremes[14]. The increase in seasonal maximum temperatures is some three times greater than the increase in seasonal minimum temperatures in summer, when the greatest warming occurs[14]. The trend in the frequency of hot days during July-August for the period 1948-2002, when temperature rose by more than one standard deviation above the mean for the same period, was 0.13 days/yr (significant at the 97.5% level), while the trend in cool days (with temperatures more than one standard deviation below the long-term mean) was 0.014 days/yr[14].

Coupled with increases in temperature and the general (although not universal) observed decline in rainfall in the region is a trend towards more frequent and severe drought conditions. For example, Israel declared a drought in June 2005 after a year in which rainfall in the Lake Kinneret catchment was reported to be some 80-85% of the mean value, following series of low-rainfall years which resulted in low lake levels[i].

Definitive changes in the intensity of rainfall and runoff events are yet to be identified. The changes in rainfall at different Jordanian meteorological stations, described above, suggest conflicting trends. At some stations, increased rainfall coupled with a reduction in rain days indicates a shift to more intense rainfall events, while at others, reduced rainfall coupled with an increase in rain days suggests less intense precipitation.

[i] IRIN, 5 June 2009. “Drought declared as five dry winters take their toll.” http://www.irinnews.org/Report.aspx?ReportId=84715

4. Global and regional climate projections

Climate change projections for the region containing the study area are available from a number of studies, employing a variety of models. Some of these studies focus specifically on the Mediterranean or east Mediterranean region, although none examine changes within the study area, and even high resolution studies are at best only broadly indicative of potential future changes. Furthermore, most studies have focused on scenarios in which projected greenhouse gas emissions are lower than is likely to be the case in the light of current trends in emissions, and are therefore likely to underestimate warming at the global (and by extension also at the regional) scale. Caution must therefore be exercised when using climate projections for decision-making, and projected changes in climatic variables should be used only to provide very broad characterizations of how climate might evolve in the future. Most projections focus on temperature and precipitation, although a few examine potential changes in other parameters such as sea-level pressure and atmospheric water vapour content. However, no studies provide projections of climate variables at the local scales that are especially relevant to the RSDSC FS.

4.1. Temperature projections

4.1.1. Global temperature projections

Global mean surface temperature is projected to rise over the 21st century as a result of the continuing increase in atmospheric greenhouse gas concentrations resulting from human activities, principally the burning of fossil fuels and changes in land use. The IPCC AR4 projections indicate that, globally, the period from 2011-2030 is likely to be 0.65°-0.69° C warmer on average than the period from 1980-1999, based on results from three different emissions scenarios[26]. This warming increases to 1.3°-1.8° C for the period 2046-2065, and to 1.8°-4.0° C for 2090-2099[i]. These warming values are in addition to the warming of around 0.6° C that occurred over the course of the 20th century.

The increase in the range of these warming projections with time is due to a combination of uncertainties in future greenhouse gas emissions and climate sensitivity, and the uncertain role of feedback mechanisms in the climate system. Projections for the earlier half of the 21st century are relatively insensitive to assumptions about emissions, as a result of the time taken for the climate system to respond to increased atmospheric greenhouse gas concentrations. Uncertainties associated with feedback mechanisms are the result of an incomplete understanding of the global carbon cycle, which might act to reduce or amplify warming. The risk that warming will be amplified by positive feedbacks is likely to increase at higher levels of warming. To place these projections in context, particularly for the latter part of the 21st century, it should be pointed out that greenhouse gas concentrations are currently rising at a rate comparable with that associated with the highest-emissions scenarios used by the IPCC. A continuation of current policy regimes in the short to medium term is likely to result in a commitment to a warming of around 4° C or more by 2100[27].

[i] These figures represent averages across a number of models for the lowest and highest emissions scenarios respectively. The full range of projected warming (i.e. across individual models) is 1.1°-6.4° C.

4.1.2. Regional temperature projections

A number of global and regional modelling studies yielding temperature projections for the mid to late 21st century over the east Mediterranean region are described below, with projected warming values for the late 21st century summarized in Table 2.

The IPCC (2007) presents aggregated average warming projections to 2100 for a range of emissions scenarios for the Saharan (SAH) region and the Southern Europe and Mediterranean (SEM) region. Both of these regions extend over the longitudes of the study area, the majority of which lies within the SAH region, with the Dead Sea located in the SEM. The projected warming by 2100 averaged over the SAH region ranges from around 3° C to 7° C across low to high emissions scenarios[28]. The range for SEM is similar, with a slightly lower maximum warming of around 6.5º C.

For the medium emissions A1B scenario, the IPCC provides more detailed information on projections and projects a warming of some 2.5°-3.5° C by the middle of the 21st century for the SAH region. For the period 2080-99, relative to 1980-99, the projected warming under the A1B scenario is cited as 2.2º C to 5.1º C. Maps of projected warming by 2080-99 for the A1B scenario indicate a mean annual increase in temperature of between 3º C and 3.5º C over the RSDSC study area, extending from the Gulf of Aqaba to the Dead Sea. Projected summer warming for the A1B scenario, averaged across nineteen models, is between 3.5º C and 4º C, with a warming in winter of 2.5º-3º C[28]. However, it should be noted that the A1B scenario is a medium emissions scenario, and is likely to be conservative in its representation of future greenhouse gas emissions, with high emissions scenarios more accurately reflecting current and future trends in emissions[27].

In a high resolution study of future changes in precipitation and runoff in the "Fertile Crescent" region (extending over much of the Arabian Peninsula) under the A1B scenario, using the Japan Meteorological Agency model (JMA), Kitoh et al. (2008) examine projected changes using temperature output from models representing "moderate" and "high" climate sensitivity respectively[29]. Climate sensitivity is defined as the equilibrium warming resulting from a doubling of greenhouse gas concentrations, measured in CO_2 parts per million equivalent (ppme), with respect to the late pre-industrial value of around 268 ppme. Climate sensitivity is 3.2º C and 4.3º C in the moderate and high sensitivity models respectively[30]. The two models employed produce a mean annual surface warming (for 2080-2099, relative to 1979-1998) of 2.6º C and 4.8º C respectively in the target region. While the moderate value is closer to the IPCC's "most likely value" of climate sensitivity of around 3º C[26], this should be weighed against the use in this study of the moderate emissions A1B scenario, which is very likely to underestimate future emissions.

A downscaling study of projected temperature changes in the Mediterranean area by Hertig et al. (2008) examined changes to 2100 under the medium emissions B2 emissions scenario, using output from two global climate models, ECHAM4/OPYC3 and HadCM3[31]. Most of the Mediterranean region is projected to warm by between 2º C and 4º C by 2071-2100 compared with 1990-2019, with a warming of between 3.5º C and 4º C in winter (December-January) over land regions in the eastern Mediterranean, including the study area. Increases in winter temperatures are not smooth, and data subject to an 11-year smoothing exhibit considerable variation, with decadal-scale periods of warming and cooling superimposed on the long-term trend. Short-term changes can be large in the smoothed time series, with changes of 1º C or more occurring over decadal scale periods. The smoothed time series of winter mean temperature for the eastern Mediterranean suggests a warming during this season of around 1º C by 2030 and 2º C by 2050.

Giorgi and Lionello (2008) examined output from the ensemble of models used in the IPCC AR4 and from the European PRUDENCE project, focusing on the Mediterranean and its sub-regions[32]. Under the A1B scenario, average warming over the study area by 2071-2100 (relative to 1961-1990) is 2º-3º C for December-February, 3º-4º C for March-May, 4º-5º C for June-August, and 3º-4º C for September-November.

A small number of studies have examined potential temperature changes in the wider region containing the study area under the high emissions (and thus more “realistic” in the light of recent emissions trends) A2 scenario. A study by Somot et al. (2008) using the Sea Atmosphere Mediterranean Model (SAMM), in which a high resolution global climate model is coupled with a regional model for the Mediterranean region, examined differences between sea surface temperatures (SSTs) and air temperatures at 2m elevation between 1961-1990 and 2070-2099 precipitation, under the A2 scenario, for Europe and the Mediterranean[33]. Warming values were presented for a number of different sub-regions, although none of these included the southeastern Mediterranean or the study area. However, graphical depictions of changes in SST indicate an increase in the southeast Mediterranean of 2º-2.5º C in winter and 2.5º-3º C in summer. Air temperatures over the study area (Gulf of Aqaba to Dead Sea) increased by 3º-4º C in winter and 3º-5º C in summer.

A recent study of output from the RegCM regional climate model by Alpert et al. (2008) identified an average projected warming by 2071-2100 (relative to 1961-1990) over the eastern Mediterranean of 3º-5º C for the high emissions A2 scenario and 2.5º-3.5º C for the medium emissions A1B scenario, with greater warming over land regions than over the sea[15]. Extreme daily temperatures over northern Israel increased by 6º C. Over the RSDSC study area, summer warming was between 3.5º C and 4º C for the A1B scenario, and between 5º C and 5.5º C for the A2 scenario.

Hemming et al. (2008)[34] examine projected temperature changes over the wider Middle Eastern region for a number of time periods under the A2 scenario using the PRECIS high resolution regional climate model, and find increases in annual mean temperature of 1.2º C by the 2020s, 2º C by the 2040s, and 3.2º C by the 2070s (relative to the 1990s). Warming over the RSDSC study area broadly reflects the wider regional warming, although by the 2070s the study area is situated at the edge of the area of greatest warming, within which warming reaches 4.2º C. Warming is greatest in summer and lowest in winter. Minimum temperatures increase at a faster rate than maximum temperatures, with minimum temperatures rising by 1.6º C, 2.7º C and 4.3º C by the 2020s, 2040s and 2070s respectively, compared with respective increases in maximum temperatures of 1.4º C, 2.4º C and 3.8º C. The study area is located in an area that experiences the largest increases in spring and summer minimum and maximum temperatures, with summer minimum and maximum temperatures increasing by around 2º C by the 2020s, 3º-4º C by the 2040s, and approaching 5º C by the 2070s.

Table 2. Annual and seasonal projected warming for the late 21st century from a variety of global and regional modelling studies over the RSDSC study area and the wider region. MED indicates the entire Mediterranean region, SAH indicates the Saharan region as defined in the IPCC AR4, and SEM indicates the IPCC Southern Europe and Mediterranean region. Ranges of projected temperature increases are given, except where studies quote mean warming values. Ranges are as quoted in the text, or estimated from graphical depictions of temperature projections (focusing on the RSDSC study area), depending on the source.

Model/Study	**Winter (DJF)**		**Spring (MAM)**		**Summer (JJA)**		**Autumn (SON)**		**Annual**	
	min	max	min	max	min	max	min	max	min	max
IPCC all scenarios SAH (Christenen et al 2007)									3	7
IPCC all scenarios SEM (Christenen et al 2007)									3	6.5
IPCC A1B SAH (Christenen et al 2007)									2.2	5.1
IPCC A1B study area (Christenen et al 2007)	2.5	3			3.5	4			3	3.5
JMA A1B high, Mid. East (Kitoh et al. 2008)									4.8	
JMA A1B low, Mid. East (Kitoh et al. 2008)									2.6	
ECHAM B2, MED (Hertig et al. 2008)	3.5	4							2	4
Ensembles A1B, study area (Giorgi et al 2008)	2	3	3	4	4	5	3	4	3	4
RegCM A1B study area (Alpert et al 2008)					3.5	4				
RegCM A2, study area (Alpert et al 2008)					5	5.5				
SAMM A2 study area (Somot et al 2008)	3	4			3	5				
PRECIS A2, study area (Hemming et al 2008)	3	3.5	3	4	3.5	4.5	3.5	4.5	3	4

4.1.3. Assessment of likely future changes in temperature

The projections described above indicate a range of potential mean annual warming over the study area of between 2º C and 7º C by the final decades of the 21st century (broadly speaking the 2070s to 2090s), across a range of emissions scenarios. Warming at the upper end of this range is associated with the IPCC projections, which are based on global climate models. Of the regional models examined, the majority examine medium emissions scenarios, with only one study (Hemming et al., 2008) providing estimates of potential late 21st century warming under a high emissions scenario. The range of projected warming (above late 20th century values) for these regional projections is from 2º-4.8º C, with the upper end of this range associated with a high estimate of global climate sensitivity. A more reasonable and representative range would appear to be 2º-4º C, with three out of four studies indicating a minimum projected warming closer to 3º C than 2º C. A projected mean annual warming of some 3º-4º C by the late 21st century (2070s) therefore appears to be representative of the (albeit limited number of) regional climate model projections examined here.

Those studies that provide projections for earlier decades indicate a warming over the study area of around 1º C by the 2020s-2030s (based on two studies), 2º C by the 2040s (based on one study) and between 2º C and 3.5º C by the 2050s (based on three studies including the IPCC projections, and relative to the late 20th century).

Lower and higher levels of warming to those indicated above are plausible, although it is suggested that lower warming is unlikely given that the low ends of the ranges are associated with medium emissions scenarios that are highly conservative when compared with current emissions and

Changes in seasonal, monthly and daily temperatures and temperature extremes are likely to exhibit considerable deviation from the projected changes in annual mean temperatures. Summer (June-August) temperatures are projected to increase by between 3º C and 5.5º C in the study area and adjacent regions by the late 21st century, across a range of scenarios, with the highest daily extreme temperatures increasing by a comparable amount or greater. Warming is projected to be less pronounced in other seasons, and lowest in winter. Regional warming patterns are likely to exhibit a high degree of spatial and temporal variability, with warming being greater over land than over the oceans, and warming in coastal areas being less than over continental interiors. Warming trends may be masked for short periods (of the order of years) by internal climatic variability, and this might result in large changes occurring over short timescales. Nonetheless, the above projected warming values may be taken as indicative of likely average temperature changes over the study area. Warming scenarios for the RSDSC are provided in Annex I.

4.2. Precipitation projections

4.2.1. Review of precipitation projections for the eastern Mediterranean

There is widespread agreement across climate models that the entire Mediterranean region will become considerably drier over the course of the 21st century. However, the high degree of spatial variation in topography and current climate conditions in and around the RSDSC study area means that results from global models, which cannot resolve these details, should be treated with caution. Some recent studies have used regional climate models to assess potential future changes in precipitation in the eastern Mediterranean and Middle East, and these are better able to resolve topography and capture the high degree of spatial heterogeneity in climatic conditions. Results from individual studies, many of which employ results from multiple models, are summarized below, and in Table 3.

All the models considered in the IPCC AR4 simulate a decline in rainfall over the study area by the late 21st century, with an average decline in mean annual and winter (December-February) rainfall of 20-30% for the medium emissions A1B scenario[28].

Regional modelling studies of the Mediterranean region (including the study area) using the A1B scenario by Mariotti et al. (2008) indicate an average decline in precipitation over land regions of around 8% for the period 2020-2049, and 15% by 2070-2099, compared with 1950-2000[35]. The modelled amplitude of the average decline by 2020-2049 is equivalent to that associated with the driest episodes experienced during the 20th century. Climatic variability will mean that the region will experience episodic droughts exceeding in magnitude anything experienced during the 20th century by the early-middle 21st century.

Giorgi and Lionello (2008) use model ensembles to examine projected changes in precipitation over the Mediterranean region for the late 21st century for three different emissions scenarios, and for earlier periods for one scenario (A1B)[32]. For the A1B scenario they find a projected decline in precipitation over the study area for the period 2071-2100 (compared to 1961-1990) of 20-30% for winter (December-January), 30-40% for spring (March-May), and 0-20% for summer (June-August). In the autumn (September-November), the study area is situated in a zone where the projected precipitation change exhibits a steep gradient, with a projected increase in precipitation of up to 10% in much of the northern Gulf of Aqaba, and a decline of 0-20% over the RSDSC study area, increasing northwards from around zero at the head of the Gulf of Aqaba.

The ensembles study of Giorgi and Lionello (2008) also describes simulated changes in precipitation under the A1B scenario for the 2020s and the 2050s[32]. Compared with the 1970s, winter precipitation over the study area shows a slight decrease (less than 10%) by the 2020s, with a larger decrease of 20-30% by the 2050s. Summer precipitation is reduced by up to 10% in both the 2020s and 2050s, although in the 2050s a zone of increased precipitation is situated immediately south of the study area, extending to the northern parts of the Gulf of Aqaba. Considering the projected reductions in winter precipitation of less than 10% by the 2020s under the A1B scenario, it is worth noting that rainfall has already declined by more than 10% (with reference to the same baseline period, the 1970s) at a number of stations in the region, particularly in drier locations[2,16].

For the B1 scenario, projected precipitation over the RSDSC study area declines by 10-20% in winter and 10-30% in spring in the ensembles study[32]In summer, precipitation increases by some 20% in the north of the study area to over 40% in the south, while in autumn it increases by between about 0% and 10%.

For the A2 scenario, projected precipitation in the ensembles study over the RSDSC study area declines by 30-40% in winter, and over 40% in spring. In summer precipitation increases by 0-40%, while in autumn the situation is somewhat similar to that of the A1B scenario, with the study area situated at a transitional location and projected precipitation changes ranging from –10% to +10%, with positive changes over the northern Gulf of Aqaba and negative changes over the Dead Sea.

The high emissions A2 scenario SAMM study by Somot et al. (2008) described above suggests a decline in winter precipitation of 0.2-0.5 mm/day, equivalent to 18-45 mm over the approximately 90-day December-February winter period[33]. Such a reduction would represent a considerable proportion, and perhaps the majority, of rainfall over this period within the study area, where average annual rainfall is less than 100 mm per year, with just over half of the precipitation falling in December-February. Reductions at the lower end of this range would represent over half of the current average annual rainfall in the southern parts of the study area, while reductions at the upper end of the range would represent similar reductions in the northern parts of the study area.

Alpert et al. (2008) find a projected decline in winter (December-February) precipitation of 15-75 mm or about 10-30% over the eastern Mediterranean by 2071-2100 (compared to 1961-1990) under the high emissions A2 scenario, using the RegCM model[15]. The projected decline is around 15 mm at the northern end of the RSDSC study area, and less than 15 mm over much of the proposed conveyor route. Projected reductions in winter rainfall are near-zero under the B2 scenario.

Hemming et al. (2008)[34] examine precipitation projections for the 2020s, 2040s an 2070s using regional and global climate model output, and highlight the fact that the regional climate model simulations project higher amounts of precipitation than the global model simulations, due to the former's better representation of topography and convection. The PRECIS regional model simulates a decline in precipitation over the RSDSC study area and immediately adjacent regions of 0-20% by the 2020s, 0-30% or more by the 2040s, and 10-30% or more in the 2070s. The decline is greater over the northern parts of the study area, approaching or around 10% by the 2020s, and with the decline in precipitation over most of the study area exceeding 10% by the 2040s, and 20% by the 2070s.

Seasonal projections using the PRECIS model indicate a more complex situation, in which high spatial variability in projected precipitation changes is combined with projections of both increased in decreased precipitation depending on location and season. Precipitation declines by 0-30% in spring (March-May) in the 2020s and 2040s, and by 30-60% at the extreme southwest and northeast of the study area in the 2070s. However, a localized anomaly indicates an increase of up to 40% over the Dead Sea in all three periods. In summer (June-August) projections indicate changes in precipitation of –30% to +40% over the study area, with declines of over 40% over the Dead Sea, in all three periods, with spatial heterogeneity in the fields of projected changes increasing over time. A similar situation pertains in autumn (September-November), albeit with less spatial variation than in June-August. A notable feature of the autumn projections is an area of projected drying (of up to 30%) extending approximately south to north, and approximately coincident with the Wadi Araba and Jordan Valley, adjacent to areas in which precipitation is projected to increase by between 0 and 40%. However, localized anomalies over the Dead Sea basin indicate an even large drying, of up to 60%. A combination of increased and decreased precipitation is also evidence in December-February, although drying is more dominant in this season, and more uniform across a zone that extends across the central and northern Levant and south into the study area. Nonetheless, increased rainfall is projected in winter over the far south of the study area, over parts of southern Israel, and over the high elevation regions southeast Jordan and northwest Saudi Arabia adjacent to the southernmost parts of the study area.

Table 3. Projected percentage changes in precipitation over the study area and (for CMIP3) the Mediterranean region in winter (DJM), spring (MAM), summer (JJA) and autumn (SON), and annually.

Model	DJF	MAM	JJA	SON	Annual
IPCC A1B study area (Christenen et al 2007)	-30 < -20		-5 < 0		-30 < -20
CMIP3 A1B (Mariotti et al. 2008)					-15
Ensembles A1B study area (Giorgi et al 2008)	-30 < -20	-40 < -30	-20 < 0	-20 < 0	
Ensembles B1 study area (Giorgi et al 2008)	-20 < -10	-30 < -10	+20 < +40	-10 < 0	
RegCM B2 study area (Alpert et al. 2008)					0 < 5
Ensembles A2 study area (Giorgi et al 2008)	-40 < -30	< -40	0 < +40	-10 < +10	
RegCM A2 (Alpert et al. 2008)					-30 < -10
PRECIS A2, study area (Hemming et al 2008)	-30 < 0	-60 < 0	-30 < +40	-30 < +40	-30 < -10

4.2.2. Assessment of likely future changes in precipitation

The majority of model projections indicate a significant reduction in precipitation over the RSDSC over the course of the 21st century, with reductions in mean annual rainfall ranging from around 10-30% by the mid-late 21st century in the majority of simulations, representing both medium emissions (A1B) and high emissions (A2) scenarios. Only one example from those reviewed here indicates an increase in rainfall, of less than 5% and associated with the somewhat unrealistic (given current and projected emissions) B2 scenario. The ENSEMBLES study does not provide data on projected changes in annual precipitation, but indicates possible reductions in winter and spring of more than 30% which, coupled with the projections for summer and autumn, suggest that annual reductions of more than 40% might be plausible.

Three of the studies reviewed here provide projections of precipitation for the early to mid 21st century. The two studies based on the medium emissions A1B scenario indicate a reduction in precipitation of around 10% or less prior to 2050, with one of these representing the winter period only. The PRECIS regional climate model study indicates a reduction of up to 20% by the 2020s and up to 30% by the 2040s.

The two studies that provide seasonal projections under the high emissions (and arguably most realistic) A2 scenario indicate reductions in precipitation in excess of 30% in spring (both ENSEMBLES and PRECIS studies) and winter (ENSEMBLES). These studies indicate a potential increase in summer precipitation over at least parts of the study area, although this season makes a very small or negligible contribution to annual rainfall totals. In autumn, when rainfall is strongly influenced by the behaviour of the Red Sea Trough, both of the A2 simulations indicate an increase in precipitation over some parts of the study area, and a decrease over others. In the ENSEMBLES A2 simulation the study area is situated at the autumn transition between positive changes in precipitation to the south and negative changes to the north. In the higher resolution PRECIS study, autumn precipitation changes are negative in an area approximately corresponding to the Wadi Araba and Jordan Valley, and positive east and west of this area.

The high degree of spatial heterogeneity in patterns of precipitation changes projected by the high resolution regional PRECIS model is in marked contrast to the much more zonal patterns of change projected by global climate models, and indicates that output from the latter should be used with caution. The geographical transitions between positive and negative projected changes in precipitation in both regional and global model output further indicate that caution should be exercised when assessing potential future precipitation changes in the study area. Such spatial variability is not surprising given the complex and extreme topography of the region, and observations indicating reduced rainfall in some areas and increased rainfall in others over recent decades.

The spatial transitions between projected negative and positive precipitation changes in autumn are of particular interest given the role of the Red Sea Trough in rainfall generation in this season. Projections indicating a possible increase in rainfall over parts of the study area in autumn are at odds with the large observed declines in rainfall at some stations in the Wadi Araba[20]. While it is not clear whether these observed declines are likely to be sustained over time, this apparent contradiction between observations and simulations raises the possibility that interactions between the RST and other aspects of the regional circulation may not be captured adequately by the models.

Our understanding of the potential future evolution of rainfall in the RSDSC study area would benefit from further modelling studies. In this context it is noted that high-resolution studies of future climatic conditions in northern Israel and the Jordan Valley have been conducted by researchers at Tel Aviv University and their colleagues working under the auspices of the GLOWA project. Such studies might be replicated for the hitherto neglected area immediately to the south, through which the proposed RSDSC would transit, given sufficient time and resources. In the meantime, some general and somewhat speculative precipitation scenarios are described in Annex I.

4.3. Regional runoff projections

The precise impacts of climate change on absolute water availability will be closely linked with changes in runoff, which at any given location will depend on a variety of factors including changes in temperature, precipitation evapotranspiration, wind regimes land use and land surface properties, as well as topography and hydrogeology. Detailed studies of the impacts of climate change on water availability in the form of surface runoff in the study area and its sub-regions are not available. However, studies are available for other regions, including some of those adjacent to the study area.

Even if average rainfall was to remain unchanged, higher temperatures would result in a reduction in surface water resources and groundwater recharge as a result of increased evapotranspiration (ET). For example, a study of the sensitivity of water resources to climate change in Morocco concluded that a 1° C increase in average temperatures (with no change in rainfall) over the catchment of the country's largest dam would result in a decline in surface runoff of some 10%, equivalent to losing one dam per year when extrapolated across the entire country[36]. In Jordan, Abdullah and al-Omari (2008) conclude that a 2º-4º C average rise in temperature could result in a reduction in flow in the Azraq basin of 12-40%[37]. According to Abu Taleb (2000)[8] ET can be expected to increase by some 6% for every 1º C rise in temperature. Under the scenarios associated with highest warming discussed above, this would translate into an increase in ET of something in the region of 25-30%.

Higher ET rates will act in conjunction with projected reductions in precipitation to reduce runoff rates and groundwater recharge. For example the 15% average decline in precipitation over Mediterranean land regions simulated in the study by Mariotti et al. (2008) mentioned above translates into a 20% average decrease in the availability of surface water when increases in evaporation are taken into account, according to the same study[35]. The IPCC AR4 presents two global maps of projected changes in runoff for the medium emissions A1B scenario, indicating a decline of 10-20% for the period 2041-60 (relative to 1900-70) and 30-50% for the period 2081-2100 (relative to 1981-2000)[38] in the region containing the RSDSC study area.

A recent study using a high resolution (20 km x 20 km) global climate model based on the Japanese Meteorological Agency (JMA) operational numerical weather prediction model concluded that streamflow in the rivers of the "Fertile Crescent" region is likely to decline dramatically, with a modelled decline in the flow of the Jordan River of 82% and 98% for moderate and high values of global climate sensitivity respectively under the high emissions A2 scenario[29]. However, Ben-Zvi and Givati (2008)[39] question the reliability of this study on the grounds that the JMA model fails to represent present day patterns of precipitation in the Fertile

Crescent region accurately, and significantly underestimates the current streamflow in at least some of the region's rivers. The implications of these factors are that the projections for the Jordan River and the wider Fertile Crescent region may overestimate likely future reductions in streamflow.

Given the suggested 6% increase in ET per 1º C temperature rise and the estimated 10% reduction in runoff per 1º C temperature rise for the specific case of Morocco, we may conclude that changes in temperature alone may reduce the availability of useful surface water by several tens of per cent by the late 21st century given the projected range of warming for the study area and wider region. Projected reductions in rainfall of up to 30% or more over the study area and adjacent regions will result in reductions in surface water resources of a similar magnitude or greater. While the high resolution modelling study indicating an 82-97% reduction in streamflow in the Jordan River basin may overestimate the impact of climate on water resources, the combined impact of projected increases in temperature and reductions in rainfall could plausibly result in the loss of the majority (i.e. over half) of the region's surface water resources under a worst-case scenario, although changes in the ratio of precipitation to ET, and in local surface runoff, could exhibit considerable spatial variation. The above considerations indicate that a decline in runoff of some 50% probably represents a reasonable illustrative worst-case scenario for the purposes of assessing plausible climate change impacts on water resources by the mid-late 21st century, although considerable uncertainty remains.

4.3.1. Basin-scale runoff projections: the Zarqa and Yarmouk river basins, Jordan

Jordan's SNC describes the results of sensitivity studies based on incremental scenarios, which examine the impacts of prescribed changes in temperature and rainfall on surface runoff for the Jordanian sectors of the Zarqa and Yarmouk river basins, using the Water Evaluation and Planning (WEAP) system model. These sensitivity studies focus on the impacts of temperature changes combined with different *increases* in rainfall, and therefore yield little information on how a decline in rainfall might affect water resources. The results indicate that increases in rainfall of 10% and 20% are likely to more than compensate for additional evaporative losses associated with warmings of 2° C and 4° C respectively (Table 4). However, with no change in rainfall, a warming of 4° C is projected to result in a decline in runoff of at least 20% in the Zarqa basin and 9% in the Yarmouk basin. In the Zarqa basin additional evaporative losses associated with a warming of 3° C are projected to offset the additional runoff resulting from a 10% increase in rainfall[2]. It may be inferred from these results that plausible warming values combined with expected reductions in rainfall are likely to reduce runoff by the order of tens of percent by the middle of the 21st century.

Simulations using global climate model output (as opposed to incremental scenarios) to drive the WEAP model, also described in Jordan's SNC, produce mixed results. The Simulations using the Australian CSIROMK3 model indicate a reduction in runoff in the Zarqa basin of some 25% by the middle of the 21st century, with the greatest reduction in January, while simulations with data from the German ECHAM5OM and UK HADGEM1 models indicate little or no change in runoff. However, simulations using output from all three models indicate reduced runoff in the Yarmouk basin, with reductions of up to 30% that are particularly pronounced in March[2].

The results of the WEAP modelling studies highlight the fact that runoff responses to climate change will vary from one river basin to another, indicating that caution must be employed when using regional climate change projections to infer information about potential changes at sub-regional scales. Nonetheless, the results from the WEAP studies broadly reflect those of the global and regional studies discussed above, indicating that changes in runoff of tens of per cent might be anticipated as a result of plausible changes in temperature and rainfall.

Table 4. Modelled changes in surface runoff for the Zarqa and Yarmouk river basins under different incremental precipitation-temperature scenarios, based on results from the Water Evaluation and Planning (WEAP) system model presented in Jordan's SNC[2].

Scenario		Runoff projections	
Precipitation	Temperature	Zarqa Basin	Yarmouk Basin
< +10%	< +2° C	+5%	+5%
~ +20%	~ +1° C	+30%	> +12%
~ +20%	~ +4° C	+22%	> +9%
No change	< +4° C	-20% or more	-9% or more
~ +10%	~ +3° C	~0%	n/a

4.3.2. Impacts on groundwater recharge

It is reasonable to assume that groundwater recharge rates will be reduced by an amount comparable to that by which runoff decreases, although recharge will also be affected by factors such as the intensity and frequency of precipitation, and any changes in the properties of the land surface that might alter infiltration rates. Little information is available regarding the quantitative impacts of climate change on recharge rates, although a study by Mizyed (2009)[40] concludes that a 16% decline in rainfall in the West Bank could result in a reduction in annual groundwater recharge of 30%, and that the decline could be as high as 50% when such a reduction in precipitation is combined with a projected increase in mean temperature of 6º C.

4.4. Future climatic extremes

The frequency, severity and duration of extreme climatic events are likely to be influenced by climate change. IPCC global projections suggest a small and statistically insignificant increase in the incidence of dry days, a small and statistically insignificant decline in precipitation intensity, and a large and statistically significant increase in the incidence of heat waves in the region containing the RSDSC study area for the medium emissions A1B scenario[26]. Giorgi and Lionello (2008) report that modelling studies indicate increased year-to-year variability in summer climate in the Mediterranean region, which will combine with mean warming to result in more frequent heat waves[32].

Alpert et al. (2008) use downscaling methods to examine the projected impacts of climate change on extreme temperatures at two locations in the upper catchment of the Jordan River, Kfar Blum and Har Knaan, at low and high elevations respectively[15]. The highest recorded daily maximum temperature at Kfar Blum for the period 1961-1990 is 42º C, while the highest daily maximum temperatures under the high emissions A2 scenario reach 48º C. At both stations maximum temperatures increase by about 6º C for the A2 scenario. Under the medium emissions B2 scenario the increase in daily maximum temperatures is around 4º C. The most common daily maximum temperatures at Har Knaan increase from around 29º C in the 1961-1990 observations, to around 32.5º C and 34º C in the A2 and B2 scenarios respectively. The variability of temperature also increases.

Projections of changes in the water cycle under the A1B scenario indicate a mean change in rainfall similar in magnitude to the driest episodes of the 20th century[35]. Climatic variability around the mean will therefore result in an increase in the severity of future drought episodes compared with the 20th century. Other studies also indicate an increase of drought in the 21st century, with increasing variability in rainfall over time as the 21st century progresses[33]. For the Mediterranean as a whole, precipitation is expected to increase in intensity during wet periods due to greater atmospheric water vapour content resulting from warming, while the wet periods are separated by longer dry periods due to feedback processes associated with generally drier land areas[33]. A decrease in the number of Mediterranean cyclones under the high emissions A2 scenario was also found in regional modelling studies of the Mediterranean region, with a statistically significant decline in the “synoptic signal” (a measure of variability in sea-level pressure indicative of the passage of cyclonic disturbances) over the RSDSC study area in winter and spring (December-May)[33].

Samuels et al. (2009) propose that extreme rainfall events may become more common in the Lake Kinneret watershed as a result of climate change, increasing flood risk, although they conclude that a concentration of rainfall in fewer, more intense events will not necessarily affect the overall flow of the Jordan River[41]. Alpert et al (2008) conclude that simulated future conditions are associated with a tendency towards a higher frequency of heavy rainfall days during autumn and early winter (October-December) for the B2 scenario, based on assessments of future changes in extremes at twelve stations in Israel[15]. The frequency of heavy rainfall days declines under this scenario for the remainder of the winter period (January-February). In contrast, under the (more realistic) A2 scenario there is a tendency for the number of heavy rainfall days to increase during spring. This study also suggests that the future behaviour of extreme events may vary considerably with location and elevation, with a greater frequency of heavy rainfall events at the higher elevation station. As in the case of temperature, interannual rainfall variability increases, indicating a shift towards a generally drier climate, but with a greater frequency of “wet” and “dry” years in which rainfall deviates from the long-term mean.

Whether the above results can be generalised for the area extending from the Gulf of Aqaba to the Dead Sea is not clear, given the very different climatic conditions pertaining in this area when compared with the upper Jordan Valley catchment of northern Israel, where detailed studies of changes at particular localities indicate increases in heavy rainfall events during different seasons for different emissions scenarios. These studies[15] also illustrate that the behaviour of extremes can differ significantly between locations within one grid box, depending on topography and elevation. Once again, the lack of data and studies for the RSDSC study area means that future changes must be tentatively inferred by examining projected changes in adjacent regions. A comparable study to that described above for northern Israel, but addressing projected changes in mean climatic conditions and extreme events for southern Israel, the Wadi Araba and the Dead Sea region would greatly enhance our understanding of the potential impacts of climate change in the RSDSC study area.

While the future evolution of extremes in the study area remains uncertain, studies of the wider region and adjacent areas suggest that interannual variability in both temperature and rainfall is likely to increase. Extreme dry periods and periods of extreme high temperatures are likely to become more frequent and protracted. While overall rainfall will almost certainly continue to decline, changes in rainfall intensity, and in the seasonal amounts and distribution of rainfall remain uncertain. It is highly plausible that the intensity of individual rainfall events will increase, although this remains speculative. Nonetheless, it would be prudent to plan for both more frequent, extreme and protracted drought periods, as well as an increase in the frequency and intensity of heavy rainfall events, and increased interannual variability of rainfall and changes in the behaviour of both cyclonic systems and the Red Sea Trough.

4.5. Sea-level rise projections

Changes in the level of the Red Sea and Gulf of Aqaba are likely to broadly reflect changes in global mean sea-level (gmsl), as discussed in more detail below under Sub-Study A. The 2007 IPCC report presented a range of projected increases in gmsl from 0.18-0.59 m by 2100 across a range of emissions scenarios, relative to the period 1980-1999. However, the methods used to calculate these values did not incorporate considerations of key processes associated with the dynamics of ice sheets, and the ranges are therefore likely to be conservative. A subsequent study by Rahmstorf (2007) estimated that gmsl could rise by up to 1.4 m by 2100[42]. Pfeffer et al. (2008) have estimated a sea-level rise (SLR) of 0.8-2 m by 2100[43], and Rignot (2009) estimates a SLR in excess of 1m by the end of the 21st century[44]. Rohling et al. (2008) find evidence that sea level in the central Red Sea rose by an average of 1.6 m per century during the transition to the last interglacial period, when the global mean surface temperature was up to 2° C higher than during the recent historical period. Recent projections of sea-level rise combined with studies of past sea-level change therefore suggest that a SLR of 1-2 m by 2100 is highly plausible.

In the longer term, sea-levels are likely to rise beyond 2 m above current levels. The 2° C warming of the last interglacial (above recent historical values) was associated with a gmsl some 4-6 m above current levels[45]. During the middle Pliocene, some 3.5 million years ago, the Earth's global mean surface temperature was some 3° C higher than during the 20th century, and gmsl was some 15-20 m above that of the present day[45]. Given the strong likelihood that the global mean surface temperature will increase by 3° C or more, and the long timescales likely to be associated with the disintegration of major ice sheets (principally the Greenland and West Antarctic Ice Sheets) an expectation that sea-levels may rise by something in the region of 1-2 m per century over the next millennium is not unreasonable.

5. Implications of climate change for water resources

5.1. Current water availability

Water scarcity and stress are major issues for the Eastern Mediterranean region, and Jordan, Israel and the Palestinian territories are heavily water stressed, with per capita water availability below the threshold for absolute water scarcity of 500 m^3/yr. According to Phillips et al. (2009: 173), “essentially all the available water is in use” in Israel, Jordan and the Palestinian Territories, with “over-abstraction and/or the unsustainable use of water” documented for certain aquifers in Israel (at least in certain years), the Gaza section of the Large Coastal Aquifer (LCA), and the Disi Aquifer and other fossil water sources in Jordan[46].

Abstraction from the Gazan portion of the LCA is currently about three times the sustainable limit of 55 MCM/yr[22]. Groundwater resources in Gaza are also affected by the infiltration of pollutants through the porous overlying sediments, and by seawater intrusion. In the medium to long term, saltwater intrusion into the LCA will be exacerbated by sea-level rise.

In 2000, it was estimated that groundwater in some Jordanian aquifers was being extracted beyond the aquifers' “safe yield”[8]. In 1999 it was reported that springs in the Azraq basin had run dry due to abstraction exceeding average recharge rates and the safe yield of the upper aquifer of the Azraq Basin[12]. At 1999 abstraction rates (and assuming no changes in recharge) groundwater levels would continue to fall at 0.7m per year, with the decline increasing over time and resulting in reduced well yields until abstraction became impossible around the year 2040[12].

Estimates of the precise amounts of water available and used in Israel, Jordan and the Palestinian Territories vary (Table 5). The greatest discrepancies are found in estimates of water use and availability in Israel and in the Palestinian Territories, where the issue of water availability is highly politicised, figures are strongly contested, and local access to water resources is influenced by a combination of economic, social, political and military factors[47,48]. For example, the AQUASTAT figures indicate that 208.4 m^3/yr per capita are available in the Palestinian territories, compared with the figure of 105 m^3/yr per capita from the Israel Water Authority (IWA)[25], and the estimate of 72 m^3/yr for actual use by Phillips et al. (2009), who describe the Palestinian territories as experiencing some of the highest levels of water stress globally[46]. The IWA estimate of 149 m^3/yr for the availability of freshwater in Israel may be contrasted with the AQUASTAT figure of 256 m^3/yr and Phillips et al's figure of 324 m^3/yr.

The figures in Table 5 for total actual renewable freshwater resources in Jordan are comparable with the figure of 867 MCM/yr for water supply in 2007 given in Jordan's SNC. However, the figure of 90-100% for renewable water withdrawn should be viewed in the context of the estimated demand in 2007 of 1504 MCM/yr, resulting in a deficit of 638 MCM[2]. It should also be noted that much of the water used in Jordan (some 54% in 2007) derives from groundwater, and that a proportion of this is from non-renewable resources[46].

Regardless of the finer details of per capita water use and availability, it is clear that water scarcity is a critical issue for Israel, Jordan and the Palestinian Authority. Without the development of new sources of freshwater, water scarcity will increase as a result of economic and demographic trends. While the evidence indicates that regional water scarcity in shared river basins tends to stimulate cooperation rather than conflict between co-riparian states[49], water supply is of key strategic importance in the region, and water scarcity needs to be addressed if regional political stability is to be secured – both internationally and at the sub-national level.

Table 5. Actual available freshwater sources for Israel, Jordan and the Palestinian territories, according to the AQUASTAT database. Total freshwater withdrawal includes withdrawals of both surface and groundwater. See text for discussion, particularly of actual water availability in the Palestinian territories.

Water resources	Israel		Jordan		Palestinian Territories	
	AQST 2003-7	Phillips 2006	AQST	Phillips 2006	AQST	Phillips 2006
Total renewable (actual), km^3/yr	1.78	2.1	0.94	0.88	0.84	0.2
Total freshwater withdrawal, km^3/yr	1.55	2.27	0.85	0.88	0.41	0.28
% of total actual renewable withdrawn	87.19	108	90.46	100	48.75	140
Total renewable per capita (actual), m^3/yr	256.8 (avail)	324 (used)	157.7 (avail)	150 (used)	208.4 (avail)	72 (used)

5.2. Future water availability in the region without the RSDSC ("no project" case)

5.2.1. Future water availability under current climatic conditions: no project case

Water scarcity and stress is projected to increase in the region as a result of economic and demographic changes, although this trend will be offset to a certain extent by improved water use efficiency and the development of new sources of freshwater, for example from an expansion of wastewater treatment.

Under the scenario in which the RSDSC is not constructed (the no-project scenario), and assuming the continuation of current climatic conditions, Jordan's current water deficit of 638 MCM/yr is projected to decline to around 611 MCM/yr by 2020[50] as water supply is increased through the implementation of the Disi-Amman groundwater project, the further development of surface water sources and the expansion of wastewater treatment. However, projected increases in supply do not keep pace with projected increases in demand, with the deficit rising to 643 MCM/yr by 2040 and 736 MCM/yr by 2060 (see Table 6 below). These deficits are likely to be met through the use of non-renewable fossil groundwater. Similar use of fossil groundwater is likely to contribute to water supply in Israel and the Palestinian Territories.

5.2.2. Future water availability under climate change: no project case

As detailed above, climate change projections for the region indicate that runoff is likely to be substantially reduced in the coming decades. The medium-emissions A1B scenario is associated with projected regional-level changes in runoff of 10-20% for the middle of the century (2040s-2060s) and 30-50% for the period 2071-2100, based on simulations with global climate models[28]. On the one hand it should be noted that these figures are based on an unrealistically "optimistic" emissions scenario, which is likely to result in a conservative estimate of the impacts of climate change. On the other hand, these results have been generated by global climate models which do not accurately represent local factors such as topography and convection processes, and which could underestimate rainfall associated with such factors. While a high resolution modelling study of future streamflow in the region indicates reductions of

82-98% for the Jordan Valley[29], the validity of these results has been questioned, based on the models poor representation of current conditions[39].

Nonetheless, basic considerations of the impacts of projected increases in temperature and reductions in rainfall suggest reductions in the availability of surface water of the order of tens of per cent by the middle of the 21st century, with larger reductions in the latter half of the century. A maximum projected warming of around 5º C by the late 21st century is likely to be associated with an increase in evapotranspiration of something in the region of 30%, based on existing estimates of temperature-ET relationships[8]. Maximum projected reductions in rainfall of 30% or more are likely to reduce surface runoff by a similar percentage or greater, based on the available studies[35]. It is therefore inferred that climate change has the potential to result in the loss of over half – and perhaps the majority of - the region's current surface water resources, with the caveats that (i) this represents a worst-case scenario, (ii) there is likely to be considerable geographic and seasonal variation in climate change impacts on rainfall, surface runoff and groundwater recharge, and (iii) more detailed, high resolution regional modelling work is therefore required before reliable projections of the potential impacts of climate change on water resources are available.

While the potential impacts of climate change on national water budgets have not been quantified, plausible changes in runoff could have large impacts on water resources. In Jordan, it is estimated that around 15% of the average annual rainfall of 7200 MCM remains as runoff, feeding rivers and wadis, and recharging groundwater, the remainder being lost through evapotranspiration[8]. Abu-Taleb provide a figure of 7200 MCM for average annual rainfall, meaning that on average some 1080 MCM per year contributes to these processes[8]. Scott et al. (2003) provide a figure of 850 MCM/yr for Jordan's renewable fresh water (including allocations under international water sharing agreements), of which an estimated 575 MCM/yr is surface water and 275 MCM/yr is renewable groundwater[51]. Most of Jordan's 296 MCM/yr of developed surface water resources is derived from runoff in the catchments of the Jordan and its tributaries[2], and this figure is projected to increase as Jordan strives to increase its water supply.

Based on these figures, a 50% or greater reduction in runoff under a worst-case scenario could translate into a loss of hundreds of MCM/yr in Jordan alone, reducing surface water availability by the order of 300 MCM/yr, and groundwater recharge by the order of 150 MCM/yr. Based on the figure of 575 MCM/yr for available surface water, such a reduction would result in the total available surface water being reduced to an amount comparable with the current usage of 296 MCM/yr, making further development of surface water impossible. As it is unrealistic to assume that all surface water could be captured and exploited, the implication is that climate change is likely to result in a decrease in the availability and consumption of surface water. A proportional decline in *accessible* surface water of 50% would translate into a loss of just under 150 MCM/yr, or around 17% of current total water supply for Jordan (Table 6). Put another way, such a loss would increase Jordan's current water deficit of 638 MCM/yr by around 20-24% (depending on which of the deficit values for different periods provided in Table 6 is used) based on considerations of surface water alone. More efficient use of surface water resources could reduce the magnitude of the loss, but the practical implication of such a scenario is that additional investment in the development of surface water resources would not increase supply, but merely mitigate the decline in surface water availability due to climate change.

Added to any reduction in surface water resources would be a decline in renewable groundwater resources. Reduced recharge rates might have a more-or-less immediate impact on the productivity of groundwater resources in some locations, while in others such a reduction might bring forward the date at which aquifers become unproductive. The projected decline in groundwater recharge for the West Bank for a 16% decline in rainfall and a 6º C warming is around 50%[40]. While the impacts of climate change on groundwater recharge are likely to vary considerably with location, this suggests that a 50% decline in runoff under a worst-case climate change scenario could be associated with a similar magnitude reduction in groundwater recharge. If such a decline were realized in Jordan, it would increase the effective water deficit by around 39-47%, given that all Jordan's renewable groundwater resources are effectively being used.

For Jordan, a 50% reduction in surface water and groundwater recharge would result in a reduction of available surface water from 575 MCM/yr to 287.5 MCM/yr, and a reduction in groundwater recharge from 275 MCM/yr to 137.5 MCM/yr. If we make the somewhat arbitrary, but reasonable, assumption that some two thirds of surface water resources are harnessed, and assume that all renewable groundwater resources are used, the "worst-case" scenario for Jordan in the latter part of the 21st century involves a loss of renewable water resources of around 230 MCM/yr. This figure represents an extremely crude estimate of the potential magnitude of the impacts of climate change on Jordan's water resources, and should be viewed as an indicative guide to a plausible outcome at best.

Israel and the Palestinian Territories face similar stresses. Murakami (1995) provides a figure of 1500 MCM/yr for combined surface water and groundwater recharge in Israel, with a further 500 MCM/yr received by Lake Kinneret. Inflow into Lake Kinneret is around 630 MCM/yr, around 80% of which comes from the Jordan River. The difference between inflow to the lake (in the form of runoff, springflow and direct precipitation) and evaporation is around 400 MCM/yr, and this is classified as "available" freshwater, providing some 25% of Israel's water needs. Israel relies on the Jordan River for some 30% of its water use[46], utilising flow derived from runoff both within and outside its borders. Reductions in surface runoff comparable to those indicated by the more "pessimistic" scenarios runoff would have significant implications for water supply in Israel and the Palestinian Territories, as well as for Israel's ability to meet its obligations to supply water to Jordan.

Increased temperatures and reduced rainfall will also increase demand for water, particularly for the purposes of irrigation. Data from Egypt indicate an increase in irrigation demand of 2-3% for every 1º C temperature rise[8], while projections for the West Bank suggest that increases in temperature of up to 6º C could increase agricultural water demand by up to 17%[40]. These represent the direct impacts of higher temperatures; it is possible that reductions in groundwater availability will further increase irrigation demands.

5.3. Future water availability with the RSDSC ("with project" case)

5.3.1. Future water availability under current climatic conditions: with project case

Under current climatic conditions the construction of the RSDSC will alleviate water stress but will not provide all the necessary additional water to meet demand in all or any the Beneficiary Parties.

Jordan, the likely principal beneficiary of the desalination component of the RSDSC, plans to develop its water resources to 1632 MCM/yr by 2022[2], almost doubling its supply while reducing its dependence on groundwater. This projected increase in water availability assumes an increase in treated wastewater supply to about 256 MCM/yr, the further desalination of inland brackish water sources, and requires the construction of the RSDSC or an equivalent/comparable scheme[2]. Wastewater treatment and additional supply from the RSDSC or equivalent scheme would be used to reduce Jordan's dependence on groundwater, much of which is not replenished under current climatic conditions.

The planned supply of water to Jordan for 2022 is 560 MCM/yr greater than the projected available supply in 2020 (Table 6). Based on the projected RSDSC supply of desalinated water (Table 6) and a hypothetical allocation to Jordan of around 70% based on illustrative figures used for the Feasibility Study, the proposed RSDSC would meet approximately 35-40% of Jordan's water deficit in 2020, depending on which figure is used for demand (the figure of 1632 MCM/yr in Jordan’s SNC, or the projected demand of 1683 MCM/yr). By 2060, the RSDSC could provide water equivalent to around 80% of the projected deficit (Table 6). The remaining water deficits under a scenario in which the RSDSC is constructed, proportional allocations remain at 2020 levels, and water demand increases as projected for Jordan, are listed in Table 6. However, it is stressed again that these allocations are hypothetical, as allocations between the Beneficiary Parties have not been agreed.

Table 6. Current and projected water supply, demand and deficit (MCM/yr) for Jordan without the RSDSC and without considering the impacts of climate change (columns 2-4), and projected future supply from the proposed RSDSC (columns 5-6). Column 7 indicates the deficit for Jordan assuming that 70% of the supply is allocated to Jordan up to 2060. Is must be stressed that this figure is hypothetical and for illustrative purposes only, as allocations have not yet been agreed. Figures from Coyne & Bellier[50], except for 2007, from Jordan's SNC[2].

	Without RSDSC or climate change			RSDSC supply		Deficit with RSDSC*
Year	**Supply**	**Demand**	**Deficit**	**To Jordan**	**Total**	
2007	867	1505	638	-	-	-
2020	1072	1683	611	230	310	381
2030	1138	1780	642	310	410	342
2040	1213	1856	643	370	540	273
2050	1294	1981	687	460	670	227
2060	1375	2111	736	560	850	176

As indicated above, tackling water demand in Jordan will require the expansion of supply from other sources, such as wastewater. Al-Omari et al. (2009) investigated water deficits for the short to medium term in the Amman Zarqa Basin (AZB), in which the majority of Jordan's population and economic activity is located, and projected a deficit of 47.74 MCM/yr in 2020[52]. This figure assumes that the RSDSC is combined with advanced waste water treatment (AWWT), and rises to 160.04 MCM/yr for a scenario in which the RSDSC is constructed but AWWT is not developed, and to 168.29 MCM/yr under a business-as-usual water use scenario. The relatively small impact of the RDDSC is due to the high agricultural demand in the AZB, and the fact that desalinated water from the RSDSC is earmarked for non-agricultural use.

5.3.2. Future water availability with climate change: with project case

As indicated above, climate change could have a severe impact on regional renewable water supplies by the mid-late 21st century, resulting in the loss of a significant proportion of the currently available surface water and renewable groundwater resources. Under a "worst-case" scenario it is conceivable that surface water resources and groundwater recharge will be reduced by some 50% or more.

Under such a worst-case scenario, the loss of water resources resulting from climate change in the combined territories of the Beneficiary Parties could exceed the additional water produced by the desalination component of the RSDSC. In Jordan, likely to be the main beneficiary of desalination, the loss of water resources could be comparable with, but would be unlikely to equal or exceed, the amount of water provided by the RSDSC. Under a hypothetical scenario in which Jordan received some two thirds of the desalinated water from the RSDSC, a 50% reduction in runoff due to reduced rainfall and higher temperatures could result in a loss of renewable water resources equivalent to up to about 80% of the additional freshwater produced by the RSDSC (based on a 50% reduction in current total surface water flow of 575 MCM/yr and groundwater recharge of 275 MCM/yr, and a total RSDSC freshwater output of 850 MCM/yr). However, given that less than 100% of the total surface water resources are likely to be exploited, the loss of actual accessible water resources due to climate change is likely to be equivalent to a considerably smaller percentage of the additional RSDSC water. In the event that both renewable groundwater and surface water resources are reduced by around 50%, with two thirds of the former and all of the latter being exploited (see "no project" case with climate change, above), climate change losses (based on an indicative figure of 230 MCM/yr) would be equivalent to around 40% of the additional RSDSC water supply with desalination operating at maximum capacity.

These very general, and somewhat hypothetical, examples illustrate that up to around half of the projected desalinated water from the RSDSC might be required simply to offset the impacts of climate change on water resources, at least in Jordan, under certain allocation regimes. If the majority of water is allocated to Jordan, the amounts supplied to Israel and the Palestinian Territories might be entirely used up offsetting the impacts of climate change in whole or in part.

Even under a less extreme climate change scenario, a significant proportion of the fresh water produced by the RSDSC is likely to be used offsetting the effects of climate change. From a climate risk perspective, and environmental considerations notwithstanding, these conclusions emphasise the importance of the desalination component of the proposed project, and the utility in developing desalination capacity to its maximum possible extent as rapidly as is practical.
The practical implication of climate change for development is that future water deficits are likely to be greater than currently projected, even with the RSDSC.

6. General implications of climate change for the proposed RSDSC

6.1. Implications for project rationale

The projected declines in rainfall and runoff associated with climate change pose considerable challenges for the region, even without the additional demand that will result from demographic and economic trends. The impact of climate change on water resources will very likely intensify over time, reducing renewable water resources by the order of tens of per cent by the middle of the 21st century. Under the worst case scenarios, climate change has the potential to reduce renewable water resources for the RSDSC Beneficiary Parties by 50% or more during the latter half of the century.

New sources of freshwater are urgently need as a result of existing water stress, which will be exacerbated by increased demand as populations grow and national economies develop. Climate change will increase projected water deficits (based on anticipated demand under current climatic conditions), making the development of these new sources of freshwater even more urgent. In the absence of a RSDSC or equivalent schemes, climate change is likely to increase future deficits by tens of percent. In the case of Jordan, the total water deficit without a version of the RSDSC or equivalent could increase by around 40% by the late 21st century.

In Jordan, projected water demand will not be met, even with the proposed contribution of desalinated water from the RSDSC under continued current climatic conditions. However, in the absence of climate change, the RSDSC contribution would result in a steady decline in Jordan's water deficit over time, as desalination capacity increased. Climate change could result in a 2-3 fold increase in the size of Jordan's projected water deficit (141 MCM/yr in 2060 without climate change: Table 6) by the late 21st century. Qualitatively similar situations will be faced by Israel and the Palestinian Authority, which will also face large losses of surface water.

In the absence of other schemes to import water from outside its borders, it is difficult to see how Jordan will be able to meet the projected demand for water without the RSDSC or equivalent project, even before the impacts of climate change are considered. When climate change is factored into considerations of future water supply, it is possible that up to around half the projected supply of desalinated water from the RSDSC beyond 2060 will be needed to replace surface water supply lost as a result of climate change. While this means that a sizeable proportion of any desalinated water derived from the RSDSC will be "lost" to climate change, reducing the anticipated gains in the form of additional water under the RSDSC scheme, it might be argued that the potential impacts of climate change make such a scheme even more urgent.

6.2. Implications for RSDSC in the context of alternative proposals

Alternatives to the RSDSC have been proposed, including the transmission of desalinated water from the Mediterranean to the Dead Sea via a number of alternative routes through Israeli and Palestinian territory. In the 1970s the southernmost Katif route was proposed, while in 1996 the more northerly Hadera route was proposed. The latter would have raised the level of the Dead Sea and provided similar amounts of desalinated water, with a similar country allocation, to the currently proposed RSDSC[53].

Much more recently, the Jordan River-Dead Sea (JRDS) system has been proposed, involving replenishing the Jordan River using desalinated water from the Mediterranean coast and/or freshwater derived from Turkish river outflow into the Black Sea, transported by sea to the Israeli coast at Hadera and fed into an overland conveyor[53]. The JRDS system would initially produce water to substitute for that taken from Lake Kinneret, contributing to the rehabilitation of Lake Kinneret and the Jordan River, then increase input into the Kinneret-Jordan system while also providing freshwater for Jordan and the Palestinian Authority. The relative economic and other merits of schemes such as the JRDS are being evaluated in the separate Study of Strategic Alternatives, which is being conducted as part of the wider RSDSC Feasibility Study.

Any rehabilitation of the Lake Kinneret-Jordan River-Dead Sea system would need to supply enough water to compensate not only for current abstraction and diversion of runoff, but also for the impacts of climate change. Flow in the Jordan River basin has been estimated at 1250-1600 MCM/yr, and essentially all of this water is currently used by the co-riparian countries. Even under scenarios associated with more modest impacts, projected reductions in runoff are likely to mean that any scheme to rehabilitate the Jordan River basin would need to find additional volumes of fresh water amounting to several hundred MCM/yr to compensate for the effects of climate change, over and above baseline rehabilitation volumes. Climate change will also increase the demand for water, particularly for irrigation, further increasing the amounts of new water likely to be needed. The additional desalination/importation needs likely to result from climate change might therefore comparable to the proposed supply resulting from any single desalination and transmission scheme such as the RSDSC, or any one of the proposed Mediterranean conveyors.

Further studies are required to assess the implications of climate change for the feasibility and efficacy of the various other proposed water delivery and rehabilitation schemes, such as the JRDS system. However, given the increasing demand for water in Israel and the Palestinian Territories, the additional supply needs that will result from climate change, and the finite rate at which desalination capacity can be developed, it appears unlikely that water security in Israel, Jordan and the Palestinian Territories will be met by any single large engineering scheme designed to deliver desalinated water from either the Red Sea or Mediterranean. It appears more likely that future water needs will require a number of such schemes, encompassing a version of the RSDSC, the transfer of large amounts of desalinated water from the Mediterranean, and possibly the transport of freshwater from other countries or regions under schemes such as that envisaged for the transport of river outflow from Turkey to Israel.

Considerations of environmental impacts notwithstanding, climate change strengthens the argument in favour of the RSDSC, or some variant thereof, as part of a wider regional network of freshwater conveyors. Of course, considerations of climate change and its implications represent only one set of criteria to be considered when assessing the feasibility of the project. While the lifetime of the proposed RSDSC is of the order of 100 years, the transport of similar or larger volumes of water from the Red Sea or elsewhere is likely to be required in the longer term.

PART II: SUB-STUDIES

7. SUB-STUDY A: Gulf of Aqaba

7.1. Context: Geography, climate and oceanography

The Gulf of Aqaba is a semi-enclosed terminal basin some 180 km in length, 5-25 km wide (with an average width of about 16 km), and up to around 1820 m in depth (average depth is around 800 m)[54]. The Gulf of Aqaba is connected to the Red Sea by the Straits of Tiran, which are some 2 km wide, 5 km long, and consist of two channels with depths of up to 252 m (the Enterprise Passage) and less than 100 m (the Grafton Passage)[55]. Red Sea water enters the Gulf of Aqaba in a flow that extends to some 100 m depth through the Straits of Tiran, below which (in the Enterprise Passage) there is a return flow of deep water from the Gulf to the Red Sea, with the Gulf of Aqaba being an important sources of deep water formation for the northern Red Sea[56].

Arid climatic conditions drive strong evaporation in the Gulf of Aqaba, estimated at 1 cm day^{-1} by Assaf and Kessler (1976[57]; subsequently cited in Wolf-Vecht et al., 1992[58]), 0.5-1 cm day^{-1} by Berman et al. (2000[54]), 1.1 cm day^{-1} by Labiosa et al. (2005[59]), and 3500 mm yr^{-1} by the SMART study performed in 2005[60]. A much lower figure of 1.6-1.8 m yr^{-1} is estimated by Ben Sasson et al. (2009[61]).. Shallow waters originating in the Red Sea cool and become more saline as they travel north, resulting in a thermohaline circulation in which dense, cool, saline water sinks, driving an overturning in which flow in the upper layers is from south to north and flow at lower levels is from north to south.

In summer the upper mixed layer (the layer directly influenced by the overlying atmosphere) typically extends to depths of 10-20 m or more, with a thermocline at around 200 m[61,62]. In winter the upper mixed layer can extend to depths of greater than 50 m, with convection typically extending to 250-450m[63], and sometimes extending to the bottom of the northern Gulf at around 700 m depth[62,64,]. Winter convection results in the formation of deep water which sinks, spreads south and ventilates the deep water mass[62].

Maximum temperatures occur in the upper mixed layer in August, with minimum temperatures in March, when water is well mixed to a depth of 300 m or more as a result of winter convection[Erreur ! Signet non défini.]. Sea surface temperatures in the northern Gulf of Aqaba range from around 21º C in winter to 27º C in summer, and winds are northerly or north-northwesterly for most of year[65].

7.2. Observed and projected changes in the Gulf of Aqaba

7.2.1. Changes in temperature, salinity and circulation

Gertman and Brenner (2004) analysed historical observations of water temperature and salinity near Eilat, and found a positive linear trend in temperature in the upper layer of 0.02º C per year[63]. However, they concluded that this trend was not significant in the 95% confidence interval. A significant long-term increase in temperature of about 0.03º C per year since 1989 was detected in the lower layer. Surface temperatures in the Gulf were low in the winter of 1989, falling to 20.5º C, when severe weather conditions resulted in strong vertical mixing, lowering the temperature of the deeper layers. The increase in temperature in these layers after 1989 therefore may be explained by the integration of warmer water from the upper layer into the deeper waters during winter vertical mixing in subsequent, more “normal” years, rather than any significant, progressive warming of the Gulf due to higher temperatures in the overlying atmosphere. While such processes may be operating, they are not sufficiently strong to be statistically detectable. Gertman and Brenner (2004) speculate that increasing salinity in the upper layer might have played a role in enhanced mixing of warmer upper waters into the deeper surface waters, but caution that salinity data are too few in number and poor in quality for the identification of salinity trends.

While climatically-driven temperature trends in the waters of the Gulf of Aqaba are yet to be firmly identified, a continuation and acceleration of warming in the region may be expected (see section 2.3 above), resulting in the transfer of heat from the atmosphere to the water of the Gulf, and the warming of the latter. Warming of Red Sea waters will also result in increased temperatures within the Gulf of Aqaba. However, rates of future warming in the Red Sea and Gulf of Aqaba are currently uncertain.

7.2.2. Changes in marine ecology

The ecosystems of the northern Gulf of Aqaba are already subject to anthropogenic stresses, which vary across locations and ecosystems. Marine ecosystems in the Gulf of Aqaba are already subject to pressure from pollution and eutrophication, although descriptions of the state of coral reef communities off the Israeli and Jordanian coasts differ. Eilat’s coral communities have been described as being in a “critically frail state of health”[66], although a number of studies described in the Red Sea Study conducted as part of the RSDSC Feasibility Study question this assessment, and indicate either less pronounced deterioriation in, or a recovery of, certain aspects of the marine ecosystem off the Israeli coast of the Gulf of Aqaba[67]. The corals of Aqaba were reported in 2004 to be in relatively good condition[68]. The latter are reported to support 151 coral species and 280 fish species, and to have been unaffected by the widespread global bleaching that affected many reefs in 1997/98, which was associated with a strong El Niño event.

7.2.3. Changes in sea-level

As indicated above, changes in sea-level at the head of the Gulf of Aqaba are likely to reflect changes in global mean sea-level. However, as in all coastal areas, the relationship between global mean SLR and local SLR will depend on a combination of factors, including changes in ocean circulation (which can alter sea-levels at local and regional scales) and relative sea-level change associated with land movements (i.e. uplift and/or subsidence).

The Gulf of Aqaba is an extension of the Levantine or Dead Sea Fault, and part of the Red Sea Rift, and is therefore tectonically active. However, while there are a number of published studies on tidal and sea-level variations in the Gulf of Aqaba[69], these focus on short timescales, and data on longer-term changes in (relative) sea-level in the Gulf of Aqaba are currently unavailable. Nonetheless, there is no evidence to suggest that land movements will result in changes in sea-level that deviate significantly from changes in gmsl.

7.3. Future conditions in the Gulf of Aqaba under climate change without the RSDSC ("no project" case)

To date, no studies have been conducted on the emerging or potential impacts of climate change on the Gulf of Aqaba, and the resolution of even the most advanced climate models is insufficient to resolve processes operating at the geographic scales representative of the Gulf of Aqaba. Any conclusions about such impacts must therefore be extremely tentative, consisting of speculation informed by a combination of historical observations (where available), comparisons with other regions, and consideration of projected changes operating at scales larger than those characterising the geography of the Gulf. The conclusions presented here should be seen as preliminary, framing issues to be investigated more thoroughly through dedicated modelling studies.

7.3.1. Climate change impacts on the Gulf of Aqaba at the basin scale

Whatever the magnitude of any future warming, such a trend would have two principal, and opposing, impacts. On the one hand warming of the surface layer will tend to enhance stratification of the water column, acting to reduce convection and vertical mixing. On the other hand, warming will result in enhanced evaporation, increasing salinity and water density (both within the Gulf of Aqaba and of the Red Sea waters entering the Gulf through the straits of Tiran), which will act to increase convection and the formation of deep water. The net impact of warming will depend on the balance between these two processes, which may vary with season (perhaps with greater stratification in summer and greater convection in winter, although this is speculative), and might be investigated further through modelling studies.

Changes in wind speed and direction also have the potential to influence circulation within the Gulf of Aqaba. However, there is currently no reliable basis for assessing how wind speed and direction might change in the future. The dominant role of topography in mediating wind regimes in the Gulf of Aqaba and the Wadi Araba may mean that climate change has little impact on wind speed and direction, although it is unclear how local geographic factors might interact with changes in climatic regimes and behaviour at the regional scale, and such a statement is somewhat speculative.

7.3.2. Climate change impacts on marine ecosystems in the Gulf of Aqaba

While no significant bleaching has been recorded in the Gulf of Aqaba to date, climate change will result in higher ocean surface temperatures, and a greater likelihood of extreme high temperature events associated with coral bleaching. The future behaviour of El Niño is uncertain, although there are tentative (and highly uncertain) suggestions from palaeoclimatic data that a global warming of some 3° C might result in more frequent, or even permanent, El Niño like circulation[70,71]. While the potential for bleaching events to affect corals and thus the wider marine ecosystem in the Gulf of Aqaba in the future requires further investigation, such events will become more likely as mean and maximum air and ocean surface temperatures increase as a result of anthropogenic greenhouse warming.

Another threat to corals and other marine organisms is ocean acidification resulting from increasing atmospheric CO_2 concentrations, which can compromise the ability of certain marine organisms to build carbonate shells. A recent study by researchers from Israel and the United States concluded that "by the time atmospheric partial pressure of CO_2 will reach 560 ppm [parts per million] all coral reefs will cease to grow and start to dissolve”[72]. The atmospheric CO_2 concentration is likely to reach 560 ppm by the middle of the 21st century under current policy regimes, which are associated with high greenhouse gas emissions. Under low emissions climate change scenarios 560 ppm of atmospheric CO_2 is reached by the 2070s or 2080s[26]. Nonetheless, the impacts of ocean acidification will vary according to species, with a recent study identifying mixed responses to increases in pH across 18 different marine organisms, with calcification rates falling in some organisms, increasing in others, and remaining unchanged in one case[73].

While there is considerable uncertainty regarding the manifestations and impacts of climate change on marine life in the Gulf of Aqaba, it is reasonable to assume that climate change will increase the stresses on marine organisms through a combination of warming, ocean acidification, and perhaps sea-level rise and changes in circulation.

7.4. Future conditions in the Gulf of Aqaba under climate change with the RSDSC (“with project” case)

7.4.1. Combined impacts of climate change and the RSDSC at the basin scale

The proposed RSDSC would take up to 2×10^9 m^3 of water from the Gulf of Aqaba. Assuming an average width for the Gulf of 16 km, a length of 180 km, and a low evaporation rate of 1.7 m per year, the volume of water lost to evaporation would be approximately 4.90×10^9 m^3 per year. The maximum volume of water to be extracted by the RSDSC is around 41% of this value. A high evaporation rate 1 cm day^{-1} (based on earlier estimates) would indicate that the maximum volume of water to be extracted represented some 19% of the water lost to evaporation. More detailed calculations carried out as part of the Additional Study of the Red Sea indicate that the maximum annual withdrawal from the Gulf of Aqaba represents a proportion of 30% of the annual volume of water lost to evaporation.

Withdrawal at the RSDSC intake would increase the flow across the Straits of Tiran, as more water would be drawn north to replace the additional amount lost from the Gulf of Aqaba. An increase in the input of Red Sea water to the Gulf of Aqaba would tend to increase the temperature and reduce the salinity in the Gulf. The combined impacts of climate change and the RSDSC on water temperature within the Gulf will therefore be additive, while the impact of he RSDSC on salinity will act in the opposite direction to the impact of climate change. The importance of these processes will depend on the amount of additional Red Sea water entering the Gulf through the Straits of Tiran.

Silverman and Gildor (2008) tentatively estimate the flow from the Red Sea to the Gulf of Aqaba across the Straits of Tiran at 0.01 Sverdrups (Sv) for April-October, and 0.03 Sv for November-March[62]. While these figures are based on very limited observational data, they suggest an average flow throughout the year of some 0.018 Sv. One Sverdrup is equivalent to a million m^3 per second, making the average flow across the straits around 18,000 m^3/s. Multiplying the figure of 18,000 m^3/s by the number of seconds in a year, the annual flow across the Straits of Tiran is around $(1.8 \times 10^4\ m^3s^{-1}) \times (3.1536 \times 10^7\ s) = 5.67648 \times 10^{11}\ m^3$.

The 2×10^9 m^3 of water that would be extracted from the Gulf of Aqaba by the RSDSC is equivalent to around 0.35% of the annual inflow across the Straits of Tiran. This relatively low figure suggests that the RSDSC is unlikely to have any major, basin wide impacts on the circulation of the Gulf of Aqaba resulting solely from changes in the mass balance across the Straits. However such a conclusion must remain speculative at this stage, and further investigation (e.g. through modelling studies) is required before any firm conclusion can be reached. Furthermore changes in mass balance across the Straits of Tiran are not the only mechanisms that might influence circulation, as outlined below.

It might be concluded that the small projected increase in the input of Red Sea water resulting from the implementation of the RSDSC would have a minimal impact on water properties (e.g. temperature, salinity) in the Gulf of Aqaba at the basin-wide scale. While this may indeed prove to the be the case, it should be noted that this additional Red Sea input is of an order of magnitude comparable to the volume of water lost by evaporation. As indicated above, the planned 2 x 10^9 m^3 annual withdrawal is some 23-30% of this annual evaporative loss. It is therefore plausible that the additional inflow from the Red Sea could be sufficient to influence the properties of the surface layers of the Gulf of Aqaba. For example, an increased input of less saline Red Sea water might reduce the salinity of the Gulf of Aqaba, partially offsetting the effects of evaporation. This in turn might act to reduce convection. However, higher ocean surface temperatures in the Gulf, due to a combination of atmospheric warming driven by global climate change and an enhanced flow of warmer Red Sea waters across the Straits of Tiran, would act in the opposite direction, tending to increase evaporation. It is important to assess the relative importance of these opposing processes, for example through modelling studies, if the impacts of the RSDSC on large-scale circulation and water properties are to be understood more fully.

The impacts of the RSDSC on sea level are yet to be examined, and remain speculative. Withdrawal of water might result in a decrease in sea-level, although this would not necessarily be sustained after the initial period of adjustment during which circulation in the Gulf of Aqaba and flow across the Straits of Tiran responds to the withdrawal.

7.4.2. Climate change and RSDSC impacts in the vicinity of the intake

In the vicinity of the intake, construction of the RSDSC would affect the marine environment via its impacts on circulation and water properties, and the disruption of ecological and geomorphological systems during both construction and operation. Impacts on local circulation in the vicinity of the intake may be significant, involving changes in horizontal current strength and direction as well as changes in vertical mixing. These impacts will act alongside the combined local manifestations of climate change and basin-wide RSDSC impacts discussed above. These local manifestations of larger scale processes may also include changes in horizontal and vertical currents, as well as changes in temperature, salinity and thermocline depth.

Just as the impacts of the proposed RSDSC on local and basin-wide circulation would interact with the impacts of climate change, so would the impacts on ecosystems in the vicinity of the intake. The most obvious impacts of the construction of the intake are physical disruption to the seabed and associated marine ecology. The nature of these impacts would of course depend on the precise location of the intake, the ecosystems present at the intake location, and the area of seabed affected during construction. Once the intake is operational, changes in local circulation might affect the dispersal of marine organisms, for example in the larval stage. Any disruption to the dispersal of coral larvae, for example, might compromise the regeneration of reefs, adding to existing stresses.

It is outside the scope of this Climate Change Study to assess in any detail how climate change, changes in basin-wide circulation and water properties due to the construction of the RSDSC, and the withdrawal of water at the intake site might interact to affect (i) factors such as temperature, salinity, circulation in the vicinity of the intake, and (ii) marine ecosystems in the same locality. These impacts will depend on a wide range of climatic, oceanographic and ecological factors, on the relative importance of processes acting in opposing directions as discussed above, and on the location and design of the intake itself. The complex interactions between these various factors are best represented through detailed hydrodynamical models, the output from which might be used to drive ecosystem models. Nonetheless, it is reasonable to state that any stresses resulting from the construction and operation of the proposed RSDSC are likely to add to a range of climate change stresses, as well as other localised anthropogenic stresses such as pollution and physical disruption from tourism or shipping. It is therefore important to take account of these multiple stresses in any assessment of the potential impacts of the project in the vicinity of the intake. These issues are addressed as part of the Additional Study of the Red Sea, the results of which are reported elsewhere as part of the wider RSDSC Feasibility Study.

7.5. Recommendations

The principal recommendation regarding the implications of climate change for the proposed RSDSC in the Gulf of Aqaba is for modelling studies to address the many uncertainties identified above. From a climate change perspective, it is suggested that modelling studies focus on the following questions:

1. How will the Gulf of Aqaba respond to a warming of the overlying atmosphere of up to 6º C by 2100 (based on regional climate change projections over adjacent land regions)?
2. To what extent will warmer surface waters result in increased stratification and reduced convection, and to what extent will this effect be offset by the tendency for enhanced evaporation to increase salinity and hence convection?
3. To what extent will an enhanced flow of Red Sea water through the Straits of Tiran resulting from the implementation of the RSDSC enhance warming of the surface waters in the Gulf of Aqaba and offset increased salinity associated with enhanced evaporation? To what extent will increased northwards flow across the Straits of Tiran amplify the impacts of climate change on the Gulf of Aqaba, and to what extent will it offset them?
4. How will changes in temperature and salinity affect circulation at the basin scale, and also in the vicinity of the proposed intake locations?
5. How will sea-levels in the Gulf of Aqaba respond to the combination of enhanced evaporation, increased input of Red Sea water, and the removal of 2000 MCM/yr of water from the single location of the intake?
6. How will a warming of up to 6º C of the overlying atmosphere affect the likelihood of coral bleaching events?

It is also recommended that the intake be located away from the most sensitive and degraded ecosystems, and in particular from coral reefs, which are likely to experience increased stress from elevated ocean surface temperatures and ocean acidification as the 21st century progresses. If resources allow, it is recommended that the potential impacts of climate change on coral reef communities in the Gulf of Aqaba be assessed, along with their ability to adapt to the impacts of these changes. The role of ocean circulation in recruitment of coral larvae, and the potential impact of the proposed RSDSC intake on recruitment via its effects on circulation, is of particular interest in the context of the capacity of corals to adapt (e.g. by altering their geographical and vertical distribution within the Gulf of Aqaba).

Infrastructure associated with the intake should be designed to accommodate a sea-level rise of at least 1m by 2100, and preferably 1.5-2m. This figure might be revised in the light of studies of local sea-level responses to both climate change, global sea-level rise, and the construction of the RSDSC, in the Gulf of Aqaba.

8. SUB-STUDY B: Wadi Araba/Arava Valley

8.1. Context: geographic, climate and ecology

The Wadi Araba/Arava Valley extends for some 170 km from the Gulf of Aqaba to the Dead Sea, and is bounded to the east by the Edumean Mountains (up to ~1750 m), and to the west by the highlands of the Zinn Desert (up to ~600 m). The valley may be divided into three morphological components, namely (i) the northernmost area adjacent to the Dead Sea (the southern Ghor) some 400 m below gmsl, (ii) the central Arava Valley which extends from the southern Ghor to the watershed some 70 km north of Aqaba, where the valley reaches its maximum elevation of over 200 m above gmsl, and (iii) the gently sloping and dune-filled Aqaba Valley which extends from the watershed to the Gulf of Aqaba[74].

The climate of the Wadi Araba/Arava Valley is arid to hyper-arid, and is drier than in the immediately adjacent areas as a result of the influence of the elevated areas to the east and west[75]. Mean rainfall declines from north to south, with Goldreich and Karni (2001) reporting a north-south gradient from 50 mm to 30 mm per year, with minimum and maximum annual rainfall amounts of 8 and 113 mm respectively at Sedom[74]. Saqqah and Atallah (2004) describe annual rainfall as "usually < 100 mm" in the Wadi Araba (Arava Valley) in Jordan[75], while Jenny et al. (1990) give a range of 50-100 mm per year for a site in the central Arava Valley[76]. Mean annual temperature is around 23°-25° C, with mean summer and winter temperatures in the region of 30° C and 15° C respectively (varying with location)[74,75]. Potential evaporation is some 60-100 times the annual rainfall amount[74]. The prevailing wind direction in the Arava Valley is northerly (i.e. from the north to the south), and this situation prevails throughout the year, although the meteorological systems generating this northerly flow vary seasonally[74].

The Arava Valley is biologically important as it contains flora representative of the Sudano-Sahelian zone, even though it is situated within the generally drier Saharo-Arabian latidudes[76]. Assemblages of plant species vary with topography, soil type, and salinity. Much of the vegetation occurs in local topographic minima, for example the beds of wadis such as the Wadis Ghamar and Jeib, which flow from south to north and discharge into the Dead Sea. In such locations infiltration of runoff results in enhanced soil moisture and locally elevated groundwater levels.

8.2. Observed and projected changes in climate in the Wadi Araba

Rainfall in arid and semi-arid areas is highly variable on multiple timescales, meaning that large decreases and increases in rainfall as measured over multiple years are common. Trends are therefore difficult to identify. Nonetheless, data published by the Dead Sea and Arava Science Center indicate declining rainfall trends since the early 1990s at six meteorological stations along the Wadi Araba[77]. At Aqaba, mean annual rainfall fell from 34 mm for the period 1949-1994 to 15.4 mm for the period 1995-2007. At Eilat, mean annual rainfall fell from 30.5 mm for 1949-1994 to 14.1 mm for 1995-2007[77]. The number of years in which rainfall exceeded 30 mm fell considerably between 1968-1987 and 1988-2007 at both Aqaba and Eilat. A similar pattern is visible in the record for Sedom. At all three of these stations rainfall has been persistently low since 1995 when compared with earlier periods (extending back to the 1950s), with the exception of 2004 at Sedom, when rainfall was exceptionally high. At Hazeva, mean annual rainfall declined from 42.2 mm over the period 1988-1994 to 28.1 mm for 1995-2008.

Mean annual rainfall calculated over decadal periods for Aqaba, Eilat and Yotvata are presented by Ginat and Shlomi reinforce the conclusion that rainfall has fallen over the past few decades, exhibiting a steady decline over the three periods 1980-89, 1990-99 and 2000-08[78]. Ginat and Shlomi also highlight the lack of regional-scale rainfall events over the southern Negev and Arava Valley/Wadi Araba since 1992, and the recent (since 2006) incidence of very heavy but highly localised rainfall events. However, there is no evidence of a trend towards more frequent or extreme runoff events in the Wadi Araba.

While the above results must be treated with caution due to the variable nature of rainfall in the Wadi Araba and the short length of the records, they indicate increased aridity in recent decades that is consistent with wider regional observations and model projections.

Temperature trends in the Wadi Araba broadly reflect the regional trends discussed above, with the greatest warming occurring in summer. At Aqaba, monthly average temperature in July has increased by around 1º C since the middle of the 20th century, from 31.9º C in 1959 to 33.1º C in 2007, with a decline in the late 1960s and early 1970s followed by a generally increasing trend[78]. May and October temperatures have also increased over the same period, but by only a fraction of a degree Celsius. Mean monthly temperatures in March have declined substantially, by some 3º C, and the coldest recorded conditions in on the Israeli side of the border in the Arava Valley occurred in February 2008[78].

Data for the period 1986-2007 from Uvda Valley, in the Israeli Arava Valley, indicate a decline in wind strength since 1992, with the lowest values of drift potential (a measure of the potential for wind erosion) measured in 2006 and 2007[78]. However, these data should be treated with caution due to the high interannual variability in drift potential, the short length of the time series, and the high spatial variability of wind speed and direction when measured at the local scale, due to the influence of topography.

There is a general expectation among some specialists in the region that dust and sand storms will become more frequent and/or severe in future, as conditions become drier, vegetation cover is reduced and soil moisture and organic soil content decline. However, such an outcome is far from certain, as the mobilisation and transport of surface material depends as much on atmospheric conditions as on the state of the land surface. Reductions in wind speed might result in a lower frequency of sand and dust storms.

8.3. Future conditions in the Wadi Araba under climate change without the RSDSC (“no project” case)

Anecdotal reports suggest that the reduction in rainfall has had impacts on the ecology of the Wadi Araba, attributing mortality of Shita trees to a decline in groundwater levels (Amir Givati, personal communication), and such a decline is reported by Ginat and Shlomi[78]. However, the extent to which a reduction in rainfall has affected the ecology of the Wadi Araba remains uncertain, as do the potential impacts of any future intensification of aridity. Such impacts would most likely vary considerably across species, and many species of desert adapted flora can withstand many years of drought.

Nonetheless, even if increased aridity does not result in widespread damage to the ecology of the Wadi Araba, a regime in which rainfall is lower and/or less frequent will act generally to increase stress on flora and fauna. For example, while extant vegetation may be capable of withstanding longer dry periods between significant rainfall events, a reduction in rainfall frequency may result in fewer opportunities for germination, or adversely affect animal-assisted dispersal if it leads to increased mortality among key species of fauna[79]. Reduced rainfall may also result in reduced groundwater recharge rates and a lowering of groundwater levels, which in turn might cut off water supply from species of flora with deep roots that tap permanent groundwater sources.

While temperature changes have been uneven throughout the year, large projected future warming – at least in the majority of months - will act to further reduce runoff, exacerbating reductions in rainfall. A shift from regional rainfall events to highly localised events, suggested by recent rainfall behaviour but by no means certain in the future, would make rainfall more variable and unpredictable, with potentially quite different impacts on water resources and vegetation in different locations along the Wadi Araba.

Any lowering of the water table and/or decline in water quality (e.g. due to salinisation) in the Wadi Araba has potential consequences for agriculture, while any reduction in vegetation cover linked to a decline in water resources is likely to have an impact on pastoral livelihoods which are practiced in this sub-region.

8.4. Future conditions in the Wadi Araba under climate change with the RSDSC ("with project" case)

Within the Wadi Araba the two main climate change related issues relevant to the RSDSC are (i) physical risks to infrastructure from climate-related hazards, and (ii) the mediation of the project's environmental impacts by the impacts climate change, and vice versa.

8.4.1. Climate change risks to the project

Climate change risks to project infrastructure in the Wadi Araba will be associated with extreme events, specifically extremes of precipitation and temperature. Currently there is no observational evidence that extreme rainfall events are becoming more common or severe, although periodic floods are common and regional studies suggest that extreme events may become more common in the future. It is therefore impossible to predict with any confidence how risks associated with extreme rainfall and runoff might evolve in the future. In the event that rainfall events do become more frequent and/or severe, there will be a greater risk of (i) damage to infrastructure from flash floods, and (ii) episodic input of significant amounts of sediment and larger fluvial materials into any open sections of the conveyor.

Temperature extremes are likely to encompass both extremes of heat and cold, and climate change might make both of these events more likely. Protracted periods of high temperature have the potential to affect flow rates through enhanced evaporation, while cold extremes might depress temperatures below 0º C, as occurred in February 2008, when nighttime temperatures fell below 4º C on six occasions[78].

Any change in the frequency of sand and/or dust storms would have implications for contamination of water transmitted through open sections of the conveyor. Much of the dust deposited in the region originates in North Africa, and is transported from populated areas where dust aerosols are augmented by anthropogenic pollutants, with potential implications for water composition.

8.4.2. Interaction of project impacts with climate change

Concerns about the potential environmental impacts of the RSDSC in the Wadi Araba focus on (i) the physical disruption of the environment during construction (ii) the possibility of leakage from the conveyor, resulting in the salinisation of groundwater and the surrounding sub-surface.

Physical disruption during construction and subsequent operation of the conveyor is associated with the risk of damage to floral and faunal population via the direct destruction of habitats. Habitable niches in desert environments can be highly localised, with areas of several m^2, and even individual rocks acting as refugia for certain species, meaning that landscape disruption does not have to cover a large area to have potentially significant impacts on biodiversity. Some of these refugia house relict populations from periods characterised by wetter climatic conditions, that have been isolated by desertification. As indicated above, further aridification resulting from climate change might adversely affect population recruitment and dispersal, and also reduce the number of viable refugia, increasing the importance of the remaining refugia for the preservation of biodiversity.

Construction of the conveyor would inevitably lead to the disruption of existing drainage networks along the route of the conveyor and where access routes and other related infrastructure were developed. Disruption of drainage networks, even at very small scales, has the potential to cut off water supplies to existing floral and faunal populations, for example in highly localised refugia as described above. For example, Ward and Rohner (1997) found a mortality of 25% among Acacia trees downstream from points where roads crossed runoff channels without culverts, compared with a mortality rate of 12% upstream, illustrating the importance of runoff in sustaining even well adapted species of desert flora, and the potential for infrastructure to impact such species through drainage disruption[79]. While disruption to drainage systems during construction of a subterranean pipeline along the Wadi Araba might be wholly or largely reversed at the end of the construction phase, the construction of canal sections would result in permanent alterations to local topography and drainage.

Along the route of the conveyor any adverse impacts on drainage would be combined with the consequences of reductions in rainfall, resulting in what might be characterised as “double exposure” of biodiversity to the impacts of both the project and climate change. Reduced rainfall and disrupted runoff might act in an additive sense to accelerate die-off of vegetation in some locations.

Any leakage of Red Sea water from the conveyor as it transits through the Wadi Araba will have adverse local impacts on groundwater and ecology. Where groundwater levels are falling and/or groundwater is becoming more saline as a result of lower rainfall and reduced runoff[78], any such leakage will exacerbate existing climate change impacts. Lower levels of freshwater infiltration are also likely to reduce the potential for recovery from such events through the dilution and dispersal of minerals derived from the Red Sea water. The conveyor therefore has the potential to increase salt stress where it might already be increasing, while climate change might exacerbate the adverse impacts of leakage.

8.5. Recommendations

There is considerable uncertainty regarding the manifestations and impacts of climate change in the Wadi Araba sub-region, particularly regarding the evolution of extreme rainfall events and flood risk, and the future viability of existing ecosystems. Risks to the proposed conveyor associated with extreme events are impossible to quantify, given regional projections that suggest a possible increase in extreme precipitation events, weighed against observations that indicate recent changes in climate but no increase in the frequency or severity of such extremes in the Wadi Araba. The impacts of climate change on ecosystems are similarly uncertain, although initial indications suggest that reduced rainfall and runoff may be adversely affecting certain flora via reductions in groundwater availability and possibly quality, trends that are likely to accelerate in the future.

Climate change will pose a greater risk to sections of the conveyor that are situated on the surface and open to the air in the form of canals than to an underground conveyor in the form of a pipeline. Risks of damage associated with any (speculated) increase in the frequency and/or severity of extreme rainfall and runoff events will inevitably be higher where infrastructure is exposed on the surface, rather than located underground. Surface infrastructure will also be more exposed to increases in temperature extremes. Open canals will be susceptible to contamination from fluvial materials transported during flash floods, and airborne particulates, principally mineral dust, which might incorporate industrial and other pollutants. Open canals will also be subject to changes in evaporative losses associated with variations or trends in temperature, relative humidity, and solar radiation.

All of the climate-related parameters listed above will be affected by climate change in ways that cannot currently be predicted with any reliability, with the exception that temperatures are expected generally to increase. However, increases in temperature will not be uniform throughout the year, and the impact of higher temperatures on evaporation will be mediated by other factors such as atmospheric moisture content, solar radiation, and water temperature, which in turn will be mediated by climate change.

Transmission of Red Sea water via surface infrastructure, and particularly open canals, will therefore involve considerable operational uncertainty. Surface infrastructure will be at greater risk than underground pipelines from climate-related hazards whose future evolution is currently unpredictable. Surface infrastructure is also likely to result in a greater long-term impact on local biodiversity via disruption to drainage systems.

Placing the conveyor under the surface of the Wadi Araba in the form of a pipeline would minimise both its vulnerability to climate hazards and the operational uncertainty associated with climate variability and change on timescales ranging from hours (e.g. flash floods and contamination from dust events) to decades (e.g. long-term changes in evaporation). Surface disruption (e.g. to ecological systems and drainage networks) would be largely limited to the construction phase.

Underground pipelines would not remove risks associated with the leakage of Red Sea water into the surrounding soils and sediments. The impacts of any such leakages might be increased if the pipeline was located near to or below the upper level of the groundwater layer, with leakage directly into the water table. Whether located underground or at the surface, leakages might act in combination salinisation of groundwater driven by climate change, with knock-on impacts on biodiversity. The project might thus act to amplify the impacts of climate change and vice versa.

From the perspective of climate change risks, underground pipelines are preferable to surface infrastructure, particularly in the form of open canals, with the caveat that the implications of subterranean leakage as opposed surface leakage should be examined further. Given the importance and fragility of the ecosystems in the Wadi Araba, risks could be minimised further by constructing the majority of the conveyor as a tunnel through the mountainous areas east of the Wadi Araba. This option would effectively insulate the majority of the conveyor from risks associated with climate variability and change, and would avoid the potential ecological impacts in the Wadi Araba.

Given the large uncertainties regarding the future manifestations of climate change and the combined impacts of climate change and the project in the Wadi Araba, the tunnel option represents by far the best option from a climate risk management perspective.

9. SUB-STUDY C: Dead Sea

9.1. Context: Climatology and recent decline in Dead Sea water level

The Dead Sea is the lowest elevation and most saline water body in the world. Rainfall over the Dead Sea has been estimated at around 90 mm per year[80] based on long-term records, although a weighted average of annual rainfall totals from a number of stations around the Dead Sea for the past 25 years yields a value of 65 mm per year (consistent with observations of declining rainfall in the wider region[81]), and it is this value that is used in the water mass balance model employed in the wider RSDSC Feasibility Study. Annual potential evapotranspiration ranges from around 2000 mm to the north of the Dead Sea basin to around 3000 mm in the south, at the northern end of the Wadi Araba[80].

Salameh and El-Nasser (1999) describe a variation in average relative humidity in the Dead Sea basin from around 65% in winter to 35% in summer[80]. Krumgalz et al. (2000) present the results of measurements of relative humidity at 3m above the surface of the Dead Sea from July 1992 to June 1998, which span a range from 38% to 83%[82]. However, some 90% of the measurements fell within the range 60-75%, with around half of these within the narrower range of 65-70%.

The Dead Sea is a "terminal lake" with no outlets. For most of the Dead Sea's history its level has therefore been indicative of regional climatic variations and water budgets. However, since the middle of the 20th century the water level of the Dead Sea has been falling rapidly as a result of the diversion of runoff that would otherwise feed the lake, for agricultural, industrial and domestic use, as well as the use of water from the Dead Sea itself in the production of potash. Total past inflow of freshwater to the Dead Sea has been estimated at around 1750 MCM/yr, with 1250 MCM/yr derived from the inflow of the Jordan River[53]. Current total net inflow of freshwater has been estimated at around 300 MCM/yr[53], with the current contribution from the Jordan River estimated at less than 100 MCM/yr[83]. The remainder derives from flash floods and flow from the side wadis in the Dead Sea basin itself[84]. Additional input results from irrigation return flows, chemical industry return flows and groundwater depletion, yielding an estimated total inflow of 699.3 MCM/yr[84].

As a result of the factors described above, the level of the Dead Sea has fallen by 32 m since 1930, and, according to the most recent estimates, at a rate of over 1 m/yr over the past decade[85]. In 2008 the level of the Dead Sea was 421 m below gmsl[86].

A study in 2005 estimated that, under a business-as-usual scenario of water resource exploitation, the level of the Dead Sea is likely to fall until it stabilises at around 550 m below current gmsl. A study by Krumgalz et al. (2000), considering thermodynamic and chemical constraints on evaporation of Dead Sea surface waters concluded that, under current climatic conditions, the water level could fall to a somewhat higher minimum elevation of around 500 m below current gmsl[82]. Thermodynamic and geochemical constraints are thus likely to prevent the Dead Sea from drying completely, although the minimum possible level is dependent on climatic parameters, specifically relative humidity. Estimates of the timescales associated with an evaporative decline to a minimum water level under current climatic conditions are of the order of several centuries.

9.2. Observed and projected changes in climate in the Dead Sea basin

9.2.1. Recent historical changes in climate in the Dead Sea basin

A number of changes in climate in the Dead Sea Basin have been identified in the past fifteen years, including a decrease in solar irradiance and maximum temperature, and an increase in minimum temperature in the southern parts of the basin since the middle of the 20th century[24].

Alpert et al. (1997) described 20th century changes in pan evaporation at Sdom, at the southern end of the Dead Sea, for the period 1962-1994[87]. A steep increase in annual pan evaporation rates is apparent in the early 1980s. Prior to 1983 annual evaporation rates ranged between around 3.30 m and 3.70 m. After 1983 evaporation was between about 3.60 m and 4.00 m, falling below 3.70 m only in 1985. Average monthly increases in evaporation between 1962-1981 and 1982-1993 were between 3 and 4 cm for April-September and November (with a peak in May), around 2 cm during October, and around 1 cm for the December-March.

Alpert et al. (1997) link the above increases in pan evaporation to the decline in the Dead Sea's area and the resulting decline in the Dead Sea breeze, generated by the temperature difference between land and water, which is greatest in spring and early summer, when the largest increases in evaporation are seen. Empirical data support this explanation, revealing a slower increase in wind speed throughout the day[87]. Reduced sea breeze has resulted in a decline in relative humidity and an increase in temperature, resulting in increased evaporation. Weaker Dead Sea breezes are also likely to have resulted in a stronger penetration of the Mediterranean breeze, which reaches the Dead Sea in spring and results in the subsidence and heating of air over the Dead Sea basin, further increasing evaporation.

9.2.2. Future changes in temperature and relative humidity

The mechanisms through which climate change is most likely to influence Dead Sea water levels are elevated temperatures and changes in relative humidity in the atmosphere over the Dead Sea itself. As described above, most models project a regional warming of 3-4º C by the late 21st century, with some studies suggesting increases in mean and maximum temperatures of up to 6º C[15], at least in some seasons (with warming likely to be greatest in summer).

In general terms it may be noted that the micro climate of the Dead Sea basin is so strongly mediated by local factors such as topography and the state of the Dead Sea itself that regional projections of average conditions in the wider region are of extremely limited utility in predicting how local climatic conditions might evolve in the basin. In this context it is relevant that the PRECIS regional modelling study manages to represent spatially heterogeneous changes in precipitation at the scale of the Dead Sea basin, which indicate responses within the basin that are different from those in adjacent areas, either in magnitude or direction depending on the period of the projection and the time of year[34].

Nonetheless, it is reasonable to assume that the tendency is likely to be one in which elevated temperatures act to reduce relative humidity. A regional warming of several degrees Celsius might have a significant impact, reducing relative humidity by the order of tens of per cent.

However, future changes in relative humidity will also be mediated by factors other than temperature change, such as changes in regional atmospheric circulation, atmospheric moisture content, and precipitation. Variable warming unevenly distributed throughout the year will mean that changes in relative humidity will also vary over short (e.g. seasonal) timescales. Over the Dead Sea itself relative humidity will be strongly influenced by evaporation, which will depend not only atmospheric moisture content and temperature, but also on the salinity and chemistry of the Dead Sea surface waters. Relative humidity over the Dead Sea will also depend on local atmospheric circulation, and the advection of air over the Dead Sea surface from surrounding areas and vice versa. It is therefore impossible to produce meaningful quantitative estimates of how relative humidity will change, particularly in the atmosphere over the Dead Sea, without detailed modelling studies.

9.3. Future conditions in the Dead Sea basin under climate change without the RSDSC ("no project" case)

Future climatic changes in the Dead Sea basin will be driven by a complex set of interactions between global, regional and local processes. The situation is particularly complex due to the strong influence the Dead Sea has on local climatic conditions, which are mediated by factors that depend on the Dead Sea's surface area, temperature and salinity. Implementation of the RSDSC would itself alter the climate of the Dead Sea basin, via its impacts on these variables as discussed in the next section.

Currently, local anthropogenic factors are the dominant drivers of changes in Dead Sea volume, water levels, and chemistry, and this situation is likely to continue, at least in the near to medium term. Nonetheless, climate change has the potential to affect Dead Sea levels through changes in rainfall, air temperatures, and relative humidity.

9.3.1. Impacts of changes in temperature and relative humidity

A general reduction in relative humidity will not necessarily result in enhanced year-round evaporation. Currently, episodes of very low relative humidity are isolated events, and the results of on-site experiments examining the evaporation of Dead Sea water under current climatic conditions indicate that the impacts of enhanced evaporation during such episodes are quickly erased by the subsequent condensation of atmospheric moisture. In these experiments, evaporation from buckets stopped, and condensation from air humidity commenced, as the transition from summer to autumn climatic conditions was approached[86].

Nonetheless, higher temperatures and lower relative humidity associated with projected regional climatic trends towards increased aridity will act to enhance evaporation. It is highly likely that low humidity - high evaporation episodes will become more frequent and protracted in the future. Climate change is likely to act to accelerate the decline of the Dead Sea in the medium to long term, and to result in a lower minimum level in the future, meaning that without intervention Dead Sea levels will stabilise somewhere below the current estimate of 500-550 m below gmsl. However, evaporation from the Dead Sea depends strongly on surface water chemistry, meaning that the relationship between temperature, relative humidity and evaporation is complex and that future projections of Dead Sea decline cannot be made without recourse to further modelling studies.

9.3.2. Impacts of projected changes in rainfall, runoff and groundwater

Given that almost all of the flow of the Jordan River is diverted before reaching the Dead Sea, the main impact of climatically driven changes in runoff on the Dead Sea will be via changes in direct rainfall over the surface of the Dead Sea and in episodic discharges from the side wadis. For the purpose of the RSDSC Feasibility Study, direct precipitation over the surface of the Dead Sea has been estimated at 39.3 MCM/yr, with surface runoff including the residual contribution from the Jordan River and discharges from the side wadis and flash floods providing some 210 MCM/yr.

Projected declines in rainfall of up to 30% or more would therefore reduce freshwater input to the Dead Sea by around 12 MCM/yr. Larger declines in some projections, principally the PRECIS study (in which reductions in some seasons reach 60%)[34], suggest that the decline in direct rainfall could be in the region of 20 MCM/yr.

Projected declines in runoff of up to 50% or more for a “worst case” scenario indicate a potential further loss of freshwater input to the Dead Sea of over 100 MCM/yr by the late 21st century.

The above figures should be treated with caution for a number of reasons. First, the unique environment of the Dead Sea means that local trends might be different from regional patterns of change (although the PRECIS study resolves projected changes at spatial scales that can represent features such as the Dead Sea basin). Localised changes in circulation and temperature could have a significant impact on rainfall, evaporation and runoff. Second, the Dead Sea basin is already arid, with highly variable rainfall concentrated in a small number of short-lived events. Given the projected increase in aridity, rainfall variability is likely to increase. Mean values for annual rainfall amounts might therefore be somewhat misleading, with large variations from year to year. Third, management of the Dead Sea, including any potential RSDSC, will have a significant impact on local climatic and environmental conditions, meaning that local anthropogenic factors may well dominate over larger scale region and global climatic drivers of change, at least in the short to medium term. Uncertainty regarding future climatic conditions is therefore amplified by the uncertainty regarding the nature of future management regimes and human impacts at the scale of the Dead Sea basin itself.

A major uncertainty regarding future input into the Dead Sea is associated with the management of the Jordan River. In the event that the river is rehabilitated, for example under a scheme such as the JRDS[53], freshwater input to the Dead Sea may increase. However, it is suggested here that, even under such a scheme, the impacts of climate change and increasing demand might mean that abstraction from the lower Jordan Valley would result in flow to the Dead Sea remaining small.

9.3.3. Summary and implications for the chemical industry

In the absence of any intervention, Dead Sea levels will continue to fall due to the imbalance between inflow and loss, the latter due to a combination of evaporation and abstraction. As the Dead Sea surface area continues to decline, it is reasonable to assume that there will be a further weakening of the Dead Sea Breeze, with an associated increase in minimum temperatures and a decline in relative humidity. While evaporation will decrease over the Dead Sea itself as its surface area declines and its waters become more saline, higher temperatures and lower relative humidity in the areas immediately adjacent to the Dead Sea will tend to increase evaporation from the pans employed by the chemical industry (although this does not account for the impact of any changes in the chemical composition of the waters entering the pans on pan evaporation rates). However, these effects may be offset by any continuation of the downward trend in solar irradiance, as solar radiation is the largest single component of the energy balance that determines evaporation rates[88].

Climate change is likely to enhance the tendency towards increased pan evaporation, as a result of higher temperatures, particularly in summer (when the largest increases in temperature are expected to occur), and lower relative humidity. While maximum temperatures have decreased in recent decades as a result of reduced solar irradiance (most likely linked with increased atmospheric aerosol loadings), climate change is likely to act to increase maximum temperatures, particularly in summer.

The combined effect of continued abstraction of Dead Sea water and climate change is likely to be to increase evaporation in the pans of the southern Dead Sea Basin. Climate change is likely to act to enhance evaporation from the remaining body of water in the northern Dead Sea basin, although the impacts of climate change will interact with the factors described above in ways that can only be quantified by detailed modelling studies.

9.4. Future conditions in the Dead Sea basin under climate change with the RSDSC ("with project" case)

9.4.1. Implications of climate change for RSDSC success in rehabilitating the Dead Sea

Climate change is likely to have a significant impact on the operation of the RSDSC via its impacts on the water balance of the Dead Sea. These impacts will be realised via two principal mechanisms as outlined below.

Enhanced evaporation resulting from higher temperatures and a decline in relative humidity is likely to mean that the rate at which the water level of the Dead Sea will rise as a result of the implementation of the RSDSC will be lower than currently estimated. This effect is likely to increase over time as warming increases. However, the magnitude of this effect cannot be quantified on the basis of current information due to complex local feedback mechanisms, and modelling studies are required to understand these processes better.

Reduced rainfall over the Dead Sea and reduced surface runoff in the Red Sea basin and Jordan River catchment (including the catchments of the Yarmouk and Zarqa river basins) will act to reduce input to the Dead Sea by an amount that could exceed 100 MCM/yr by the mid-late 21st century, offsetting the input from the RSDSC.

Given that climate change and regional warming is likely to accelerate over the course of the 21st century, the greatest impacts on the operation of the RSDSC would most likely be realised towards the middle of the century and beyond. While the shift towards a more arid climate is likely to have some impact on the rate at which Dead Sea levels rise for a given inflow from the RSDSC, this impact might be small over the 25 year period during which levels would rise to the target level.

Once the target level is reached, further input from the RSDSC would be required to maintain the level of the Dead Sea, in order to compensate for the continued abstraction of water from the

Jordan River and the imbalance between inflow and evaporative losses. In the longer term, input from the RSDSC will very likely need to be increased in order to further compensate for enhanced evaporation (resulting from higher temperatures and reduced relative humidity) and a reduction in inflow (resulting from lower direct rainfall and a decline in runoff).

9.4.2. Impacts of the RSDSC on local climate in the Dead Sea basin

Based on the relationship between Dead Sea surface area, local wind regime, temperature and relative humidity as discussed above, the increase in surface area resulting from the input of Read Sea water into the Dead Sea is likely to act to strengthen the Dead Sea breeze, increase relative humidity, and reduce air temperatures, shifting conditions back towards those pertaining prior to the early 1980s (see above for a discussion of these processes). However, the input of Red Sea water as opposed to freshwater would prevent the re-establishment of the precise *status quo ante*, given the former's higher salinity. Refilling the Dead Sea with Red Sea water as opposed to freshwater would presumably result in a lower evaporation rate for any given water volume. Changes in evaporation rates resulting from changes in the salinity of the surface layers will affect the relative humidity over Dead Sea, which in turn will mediate evaporation. Surface area, salinity, evaporation and relative humidity will thus be co-dependent and will interact through a complex set of feedback mechanisms that cannot be readily predicted without recourse to modelling.

9.4.3. Summary and implications for the chemical industry

Compared with the “no project” scenario, construction of the RSDSC is likely to act to reduce evaporation rates in pans in the southern basin of the Dead Sea, as a consequence of the expansion in the Dead Sea’s surface area, the strengthening of the Dead Sea Breeze, and an associated reduction in air temperatures and increase in relative humidity. Without further modelling studies it is impossible to quantify the magnitude of the changes in these parameters that will result from construction of the RSDSC. However, while the precise impacts of climate change within the Dead Sea Basin are difficult to predict (given the extreme topography of, small spatial scale associated with, and importance of local anthropogenic factors within, the basin), climate change has the potential to offset these anticipated reductions in temperature and increases in relative humidity, especially in the medium to longer-term. It therefore seems unlikely that the construction of the RSDSC will result in the re-establishment of local climatic conditions pertaining prior to the Dead Sea’s decline, and it might be expected that pan evaporation rates will remain higher than they were in the middle of the 20th century. The RSDSC would not restore the Dead Sea to its original level, which might also reduce the extent to which the climatic *status quo ante* (e.g. as represented by the strength of the Dead Sea Breeze) is likely to be realised.

Nonetheless, this prognosis must remain speculative pending further detailed modelling studies of the combined impacts of climate change and the proposed RSDSC on the local climate of the Dead Sea basin, and other factors introduce further uncertainties. Changes in the properties of the Dead Sea waters compared with the mid 20th century resulting from the restoration of its level with Red Sea water than fresh water will have implications for evaporation compared with the *status quo ante*, as indicated above. There are also uncertainties concerning possible future changes in solar irradiance, which declined over Israel throughout the late 20th century. This decline may continue or reverse, depending on a combination of local and regional anthropogenic and meteorological factors. Restoration of the Dead Sea with brine rather than fresh water, and any further decline in solar irradiance, will result in lower evaporation from the main body of the Dead Sea (northern basin), and lower solar irradiance will act to reduce evaporation from the pans of the southern basin.

This Climate Change Study does not assess the potential impacts of the proposed RSDSC on the properties of the Dead Sea itself, and this issue is addressed in the additional studies of the wider feasibility study.

9.5. Recommendations

Assumptions about the future mass balance of the Dead Sea, and future rates of increase in Dead Sea levels, are likely to have to be revised as a result of the impacts of climate change. Under current design parameters, maintaining projected rates of increase in Dead Sea levels are likely to require a reduction in the proportion of Red Sea water desalinated, in order to compensate for the reduced inflow and increased evaporation resulting from climate change. Alternatively, the amount of water conveyed from the Red Sea might be increased, or the timescale for rehabilitation of the Dead Sea revised.

The proposed RSDSC project would need to accommodate the effects of climate change, either through changes in the conveyor's design and/or operation, or via adjustments in expectations of the time taken for Dead Sea levels to be raised to their target level.

The following recommendations are made:

1. If implemented, the RSDSC project should be based on the assumption that climate change is likely to reduce freshwater inflow further, by an amount exceeding 100 MCM/yr by the latter half of the 21st century, representing some 10% of the proposed input. This loss of input will interact with changes in evaporation from the Dead Sea’s surface that are currently uncertain, to affect the rate at which the recovery of the Dead Sea’s water level can be achieved.
2. Modelling studies should be conducted to assess the potential impact on evaporation (and hence mass balance) of different levels of warming over the Dead Sea, up to 6º C by the late 21st century. These modelling studies will need to include representations of the interactions between temperature, evaporation, relative humidity and water chemistry.
3. It must be recognised that climatic conditions will not remain stable over the course of the 21st century, and that input from the RSDSC to the Dead Sea cannot be calculated based on assumptions of climatic stationarity. The design, implementation and operation of the RSDSC would need to allow for adjustments in inflow in order to sustain a stable water level. The potential range of adjustments should be assessed through modelling studies, based on the assumptions outlined above and the scenarios presented in Annex I.

Temperature and precipitation scenarios are presented in Annex I.

10. Sub-study D: Desalination and Transmission

Considerations of future water demand and of the potential for climate change to increase water deficits are discussed in section 5 above, and indicate an urgent need for new sources of potable water, lending weight to the argument for the Base Case Plus, a high system capacity (2000 MCM/yr under current options), and the rapid development of desalination capacity.

Desalination is sensitive to changes in water properties such as temperature, salinity and particulate content likely to result from future climatic variability and climate-related extremes, particularly where Red Sea water transits via an open conveyor.

Changes in rainfall, runoff, and evaporation have the potential to modulate the composition and salinity of Red Sea water while it is in transit through the conveyor where it is open to the air. Higher temperatures will increase evaporation of water in transit through an open conveyor, affecting the volumes required at the intake and the salinity of the water reaching the outflow at the Dead Sea. A reduction in rainfall and runoff will have a qualitatively similar effect (assuming open sections of the conveyor are designed under assumptions of a certain amount of freshwater input from rainfall and/or runoff). Changes in prevailing winds may also have an impact on evaporation rates. Any increase in climatic variability associated with more variable rainfall and an increase in the intensity of individual precipitation events may have implications for the management of transmission, being associated with episodic changes in the salinity, chemical composition, and sediment load of the water transiting via the conveyor. Changes and variations in water chemistry, salinity and suspended sediments will also have implications for desalination.

Changes in precipitation-evaporation ratios resulting from higher mean and maximum temperatures, more frequent and severe hot and dry episodes, and anticipated reductions in rainfall and atmospheric moisture are of concern in the context of environment impacts. A trend towards drier conditions could accelerated soil salinization, and might amplify the impacts of any salt-leaching from the conveyor into the adjacent land.

The following factors, some of which are discussed above under Sub Study B, weigh against transmission in an open canal for some or all of the transit through the Wadi Araba:

1. risk of damage to canal infrastructure from flash floods, the future behaviour of which is uncertain
2. evaporative losses which are likely to increase over time with warming, but which are difficult to quantify due to uncertainties in warming rates and the distribution of warming throughout the year (although warming is likely to be greatest in summer, with significant warming in most months in future decades)
3. solar and radiative heating of water while in transit, likely to increase over time, with potential implications for the operation of desalination plants
4. increased salinity of water while in transit due to evaporation, with potentially unpredictable fluctuations in salinity due to temperature fluctuations and input of fresh water into the canal during rainfall and runoff events, with potential implications for the operation of desalination plants
5. contamination of water by airborne particulates and pollutants such as mineral dust combined with aerosols from population centres (which might become more frequent under climate change, although this is highly uncertain)

6. physical disruption to micro-drainage, with potential adverse impacts on flora and fauna which may also be adversely affected by a shift to more arid conditions
7. risks of leakage into surrounding soils, sediments and groundwater, which may already be affected by salinisation or a lowering of the water table due to more arid conditions resulting from climate change

Based on the above considerations, an open conveyor is the least desirable option. A closed surface conveyor would address some of the above concerns but would be vulnerable to damage associated with climate-related extremes such as floods and landslides, and might also have some impact on micro-drainage. A sub-surface conveyor through the Wadi Araba would minimise these risks, but would still be associated with risks of leakage. Given the high uncertainty regarding future climatic variability and the impacts of climate change in the Wadi Araba, it is not possible to address how project impacts would interact with climate change risks.

From a climate risk management perspective it is strongly recommended that the conveyance between the Wadi Araba and the Dead Sea take the form of a tunnel under the mountainous area east of the Wadi Araba.

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Annex I: Future climate change scenarios

The area of study relevant to the RSDSC is very limited in its spatial extent, and contains areas with widely varying topography and environmental and climatic conditions. The wider region containing the study area is characterized by steep gradients in key climatic parameters such as temperature and precipitation. These factors mean that caution should be exercised when using global and regional climate change projections to assess potential changes in key climatic parameters for the study area. Furthermore, regional projections cannot simply be assumed to be representative of future conditions at sub-regional scales even in the absence of complex topography and other factors that mediate local climatic conditions. Ideally, studies of potential future changes in key climatic parameters for the RSDSC study area would be based on data generated by an ensemble of high resolution climate models, whose output had been validated against observations for the specific region of interest.

In the absence of such detailed studies (with the exception of the PRECIS study by Hemming et al. (2008), which provides high resolution projections of temperature and precipitation changes for the Middle Eastern region for several time periods) some simple climate change scenarios may be constructed using *plausible* values of temperature and precipitation, based on a review of the existing studies. These scenarios may be used to perform *sensitivity studies* to examine the potential implications of certain plausible changes for key systems and processes that are relevant to the RDSDC feasibility study. Such scenarios should be viewed as speculative scenarios informed by expert judgment based on consideration of the range of available climate change projections.

The principal application of climate change scenarios in the RSDSC feasibility study will be in examining the future evolution of the Dead sea for project and no-project cases, using the mass balance model developed by Coyne & Bellier. The key climatic parameters required to drive the model are temperature, precipitation, relative humidity and wind speed.

Scenario components/parameters

Temperature

Table 1 summarises potential changes in temperature between the late 20th and 21st centuries (and in one case the mid 21st century), as projected in a variety of climate change studies. These data are interpreted below to produce simple scenarios for future temperature changes in the region containing the study area.

The survey of the published literature indicates a range of annual mean surface warming in the wider Mediterranean/Saharo-Arabian region (encompassing the study area) of some 2°-7° C by the end of the 21st century. The highest projected warming over the study area occurs in the summer and is in the region of 5° C, with a warming of up to 6° C projected for the summer months in northern Israel, immediately northwest of the study area. Recent historical warming has also been greatest in summer.

Table 1. Projected changes in temperature for different seasons (and annually), from a variety of studies/models/scenarios, including different scenarios used in the IPCC AR4; Alpert et al., 2008 (Alpert); Giorgi and Lionello, 2008 (Giorgi); Somot et al., 2008 (Somot); Hemming et al., 2008 (Hemming); and the three models used in Jordan's Second National Communication (SNC). Projections represent different regions, including the study area, the Saharo-Arabian region between 20° and 30° N (SAH), the wider Eastern Mediterranean (E. Med.), northern Israel, and an area of 200km^2 in northwestern Jordan (NWJ). Projections for the "late 21st century" are for the latter decades of the century; Projections "by 2050" are for the period around 2050 or, for the figures from Hemming et al. (2008), the 2040s. The Hemming et al. (2008) figures are approximate, having been estimated from maps of projected seasonal and annual changes.

Study/scenario	Annual	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)	Region
Late 21st cent.						
IPCC A1B	3.0-3.5	2.5-3.0		3.5-4.0		Study area
IPCC A1B	2.2-4.2					SAH
IPCC B1	3.4-5.9					SAH
Giorgi A1B		2.0-3.0	3-4	4.0-5.0	3.0-4.0	Study area
Alpert B2				2.5-3.5		E. Med.
Alpert B2				~4.0		N. Israel
IPCC A2	4.0-7.2					SAH
Alpert A2				3.0-5.0		E. Med.
Somot A2		3.0-4.0		3.0-5.0		Study area
Hemming A2	3.0-4.0	3.0-3.5	3.0-4.0	3.5-4.5	3.5-4.5	Study area
Alpert A2				~6.0		N. Israel
By 2050						
IPCC A1B	2.0-3.5					SAH
Hemming A2	1.8-2.5	1.6-2.5	1.6-2.5	2.5-3.5	2.0-3.0	Study area
JSNC CSIRO	1.08	0.79	0.88	1.26	1.37	NWJ
JSNC ECHAM	0.76	0.48	0.95	0.99	0.90	NWJ
JSNC HAD	1.27	1.09	1.08	1.47	1.45	NWJ

These results suggest a plausible range of mean annual warming of 2°-6° C by the late 21st century in the sub-region encompassing the study area, comprising the northern Gulf of Aqaba, Wadi Araba, Dead Sea, Jordan Valley and immediately adjacent regions, The upper end of this range is extreme, and reflects the results of one regional study (Alpert et al., 2008) focusing on the summer period only, and the upper limit of the IPCC projections for the Saharan region. Nonetheless, given the uncertainty associated with climate projections, it appears reasonable to include such a worst-case scenario. Three temperature scenarios are therefore suggested, representing warming of 2° C, 4° C and 6° C by 2100, with warming occurring at a constant rate (a simplified representation of reality, given that warming will not occur in a linear manner due to natural variability, the complex way in which the climate will respond to increasing greenhouse forcing, and changes in greenhouse gas emissions over time).

An equal warming could be applied for each month of the year. However, given that warming is likely to be greatest in the summer months, based on both observed historical and simulated future warming, it is more realistic to apply a greater warming in the summer months. It is during the summer when evaporation from water bodies such as the Dead Sea is greatest; greater warming in the summer might therefore have a significant impact on the mass balance of the Dead Sea. Based on the seasonal distribution of warming in the projections described by Giorgi and Lionello (2008) for the A1B scenario, Table 2 identifies temperature changes for winter, spring, summer and autumn. These seasonal temperature increments should be applied to each month in a given season.

The temperature increments listed in Table 2 represent warming between the late 20th century (Typically 1961-1990) and the late 21st century (typically 2071-2100). Representative rates of warming may therefore be calculated by dividing the seasonal/monthly warming values by 100, to yield an plausible annual warming rate. Again, it is stressed that these warming rates are simplified, representative depictions of plausible warming scenarios, intended to assess the sensitivity of the mass balance model to different warming rates.

Table 2. Suggested temperature increments for three warming scenarios. Each seasonal increment should be applied to the monthly mean temperature values used to drive the mass balance model.

Scenario	DJF warming	MAM warming	JJA warming	SON warming
2° C warming	1° C	2° C	3° C	2° C
4° C warming	3° C	4° C	5° C	4° C
6° C warming	4° C	6° C	7° C	6° C

Rainfall

Table 3 summarises potential changes in precipitation between the late 20th and 21st centuries (and in one case the mid 21st century), as projected in a variety of climate change studies. These data are interpreted below to produce simple scenarios for future temperature changes in the region containing the study area.

Table 3. Projected seasonal changes in rainfall over, or in the vicinity of, the study area from the IPCC AR4 (IPCC); Giorgi and Lionello, 2008 (Giorgi); and Alpert et al., 2008 (Alpert), for different emissions scenarios.

Study/scenario	**Annual**	**Winter (DJF)**	**Spring (MAM)**	**Summer (JJA)**	**Autumn (SON)**	**Region**
						Study area
IPCC A1B	-(20-30)%	-(20-30)%		-(5-10)%		Study area
Giorgi A1B		-(20-30)%	-(20-40)%	-(0-20)%	(-10)-(+10)%	Study area
Giorgi B1		-(10-20)%	-(10-30)%	+(10-50)%	(-10)-(+10)%	Study area
Alpert B1		-(0-5)%				N. Israel/JV
Alpert A2		-(10-30)%				N. Israel/JV
Giorgi A2		-(30-40)%	-(≥40)%	+(0-40)%	-(20)-(+30)%	Study area
Hemming	-(10-30+)%	-(0-30+)%	-(0-60)%	(-30)-(+40)%	(-30)-(+40)%	Study area

The rainfall projections summarized in Table 2 indicate reductions in annual and seasonal rainfall of the order of tens of per cent, with the (highly uncertain) possibility of increased rainfall in the autumn. Projected declines in annual and winder rainfall are typically 10-30%. However, some studies that only provide seasonal projections indicate larger reductions in winter and spring, and the PRECIS study (Hemming et al., 2008) suggests possible declines in annual rainfall greater than 30%.The PRECIS results indicate considerable spatial variability in projected patterns of precipitation change, with increases and decreases rainfall evident in different localities within a relative small area that encompasses the study area. Nonetheless, given the dominance of the drying signal, and the figures in Table 3, it is suggested that scenarios are considered in which annual rainfall declines by 10, 20 and 40%, with the caveat that changes will exhibit a significant amount of spatial heterogeneity.

Given the possibility that autumn rainfall may increase, and the importance of this season for rainfall in the study area associated with active Red Sea troughs, a scenario in which rainfall increases by 10% might also be considered. Changes in rainfall are likely to occur in a much less continuous fashion that changes in temperature; it is suggested that these changes be applied in increments of one quarter for the years 2020, 2040, 2060 and 2085 (e.g. decreasing rainfall by 10% of its current value at each of these dates for the scenario in which rainfall declines by 40% by the end of the century). Given the uncertainty in the impacts of climate change on rainfall in different seasons, it is suggested that the above changes in rainfall (+10, -10, -20, -40%) are applied evenly across all months.

Humidity and winds

Given the data available and the complex local factors governing parameters such as relative humidity and wind speed and direction, no meaningful recommendations can be made regarding these variables. It is therefore suggested that current baseline values are used for these quantities. Any projections of changes in humidity and wind would require high resolution modelling studies validated against observational data. No such studies have been performed for the study area, with high resolution modelling studies having focused on the areas to the north of the study area to date (including the Jordan Valley and northern Israel). It is noted that one study that does examine changes in atmospheric water vapour

Freshwater input to the Dead Sea

The Dead Sea mass balance model currently assumes an input of fresh water to the Dead Sea of 210 MCM/yr, from a combination of direct precipitation (estimated at 39.3 MCM/yr), residual flow from the Jordan River (likely less than 100 MCM/yr), and runoff and flash floods from the side wadis (making up the remainder). It is suggested that this input is likely to approximately halve by the late 21st century, assuming no major changes in the management of the Jordan River.

In the longer term, and regardless of whether or not the RSDSC is constructed, other conveyors may be implemented in the region in order to address increasing water demand and declining availability driven in large part by climate change. It is therefore plausible that the RSDSC could ultimately operate alongside other schemes, including the a scheme to transfer desalinated water from the Mediterranean to the Jordan Valley, in order to rehabilitate the latter and increase freshwater supply. While it is likely that most if not all of the water supply from a rehabilitated Jordan River would be diverted before reaching the Dead Sea, it is possible that inflow from the Jordan River to the Dead Sea may increase under such a scheme. Awareness of such a possibility should be built into the design of any RSDSC.

Sensitivity studies

When combined, the above three temperature and four precipitation scenarios yield twelve climate change scenarios, assuming each precipitation scenario is potentially compatible with each temperature scenario. Scenarios are grouped into three "families" below. Each family represents a particular warming trajectory (low, intermediate or high) and contains four individual scenarios representing different precipitation trajectories (wet, intermediate, dry and extreme).

Initial runs of the mass balance model might assess the impact of warming on the Dead Seas (for the "no project" case) by comparing scenarios with different temperature trajectories but with the same changes in rainfall (e.g. Scenarios 2 and 10), or the impact of changes in rainfall by comparing scenarios with the same warming but different rainfall trajectories (e.g. Scenarios 5 and 8). The overall sensitivity of the Dead Sea to climate change might be assessed by comparing scenarios 1 and 12, representing the two most extreme sets of future conditions.

A further sensitivity investigation might assess the extent to which the mass balance of the Dead Sea, as represented by the model, is sensitive to the seasonal distribution of warming, by comparing one or more of the scenarios listed below with otherwise equivalent scenarios in which equal temperature increments are applied across all months.

Scenarios

Note that the prescribed changes in rainfall are to be applied for each of the specified years (or in a similar manner as practical), and each incremental change should be below the *original* baseline mean annual rainfall. E.g. if current rainfall is 100 mm per year, for the extreme scenarios this should be reduced to 90 mm at 2020, 80 mm at 2040, 70 mm at 2060, and 60 mm at 2080.

Scenario family 1 (low warming of 2° C)

Incremental warming of 0.02°C per year from baseline

- Monthly warming increments:
    - December-February: 0.01° C per year in each month
    - March-May: 0.02° C per year in each month
    - June-August: 0.03° C per year in each month
    - September-November: 0.02° C per year in each month
- **Scenario 1 (wet):** 2.5% increase in rainfall at 2020, 2040, 2060, 2080
- **Scenario 2 (intermediate):** 2.5% decrease in rainfall at 2020, 2040, 2060 2080
- **Scenario 3 (dry):** 5% decrease in rainfall at 2020, 2040, 2060 2080
- **Scenario 4 (extreme):** 10% decrease in rainfall at 2020, 2040, 2060 2080

Scenario family 2 (intermediate warming of 4° C)

Incremental warming of 0.04℃ per year from baseline

- Monthly warming increments:
  - December-February: 0.03° C per year in each month
  - March-May: 0.04° C per year in each month
  - June-August: 0.05° C per year in each month
  - September-November: 0.04° C per year in each month
- **Scenario 5 (wet):** 2.5% increase in rainfall at 2020, 2040, 2060, 2080
- **Scenario 6 (intermediate):** 2.5% decrease in rainfall at 2020, 2040, 2060 2080
- **Scenario 7 (dry):** 5% decrease in rainfall at 2020, 2040, 2060 2080
- **Scenario 8 (extreme):** 10% decrease in rainfall at 2020, 2040, 2060 2080

Scenario family 3 (high warming of 6° C)

Incremental warming of 0.06℃ per year from baseline

- Monthly warming increments:
  - December-February: 0.04° C per year in each month
  - March-May: 0.06° C per year in each month
  - June-August: 0.07° C per year in each month
  - September-November: 0.06° C per year in each month
- **Scenario 9 (wet):** 2.5% increase in rainfall at 2020, 2040, 2060, 2080
- **Scenario 10 (intermediate):** 2.5% decrease in rainfall at 2020, 2040, 2060 2080
- **Scenario 11 (dry):** 5% decrease in rainfall at 2020, 2040, 2060 2080
- **Scenario 12 (extreme):** 10% decrease in rainfall at 2020, 2040, 2060 2080

Annex II: Experts Consulted

The following individuals (listed in alphabetical order by surname) were consulted during the visit to the region of the climate change consultant.

Dr Pinhas Alpert, Head of the Porter School of Environmental Studies, Department of Geophysics and Planetary Sciences, Professor of Dynamic Meteorology and Climate, Tel-Aviv University, Israel.

Professor Fayez Abdullah, Professor of Water Resources & Environmental Engineering, Civil Engineering Department, Jordan University of Science & Technology (JUST), Irbid, Jordan.

Dr Munjed Al-Sharif, Coordinator, UNCT Joint Program (JP) on Adaptation to Climate Change To Sustain Jordan's MDG Achievements. Manager, UNDP component of the JP, Amman, Jordan.

Yusuf Al-Soudani, ACE, Amman.

Professor Steve Brenner, Department of Geography and Environment
Bar Ilan University, Ramat Gan, Israel.

Professor Avinoam Danin, Professor Emeritus of Botany, Department of Evolution, Systematics, and Ecology, The Hebrew University of Jerusalem, Jerusalem, Israel.

Amir Givati, Israel Water Authority, Jerusalem, Israel.

Dr Shimon Krichak, Department of Geophysics and Planetary Sciences, Professor of Dynamic Meteorology and Climate, Tel-Aviv University, Israel.

Dr Riyadh Manasrah, Marine Science Station, Aqaba, Jordan.

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