

Water Balance Computation for the Sultanate of Oman

Final Report - Executive Summary

May 2013

Ministry of Regional Municipalities and Water Resources



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Abbreviations

AAR	Average Annual Rainfall
FAO	World Food and Agriculture Organisation
GIS	Geographic Information System
JICA	Japan International Cooperation Agency
MAF	Ministry of Agriculture and Fisheries
mASL	Metres above sea level
MEDRC	Middle East Desalination Research Centre
MMC	Mott MacDonald & Co LLC
MOH	Ministry of Housing
Mm ³ /yr	Million cubic metres per year
MPG	Ministry of Petroleum and Gas
MRMEWR	Ministry of Regional Municipalities, Environment and Water Resources , former Ministry that included MRMWR
MRMWR	Ministry of Regional Municipalities and Water Resources
MWR	Ministry Water Resources, former name of MRMWR
NFI	National Falaj Inventory Project
NWI	National Well Inventory Project
NWRMR	National Water Resources Masterplan
PAEW	Public Authority for Electricity and Water
PAWR	Public Authority for Water Resources, former title for MRMWR
PDO	Petroleum Development Oman
ToR	Terms of Reference
TSE	Treated Sewage Effluent
WAA	Water Assessment Area
WAUA	Water assessment unit area

1. Overview

At the end of 2011, Mott MacDonald was awarded the contract for the Consultancy Services for the Water Balance Computation for the Sultanate of Oman. The aim of the project is to update the water balance calculations in 28 Water Assessment Areas (WAA) across Oman. Each of these WAA is subdivided into Water Assessment Unit Areas (WAUA) making up a total of 191 for the Sultanate.

Five volumes have been issued in accordance with the Terms of Reference (ToR):

- Executive Summary – a summary of the work that has been carried out and results of the water balance calculations (this report).
- Final Report – a detailed discussion of the data sources, modelling methodology and results of the water balance
- Appendix A Model Manual – which contains instructions on the pre-processing required and how to construct, run and calibrate the water balance models.
- Appendix B Model Reports – covering the details of the construction of each of the models, the data that was available and the results of the water balance.
- Appendix C Annual Water Balance by WAUA – an annual time series for each WAUA

Historically, The Sultanate of Oman has relied on its groundwater resources for domestic, agricultural, institutional and industrial water demands. Since the early 1970s, the Sultanate of Oman has benefited from a period of unprecedented growth and development in all sectors of its economy. Water consumption exceeds water availability and as a result, it is observed that some aquifers are overdrawn, there is drying of aflaj in many areas and there are impacts of saline intrusion or nitrate pollution from wastewater in other areas.

There is pressure on the Ministry of Regional Municipalities and Water Resources (MRMWR) to develop a sustainable water resource strategy to meet the future demands without constraining economic growth. A water balance study is the first step in developing a sustainable strategy and ultimately a National Water Resource Master Plan (NWRMP). A water balance study is not a national water resource master plan. It does however provide a sound scientific assessment of the available water resource both in space and time and will enable MRMWR to quantify the available resource, identify trends and test the effectiveness of alternative policies and management strategies.

The overarching objective is to determine the water balance computation using an appropriate methodology and updated data and to apply it to the same 28 Water Assessment Areas (WAA) and 191 Water Assessment Unit Areas (WAUA) defined in the 2000 NWRMP. This should allow for comparison and analysis of changes. The water balance model developed for this study has been named **Mezan Al Maa** which is the equivalent expression in the Arabic language.

There are previous studies for water resource assessment and planning in Oman which include:

- Water resources survey for north-east Oman (Renardet Sauti ICE, 1975)
- Water balance model. Preece, Cardew and Rider with Mott MacDonald (1980)
- National Water Resources Masterplan (Mott MacDonald and Watson Hawksley, 1989)
- National Water Resources Masterplan (Binnie and Partners, 2000)

Recently, the Ministry of Regional Municipalities and Water Resources has undertaken a series of investigations and studies to improve the water resource database. This includes the Hydrogeological Map

and Guidebook of Oman (MRMWR, 2011). With this improved data and understanding, it is considered appropriate to produce another water balance.

Capacity building has been integral to the project through the use of a combined MRMWR and Mott MacDonald project team, regular communication with specialist staff in Cambridge, training workshops and the production of a modelling manual.

2. Data assessments

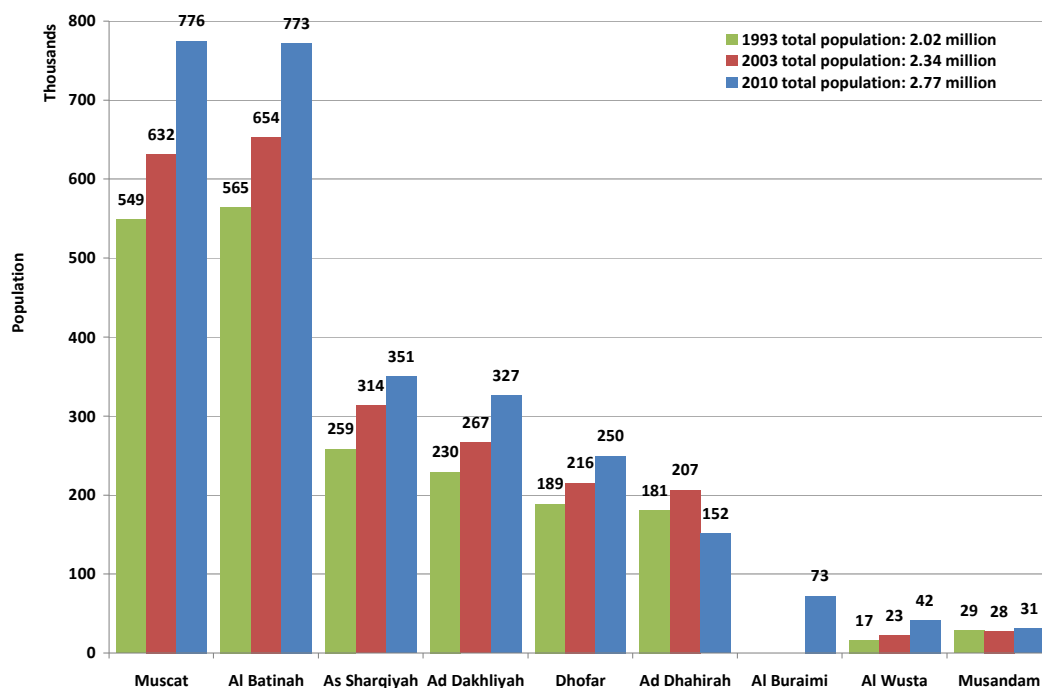
Significant quantities of data held by MRMWR have been provided for this study categorised as follows:

- Rainfall
- Potential evaporation
- Wadis
- Springs
- Groundwater levels
- Aquifer properties
- Aflaj
- Dams
- Population
- Agriculture
- Water demands
- Groundwater abstractions
- Desalination
- Waste water treatment

Each dataset has been scrutinised for its availability; uncertainties; processing required; and the important features of the data. Data which has been verified and is considered to be of acceptable quality has been provided between 1985 and 2007 which is consequently the period of time chosen for the study.

Among the major reasons for updating the water balance calculations in this study are better climatic data and the changes to population and agricultural coverage (Figure 2.1).

Figure 2.1: Population by governorate in 1993, 2003 and 2010

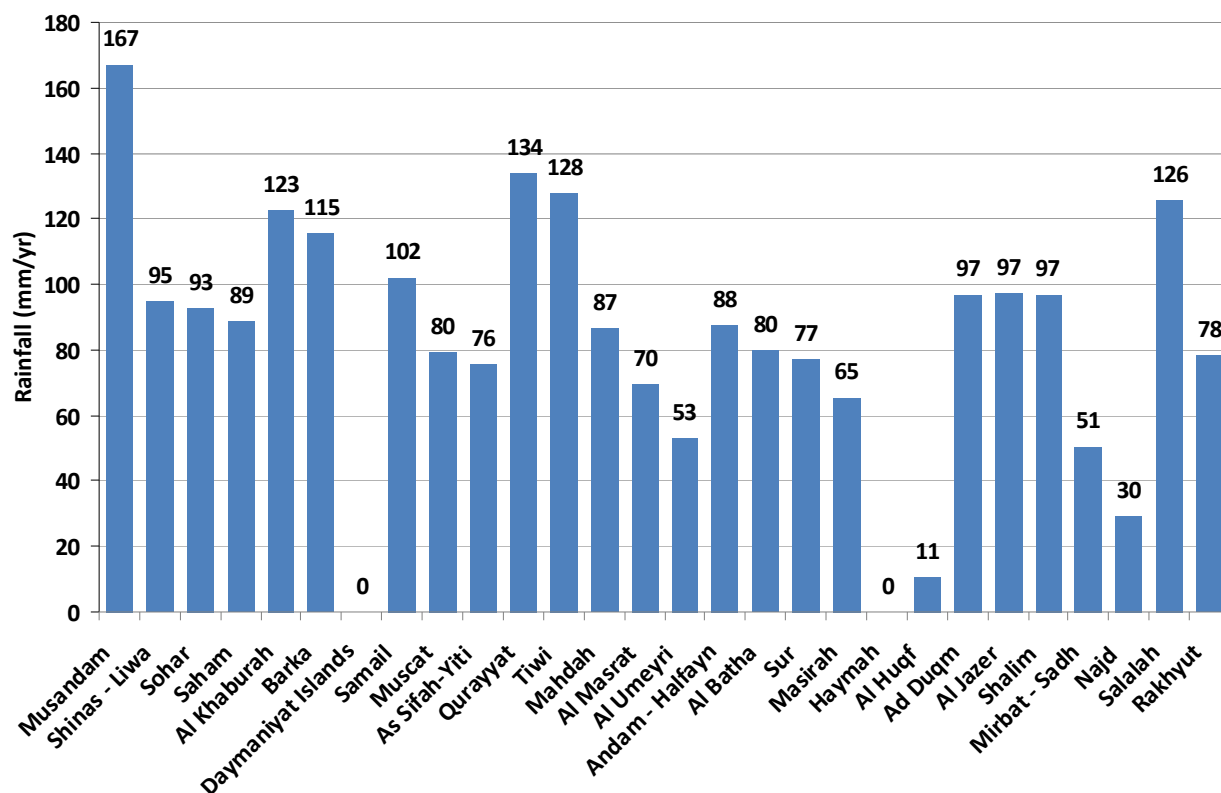


Source: Population census data for 1993, 2003 and 2010
293613/OOG/OMW/06/C 05 May 2013
293613 Water Balance Computation for the Sultanate of Oman

The total population rose from 2.02 million in 1993 to 2.34 million in 2003. Therefore in the 10 years between 1993 and 2003, the total population grew by 16.0%, and the average annual rate was 1.5%. The total population in 2010 was 2.77 million, therefore the growth increased by 18.5% in the seven years between 2003 and 2010 and the average annual rate was 2.5%. Figure 2.1 demonstrates the regional variability of population and shows the concentration of settlements in the Muscat Governorate and across the Al Batinah region.

The average annual rainfall for the country is calculated as being 51 mm/year. However, this figure is highly variable, ranging from 167 mm/year in the Musandam WAA to 0 mm/year in Haymah (Figure 2.2) with a bias towards the large areas in central Oman with little or no rainfall (e.g. Haymah and Najd). Outside of Musandam, the highest rainfall amounts are concentrated in the northern and southern parts of the country including the Salalah Plain (126 mm/year) and the WAA on the Al Batinah Plain (89-123 mm/year). Central Oman has very low modelled rainfall with 0 mm/year in Haymah and 11 mm/year in Al Huqf.

Figure 2.2: Calculated rainfall depth for each WAA

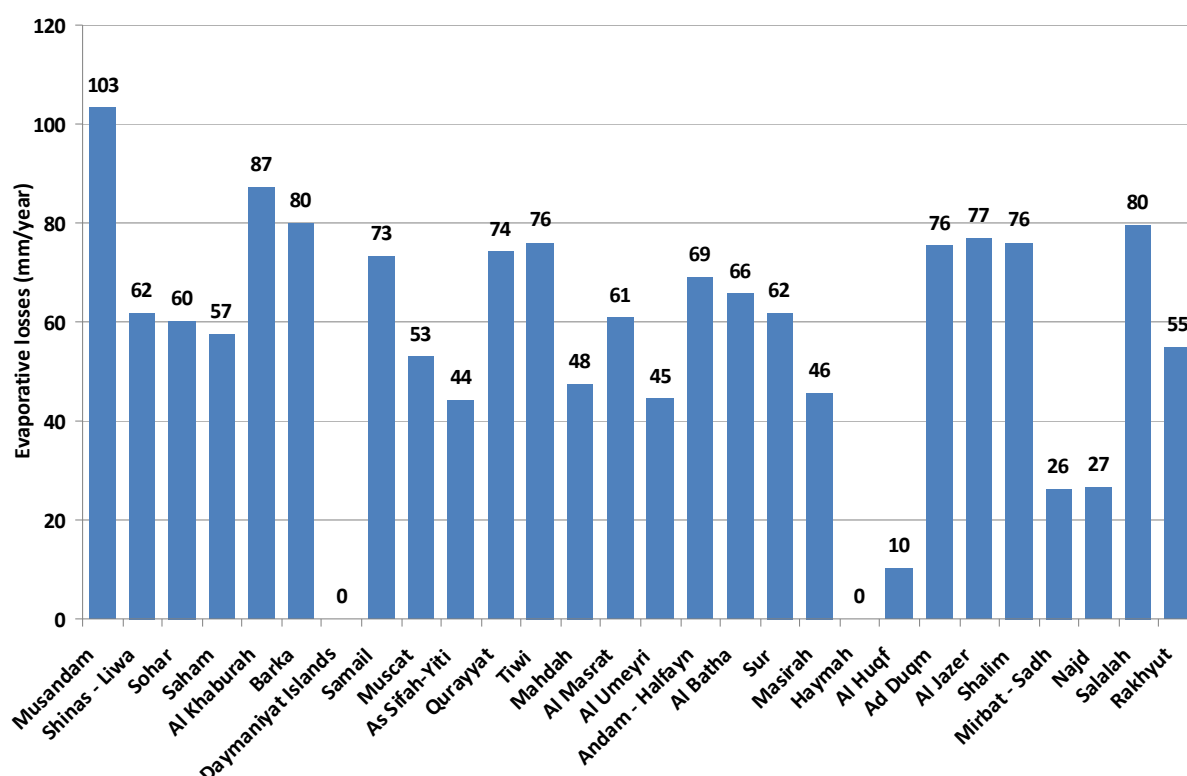


Source: Current study (2012)

Figure 2.3 shows the evaporative losses for each WAA. The figures show that Musandam, on account of its higher rainfall, has the highest loss at 103 mm/year whilst the lowest losses are at Al Huqf (10 mm/year), Mirbat-Sadh (26 mm/year) and Najd (27 mm/year). Evaporative losses are a function of rainfall and average evaporation cannot exceed average rainfall at a given location. No evaporative losses are modelled in Haymah WAA and Daymaniyat Islands as there is no rainfall.

The total loss of water from all catchments in Oman is 12,553 Mm³/yr (Table 5.3), which gives an average of 41 mm/yr.

Figure 2.3: Evaporative losses by WAA

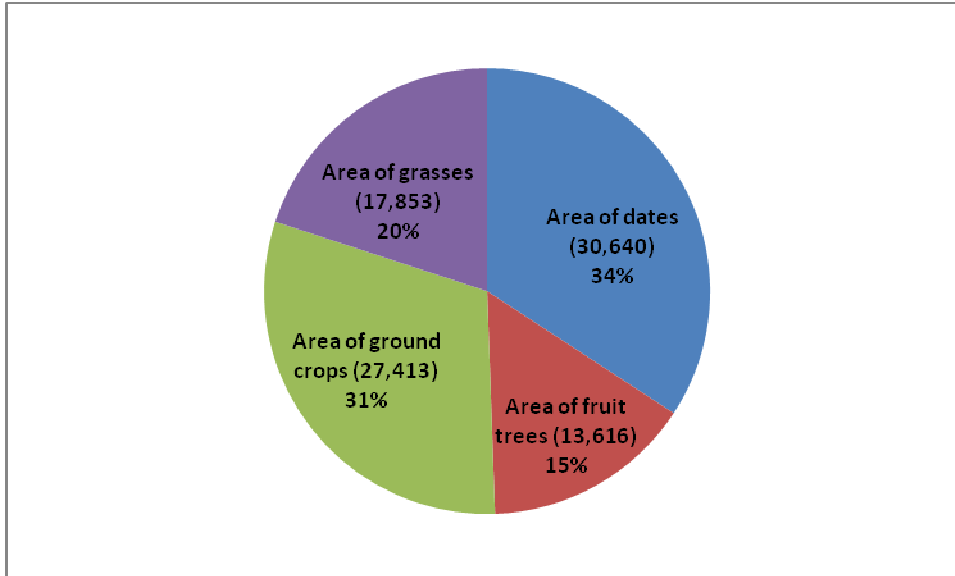


Agriculture is the main user of water in the Sultanate. Landsat satellite imagery is considered to provide the most accurate means of estimating the crop water demand. Processing of the imagery provides an estimate of the cropped area for each WAA. Figure 2.4 shows the estimates of area for dates, fruit trees, ground crops and grasses which have been derived for each WAA using the imagery for 2005.

The total area covered by crops is estimated as 89,521 hectares. Dates constitute the largest area of agricultural land at 30,640 ha (34%) followed by ground crops (13,616 ha), grasses and fruit trees. However, on a WAA basis this distribution is more mixed with some WAA mainly producing fruit trees (e.g. Andam-Halfayn) and others being dominated by grasses or ground crops (e.g. Sohar and Saham).

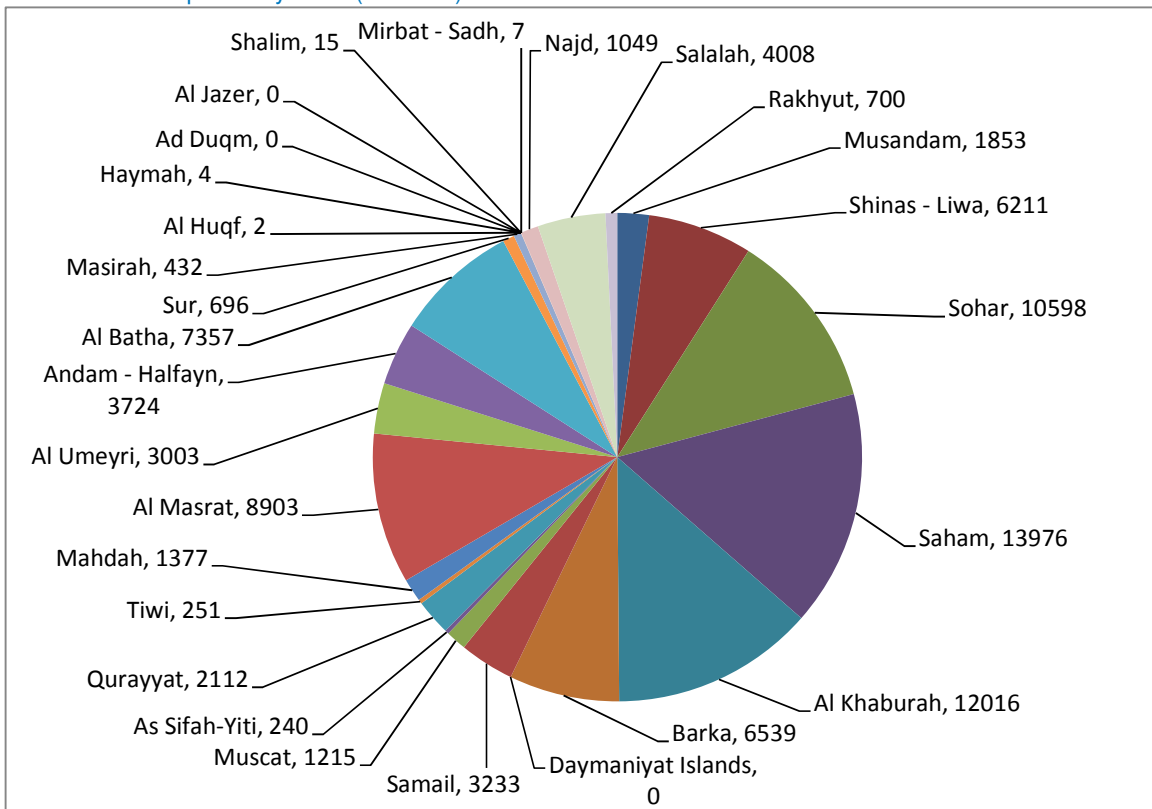
The highest proportions of agricultural land are concentrated along the Al Batinah coast (Figure 2.5). The combined area of agriculture in the Shinas-Liwa, Sohar, Saham and Khaburah WAA constitutes 42,801 ha or 48%. The largest area of agricultural land is in the Saham WAA with a total area of 13,976 ha, closely followed by Khaburah with 12,016 ha. On the Al Batinah Plain, much of the agriculture is concentrated in the lower catchments. Outside of the Al Batinah Plain, the Al Masrat and Al Batha WAA are the most important for agriculture. The agricultural areas of these two WAA is 8,903 ha and 7,357 ha respectively, comprising 10% and 8% of the total cropped area of Oman. In the centre of Oman, there is a much smaller cropped area with less than 10 ha of agricultural land in the Haymah, Al Huqf, Ad Duqm, Al Jazer and Mirbat-Sadh WAA.

Figure 2.4: Distribution of crop types in Oman (hectares)



Source: Landsat imagery (2005)

Figure 2.5: Total crop area by WAA (hectares)



Source: Landsat imagery (2005)

3. Conceptual understanding of the water balance

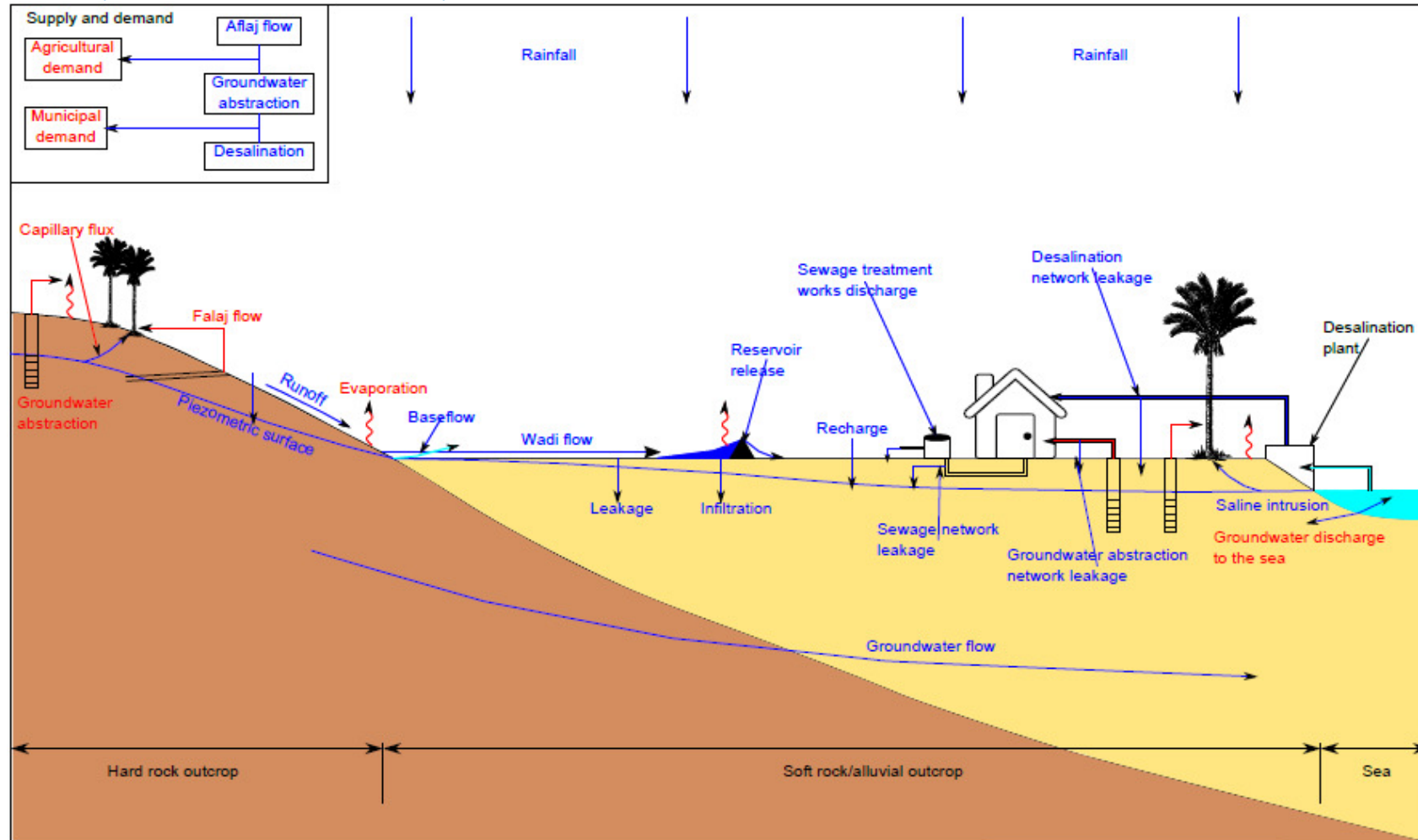
Table 3.1 gives an overview and summary description of the water balance components considered in the conceptual description of the water balance. Figure 3.1 provides a schematic overview of groundwater and surface water movement in a typical Omani geological/hydrogeological environment.

Some of the water balance components (listed in Table 3.1) are combined for use in the water balance model. In particular the gross use of groundwater for irrigation and the return flow from applied irrigation are combined in a net withdrawal from groundwater. Using the net withdrawal removes the uncertainties associated with estimation of irrigation efficiencies.

Table 3.1: Overview of water balance components

Component	Description
Natural recharge	Natural recharge is derived from rainfall and in the water balance modelling context comprises 'direct' rainfall recharge and recharge from infiltration of surface water in wadis
Irrigation return flow	Irrigation return flows are a direct consequence of application of water (from wells and aflaj) in irrigated areas
Urban recharge	Urban recharge is in different forms, including leakage losses from water distribution systems, losses from sewage systems including septic tanks, and return flows from infiltration of treated sewage effluent discharged to wadis or return flow of TSE used for amenity irrigation in urban areas
Surface water flow	Surface water flows are the ephemeral flows in the main wadis, originating from rainfall runoff and to a lesser extent from inflow from groundwater
Groundwater flow	Groundwater flow is controlled by the hydrogeological properties of the groundwater system and the hydraulic gradient in the groundwater table or piezometric surface (the latter relates to confined aquifers) and includes flow across natural boundaries, such as the sea, and flows across Oman's borders
Groundwater discharge	Groundwater discharge occurs in different forms and includes abstraction from wells, discharge from aflaj, diffuse capillary upward flow from the groundwater table in areas where this is close to ground surface and uptake by deep rooted vegetation (such as prosopis trees)
Water use for agriculture	Gross water use for agriculture is controlled by irrigation demand (a function of climatic conditions and cropping characteristics) and the efficiency of irrigation
Urban water use	Gross urban water use is a function of population and per capita water consumption, while the need of water for livestock and industry can be accommodated in the per capita consumption
Surface water storage	Surface water storage relates to reservoirs and recharge dams, the latter being used for temporary storage of wadi floods and controlled downstream releases used for enhancement of wadi bed recharge, thus reducing non-beneficial outflows to the sea or into neighbouring countries
Groundwater storage change	Groundwater storage change is controlled by the rate of change in groundwater levels over a defined time period and the storage characteristics of the groundwater system
Saline intrusion in coastal zones	Saline intrusion is defined as groundwater flow of sea water into the groundwater system and is caused by over-use of groundwater in coastal areas
Import of desalinated water	Water demand in urban areas is going to be fully satisfied by import of desalinated water

Figure 3.1: Conceptual illustration of water balance components



4. Modelling methodology

A preliminary data analysis was used to agree upon the modelling period of interest. Poor data availability means that there is not sufficient detail to undertake the water balance studies prior to 1985. Quality control and data processing is still being carried out on more recent datasets. Therefore, the most confidence can be placed in the data provided between 1985 and 2007 which was agreed to be the period of interest. The components of the modelling aspects assessed in this study can be grouped as follows:

- Hydrological modelling
- Direct rainfall recharge
- Wadi recharge
- Urban recharge
- Reservoir recharge
- Groundwater flow
- Groundwater abstraction for agriculture
- Groundwater abstraction for urban use
- Capillary flux
- Groundwater storage change

Given the large number of components of the water balance and the differing quantity and quality of data available for each WAA, it was considered important to develop a model code that was flexible yet comprehensive. Building a bespoke, combined groundwater and surface water model for the project means that the code takes account of the important characteristics of the Sultanate of Oman.

Following consultation with MRMWR, 18 water balance models were constructed based on the hydrology and hydrogeology of Oman. These are shown in Figure 4.1. For the most part, model boundaries coincide with the WAA boundaries. As data availability across the country is extremely varied, two modelling approaches have been developed to allow for these differences:

- **Method 1:** a simple water balance model with the water balance presented as long term averages. No attempt at calibration is made. This method is used for model areas with limited data availability.
- **Method 2:** fully time variant water balance with annual average flows presented. Wadi flows and groundwater heads are calibrated against the observed monitoring data. This is used in areas with good data availability and where greater detail is required.

Each model is subdivided into grid cells of varying shape and size, to reflect the lateral variation in relevant model properties. Such model grid cells are smaller than WAUA but cell boundaries do, where relevant, coincide with the WAUA boundaries. This has been done to facilitate output from the model on WAUA basis.

Where possible, the model uses information from and builds upon the work and results from the 1991 and 2000 water balance projects. Besides the more comprehensive assessment of runoff, recharge and water needs for agriculture and urban use, an important difference is that the model allows for calibration. The calculation of rainfall recharge and runoff (contributing to wadi flow) has been done using a hydrological model that is run separately from the main water balance model but is closely linked with the water balance model in operational terms. An iterative process of operation of the two models has been adopted, with output from water balance model runs informing the need for changes in parameter setting in the hydrological model.

Figure 4.1: Water balance model areas

The model time period from 1985 to 2007 has been sub-divided into monthly time steps. The model outputs the results in time variant mode for each modelled time steps and for each model grid cell. Post-processing facilities allow for combined outputs, such as for example average annual water balance components on a WAUA or WAA basis.

The surplus or deficit for each WAUA is calculated as the difference between the inputs to the WAUA flow and the abstractions for agricultural and urban use. Inputs are:

- Direct recharge
- Wadi recharge
- Reservoir recharge
- Urban recharge
- Inter WAUA flow

Outputs are:

- Agricultural abstractions
- Aflaj flow
- Urban abstractions
- Capillary flux
- Inter WAUA flow

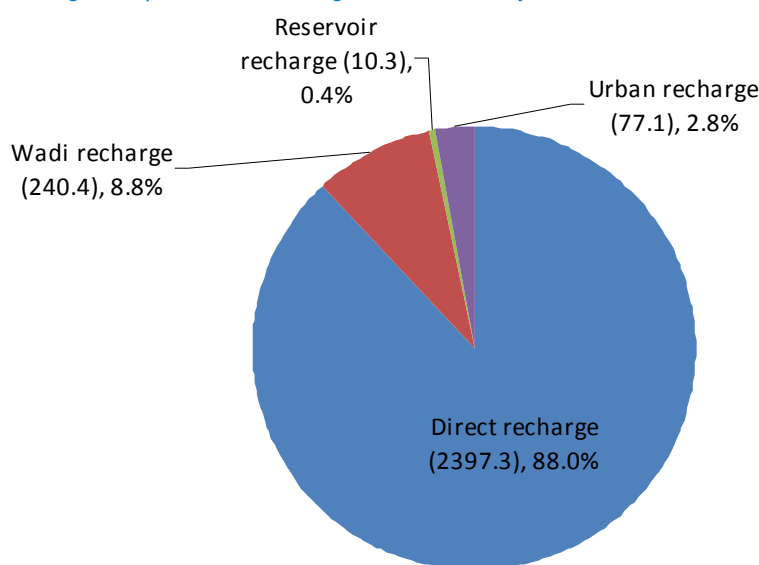
The existing WAA of Al Batha include the integration of Method 1 model area, Ash'Sharqiyah Sands constituting the three WAUA of Wahaybah North, Wahaybah South and Batain, and one Method 2 model area constituting the remaining 10 WAUA of Al Batha.

Inter WAUA flow can be an inflow or outflow component of the water balance depending on the location of the WAA/WAUA and the regional hydrogeological regime. Flow across the external boundary of a model, including saline intrusion is not considered in the derivation of surplus or deficit.

5. Results

Rainfall provides a volume of 15,841 Mm³/year to Oman with 12,553 Mm³/year lost due to evaporation and initial absorption. Direct recharge from rainfall (2,397 Mm³/year) provides 88% of the inflow with contributions from wadi recharge (240 Mm³/year), urban recharge (77 Mm³/year) and reservoir recharge (10 Mm³/year) (Figure 5.1).

Figure 5.1: Recharge components. Values given are in Mm³/year.

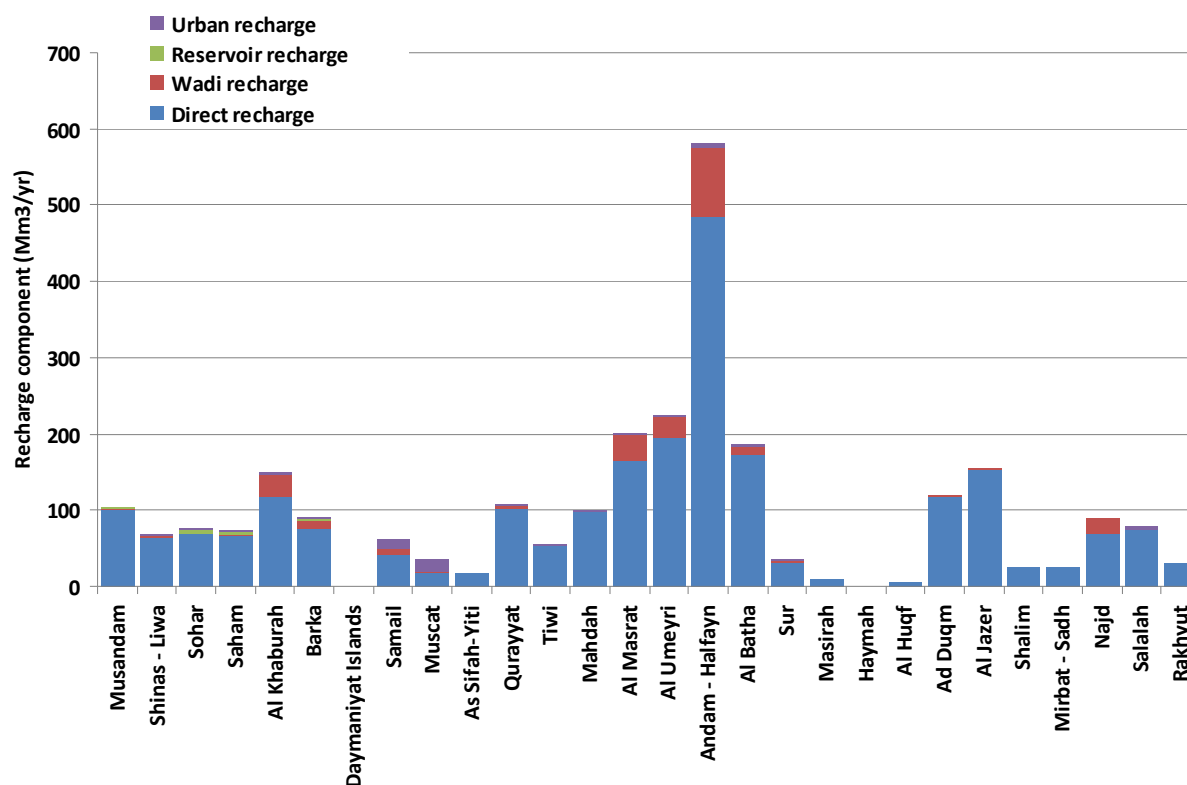


Total recharge for each WAA is shown in Figure 5.2. Rainfall or direct recharge is the main component. The total amount of direct recharge to Oman is calculated as being 15.1% of rainfall on average; the remainder is lost to evaporation, initial absorption and runoff.

Across Oman, there is a wide range in the total volume of recharge with the largest value calculated in the Andam-Halfayn WAA with an average (Mm³/year) of 485 from rainfall, 90 from wadi, 0.3 from reservoir and 5.3 from urban sources.. Andam-Halfayn also has a relatively high figure of wadi recharge (Figure 5.2). Other relatively high total recharge figures are Al Umeyri (225 Mm³/year), Al Masrat (202 Mm³/year) and Al Batha (188 Mm³/year).

Haymah, Al Huqf and Masirah show very little recharge with modelled values of 0 Mm³/year, 6 Mm³/year and 11 Mm³/year respectively. Low rainfall rates in Haymah and Al Huqf result in low recharge values. Masirah is a small island with average rainfall of 65 mm/year which leads to a low volume of recharge. In the Najd WAA, the recharge value (91 Mm³/year) is largely the amount of direct recharge to the lower Umm Er Radhuma layer; hence only a relatively small value is recorded as there is only a small area over which recharge can occur.

Figure 5.2: Recharge by WAA



Agricultural and urban water demand is met by water from a combination of different sources. Net agricultural demand (1,546 Mm³/year) is mainly met by water supplied from falaj flow and abstractions from groundwater using wells with a minor contribution from capillary flux. Gross urban demand (105 Mm³/year) is met by desalination water and groundwater abstractions. The average amounts of each source over the period of interest for this water balance are shown in Table 5.1 and Figure 5.3. Total average annual water demand for 1985-2007 is 1,651 Mm³/year.

Table 5.1: Water sources used to meet net agricultural demand and gross urban demand

Water source	Amount (Mm ³ /year)	Percentage of total
Agricultural groundwater abstraction	1,060	64.1%
Falaj flow	486	29.5
Urban groundwater abstraction	88	5.3
Desalination supply	17	1.1%
Total	1,651	100%

Abstractions for agricultural or urban demand are variable across the country. Figure 5.4 shows the distribution of these abstractions by WAA.

Figure 5.3: Contribution of different sources to meet agricultural and urban demand

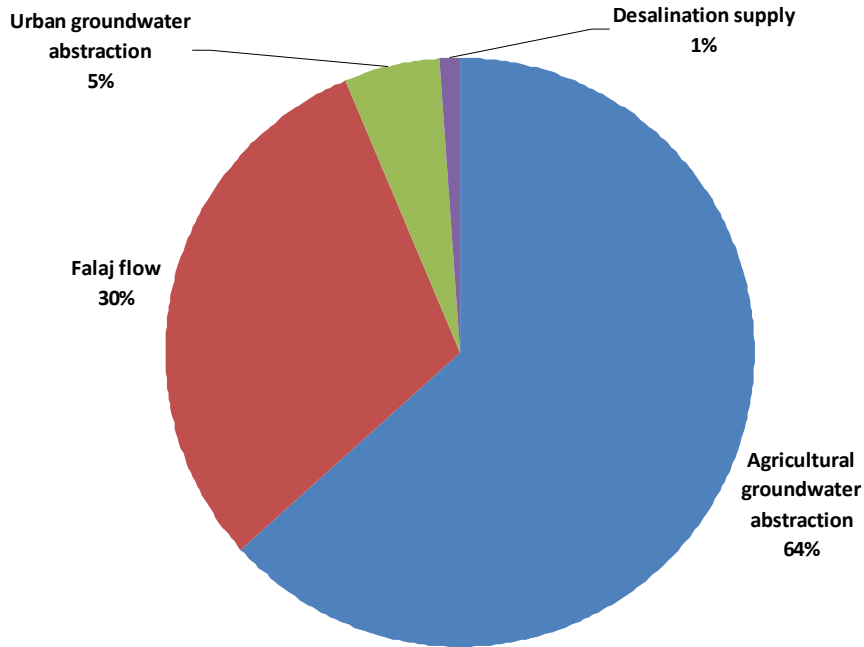
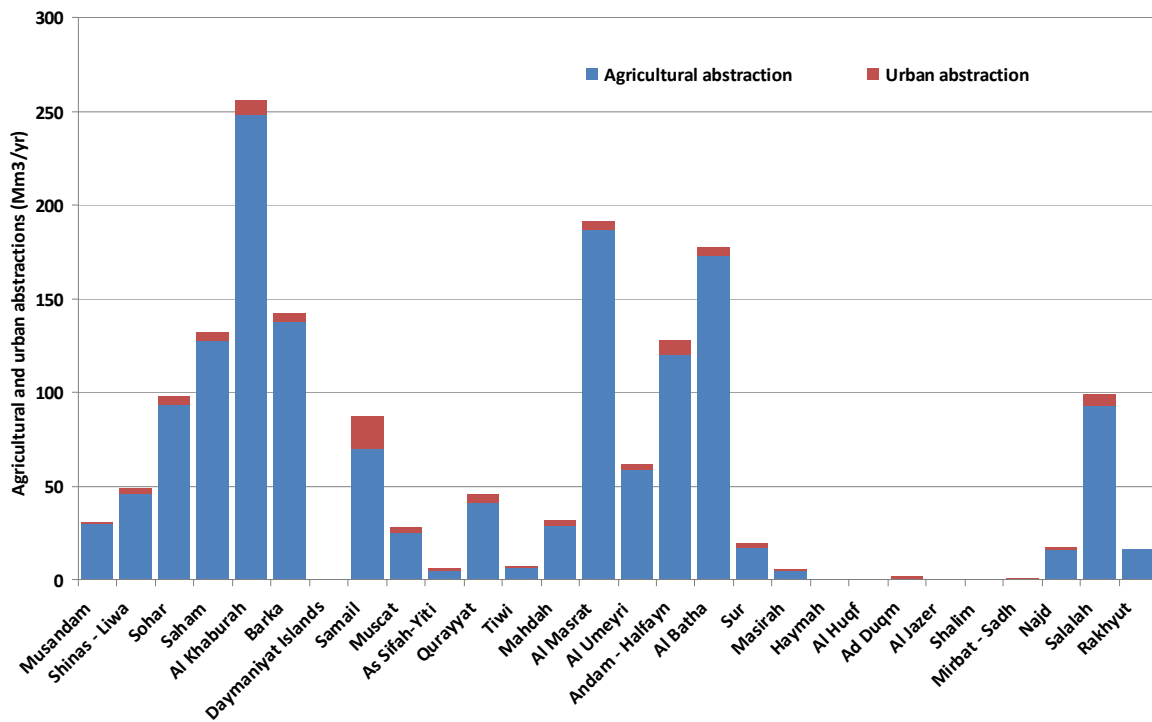


Figure 5.4: Agricultural and urban abstractions by WAA



Source: Current study (2012)

Table 5.2 contains a description of the key components of the water balance. Table 5.3 and Figure 5.5 present the values for the key components which have been calculated for the 28 WAA.

Table 5.2: Description of model output components

Component	Description	Units	Model	Used in surplus/deficit
WAA	Water assessment area	-	-	--
Rainfall	Annual average rainfall for the whole WAA as a weighted average of the component WAUA	Mm ³ /year	SCS	No
Evaporative losses	Losses due to both evaporation and soil absorption following a rainfall event	Mm ³ /year	SCS	No
Agricultural groundwater abstraction (net)	Net demand by agriculture which is met by groundwater abstraction, aflaj flow and capillary flux	Mm ³ /year	Water balance	Yes
Urban groundwater abstraction (gross)	Gross abstraction from groundwater to meet the urban demand for water that is not met by desalination distribution networks	Mm ³ /year	Water balance	Yes
Direct rainfall recharge	Recharge which occurs following a rainfall event	Mm ³ /year	Water balance	Yes
Wadi recharge	Recharge that occurs along the base of wadi and is a loss from the wadi	Mm ³ /year	Water balance	Yes
Urban recharge	Recharge as a result of network leakage and discharge of treated sewage effluent	Mm ³ /year	Water balance	Yes
Reservoir recharge	Recharge that occurs in reservoirs	Mm ³ /year	Water balance	Yes
Capillary flux	Loss from groundwater due to evaporation from the shallow groundwater table	Mm ³ /year	Water balance	Yes
Sum of inter WAUA flows	Groundwater flows across the boundaries of contiguous WAUA are summed for each WAA	Mm ³ /year	Water balance	Yes
Wadi flow	Surface water flow across the boundaries of WAA	Mm ³ /year	Water balance	No
Storage change	Change in storage over time as groundwater levels fluctuate	Mm ³ /year	Water balance	No
External flow	Groundwater flow to/from the sea or neighbouring countries	Mm ³ /year	Water balance	No
Surplus/deficit	Surplus water (positive values) or the amount that is in deficit (negative values), calculated as the difference between inputs from recharge and demands for abstraction.	Mm ³ /year	-	Sum of the above "yes" components

Out of the 28 WAA, 12 show a deficit in the water balance including all five WAA on the Al Batinah Plain. Deficits have also been recorded in Salalah and in the central areas such as Al Masrat, Al Batha and Haymah. The highest deficits are also linked with the highest demands which are primarily agricultural. The total deficit for Oman is 316 Mm³/year.

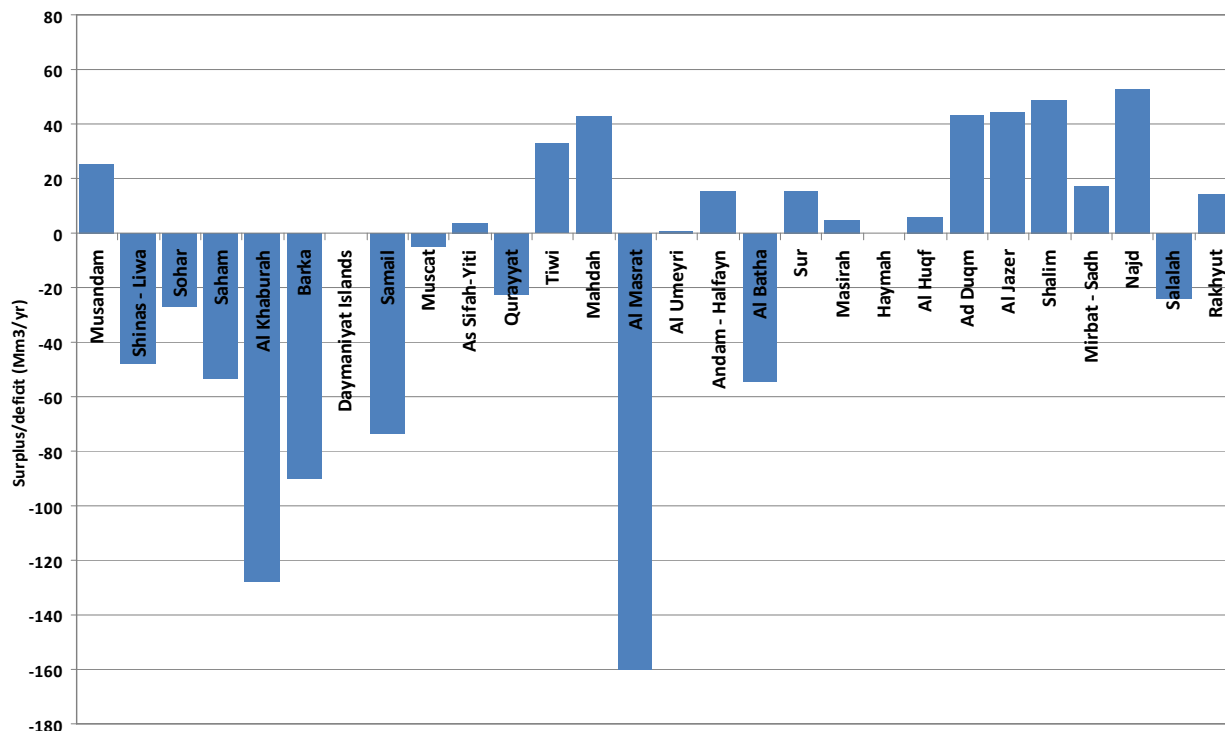
Figure 5.5 shows the deficits and surpluses by WAA across Oman. High agricultural demands are the main reason for the deficit. The Al Batinah coast has the highest demands and deficits have been recorded across the plain. In some cases, this deficit leads to saline intrusion. Deficits of 48 Mm³/year, 27 Mm³/year, 54 Mm³/year, 128 Mm³/year and 90 Mm³/year are recorded in the five WAA that make up the Al Batinah coast (Shinas-Liwa, Sohar, Saham, Al Khaburah and Barka).

Table 5.3: Key components of the water balance by WAA

WAA	Area (km ²)	Rainfall (Mm ³ /yr)	Evaporative losses (Mm ³ /yr)	Direct recharge (Mm ³ /yr)	Wadi recharge (Mm ³ /yr)	Reservoir recharge (Mm ³ /yr)	Urban recharge (Mm ³ /yr)	Agricultural abstraction (Mm ³ /yr)	Urban abstraction (Mm ³ /yr)	Capillary flux (Mm ³ /yr)	Sum of Inter WAUA flows (Mm ³ /yr)	Wadi flow (Mm ³ /yr)	External flow (Mm ³ /yr)	Storage (Mm ³ /yr)	Deficit-Surplus (Mm ³ /yr)
Musandam	1,993	333.0	206.0	100.6	2.8	0.2	0.5	-30.2	-0.8	-47.6	0.0	51.9	-36.8	-1.1	25.7
Shinas - Liwa	2,558	243.0	158.0	65.0	0.8	0.0	2.1	-46.1	-3.0	-67.5	0.6	87.8	-8.9	-0.5	-48.0
Sohar	2,804	261.0	169.0	70.5	0.9	2.6	3.3	-93.4	-4.6	-0.9	-5.3	111.7	3.6	-1.4	-27.0
Saham	2,783	247.0	160.0	66.4	1.0	4.3	3.6	-127.3	-5.0	-1.3	4.6	103.0	3.8	-0.7	-53.7
Al Khaburah	4,007	492.0	350.0	118.5	27.9	0.0	5.4	-248.1	-7.6	-30.2	6.3	79.5	-14.4	-0.8	-127.8
Barka	2,720	314.0	218.0	75.8	10.7	1.1	3.3	-137.5	-4.7	-32.7	-6.3	37.0	14.4	-0.3	-90.2
Daymaniya t Islands	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	0.0
Samail	1,841	188.4	135.0	42.6	7.5	0.7	12.2	-70.1	-17.1	-46.7	-2.5	82.9	14.1	-1.6	-73.4
Muscat	1,056	84.0	56.0	18.4	1.5	0.0	17.1	-25.1	-3.0	-23.5	9.3	18.0	-22.5	-0.8	-5.1
As Sifah - Yiti	949	72.0	42.0	17.3	0.2	0.0	0.7	-5.0	-1.0	-5.1	-3.1	26.8	-9.7	-0.5	4.0
Qurayyat	2,695	362.0	200.0	102.7	3.2	0.0	2.9	-41.6	-4.1	-84.9	-0.7	339.4	-26.5	-0.6	-22.4
Tiwi	1,488	190.0	113.0	54.9	0.1	0.0	0.5	-6.1	-0.6	-16.7	1.0	14.2	-34.7	-1.5	33.1
Mahdah	2,959	256.0	141.0	97.9	0.4	0.0	1.6	-29.0	-2.2	-25.6	0.0	30.6	-69.2	-0.4	43.1
Al Masrat	25,705	1,787.0	1,568.0	165.1	33.5	0.0	3.5	-187.1	-5.0	-175.1	4.9	177.3	-25.4	-7.8	-160.2
Al Umeyri	27,381	1,453.0	1,222.0	195.6	27.5	0.0	2.0	-58.6	-2.8	-157.8	-4.9	121.0	-4.3	-33.2	1.0
Andam - Halfayn	34,095	2,986.0	2,358.6	485.4	89.7	0.3	5.3	-120.2	-7.4	-437.7	0.0	333.7	-32.2	-75.7	15.3
Al Batha	14,189	1,136.0	933.0	172.0	12.0	0.0	3.7	-172.4	-5.2	-64.2	-0.4	75.6	-77.5	-24.9	-54.6
Sur	2,671	206.0	165.0	32.4	0.8	1.2	1.8	-17.4	-2.5	-4.2	3.3	11.8	-19.8	-0.8	15.4
Masirah	657	43.0	30.0	10.5	0.1	0.0	0.3	-5.2	-0.4	-0.2	0.0	2.8	-1.2	-4.0	5.2
Haymah	52,289	0.0	0.0	0.0	0.0	0.0	0.1	-0.1	-0.1	0.0	0.0	0.0	4.2	-4.0	-0.1
Al Huqf	9,835	109.0	102.0	6.3	0.0	0.0	0.1	0.0	-0.1	0.0	0.0	0.7	-5.3	-1.0	6.2
Ad Duqm	7,928	767.0	599.0	119.6	0.3	0.0	1.6	0.0	-2.2	-72.3	-3.4	76.6	-38.5	-6.8	43.5
Al Jazer	10,462	1,018.0	804.0	153.5	0.4	0.0	0.2	0.0	-0.2	-82.7	-26.9	98.4	-43.4	2.1	44.3
Shalim	1,681	163.0	128.0	25.4	0.0	0.0	0.0	-0.3	0.0	-6.2	30.3	5.9	-49.2	-0.5	49.2
Mirbat - Sadh	1,900	96.0	50.0	26.7	0.0	0.0	0.3	-0.2	-0.5	-1.5	-7.1	0.0	-27.5	-1.0	17.7
Najd	88,967	2,635.0	2,382.0	71.1	18.9	0.0	0.7	-16.4	-1.0	-20.4	0.0	601.9	4.0	-4.9	53.0
Salalah	2,117	266.0	169.0	73.4	0.0	0.0	4.5	-93.1	-6.3	-3.9	1.2	6.5	-6.3	-0.4	-24.2
Rakhyut	1,711	134.0	94.0	29.9	0.0	0.0	0.2	-16.0	-0.3	-5.5	6.0	16.2	-29.2	-0.2	14.3
Total	309,442	15,841.4	12,552.6	2,397.3	240.4	10.3	77.1	-1,546.3	-87.5	-1,414.2	7.0	2,510.9	-538.4	-173.3	-315.8

Note: Surplus/deficit is the sum of the green (inflow), brown (outflow) and blue components

Figure 5.5: Surplus or deficit for each WAA



Source: 2012 Water balance study

Elsewhere, deficits are also recorded in the Samail (73 Mm³/year), Al Batha (55 Mm³/year) and Salalah (24 Mm³/year) WAA. There is a close association with the areas in deficit and the agricultural demands.

Daymaniyat Islands WAA has no water demand as well no significant source of recharge and the deficit is assessed as zero.

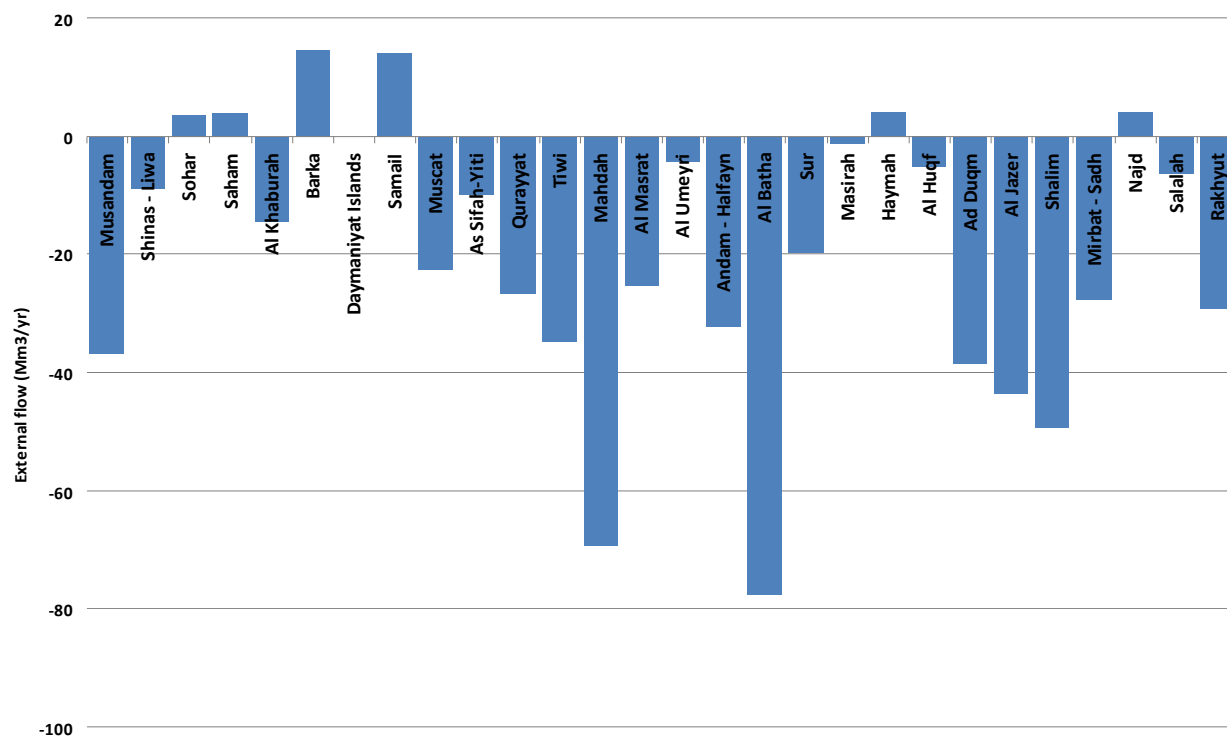
There is a surplus of water available in 15 WAA, including Shalim (49 Mm³/year) and Mahdah (43 Mm³/year). Shalim is a hard rock area with little or no agriculture. Despite having water in surplus, much of the recharge occurs on low transmissivity ophiolite aquifers and may not be easily accessible. Mahdah, in Al Buraymi region, has a surplus as there is a low agricultural demand despite above average recharge rates. However, most of the water in this region discharges to the UAE and is used to support agriculture on the other side of the border.

Other areas which have a surplus include Ad Duqm (44 Mm³/year), Najd (53 Mm³/year) and Al Jazer (44 Mm³/year). These three regions are similar in that the demand is low but the available groundwater is not easily accessible. In Mirbat-Sadh and Masirah the water balance shows a surplus which again is a reflection of the low population density and limited agriculture.

In the centre of the country, where the rainfall is lowest, the Haymah WAA has a small deficit (0.1 Mm³/year). Despite having the lowest amount of direct recharge (0 Mm³/day) there is comparatively little abstraction for either agricultural or urban use. In addition, the surrounding WAA such as Najd and Al Umeiry discharge groundwater to Haymah which means that the demands can be met.

External flow can be into or out of a WAA (Figure 5.6). Along the coast, any inflow is considered to occur in the form of saline intrusion. The greatest outflow occurs in Al Batha (78 Mm³/year) and Mahdah (69 Mm³/year) WAA to the sea and the United Arab Emirates (UAE) respectively.

Figure 5.6: External flow



Source: Current study (2012)

Saline intrusion is calculated to occur along the Al Batinah coast in the Sohar, Saham, Barka and Samail WAA with an average annual inflow of 36 Mm³/year. The amount of saline intrusion is highest in the Barka WAA (14.4 Mm³/year) with 14.1 Mm³/year in Samail, 3.8 Mm³/year in Saham and 3.6 Mm³/year in Sohar

Since these calculations provide the net external flow values for the whole WAA, a net positive or negative flow does not preclude localised differences in the external flow component. A particular example is Salalah which has an overall outflow (6.3 Mm³/year, Table 5.3) but saline intrusion is modelled in the Salalah Plain West (0.7 Mm³/year) and Salalah Plain Central (22 Mm³/year) WAUA.. Similarly, on the Al Batinah plain, the discharge to the sea in the Al Khaburah WAA occurs in the Bani Ghafir North (9 Mm³/year) and Fara' North (8 Mm³/year) WAUAs. Saline intrusion of 6 Mm³/year is calculated in the Jahawir North WAUA. Groundwater discharge to the sea in the Muscat WAA occurs mainly in the east of the WAA, in the Jabir North (32.5 Mm³/year) and Dayqah Coastal (11 Mm³/year) WAUAs. This is a product of the groundwater flow direction which is generally to the east. To the west in the Samail WAA, the Ma'abilah, Al Khawd and Hayl WAUA along the northern coast with the Sea of Oman record saline intrusion of 5 Mm³/year, 9.5 Mm³/year and 0.3 Mm³/year respectively. These locations have the most intensive agriculture..

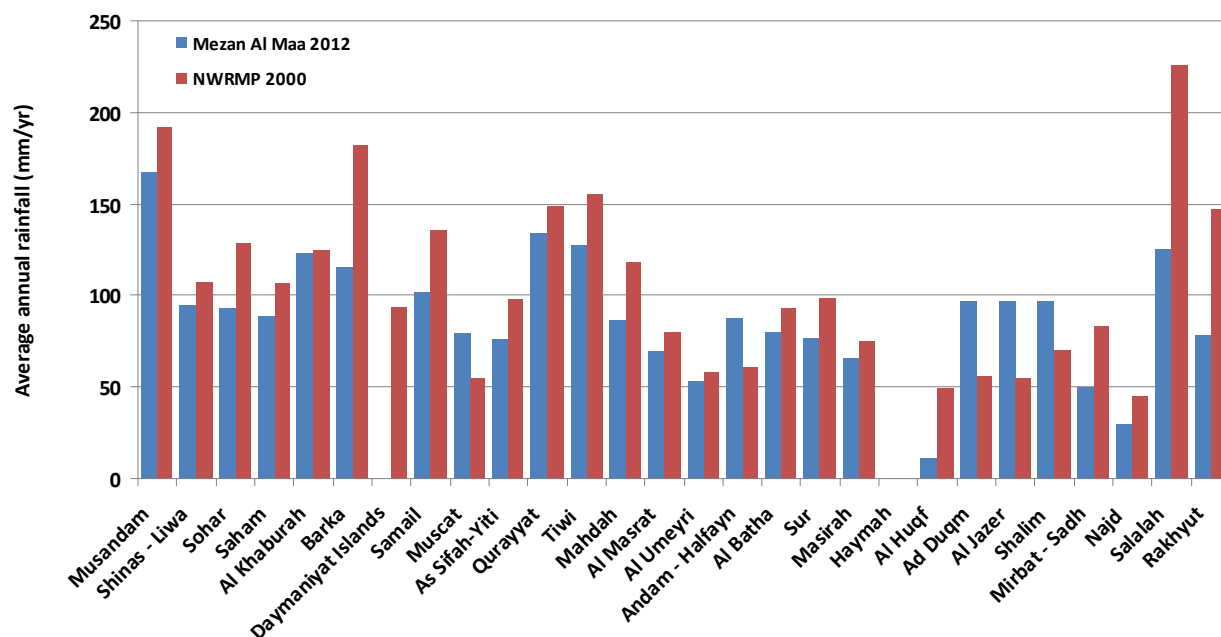
Inflows to the Najd region are concentrated along the boundary with the Republic of Yemen in the west. There is net outflow to the north and east, into Saudi Arabia and Haymah WAA. A total of 5.7 Mm³/year in the South Shihan WAUA and 7.5 Mm³/year in the South Atiyah WAUA of groundwater inflow from the

Republic of Yemen has been recorded. This groundwater flow occurs in the UER aquifer. To the north and east of the Najd WAA, there are discharges to Saudi Arabia and the Haymah WAA. These are 2.4 Mm³/year to Saudi Arabia from the North West Najd WAUA, 2.1 Mm³/year to Saudi Arabia from the North Muqshin-Atiyah WAUA and 3.8 Mm³/year from the North Central Plateau WAUA to the Haymah WAA.

A comparison of this study (Mezan Al Maa) with the previous water balance (NWRMP 2000) has identified similar trends with the Al Batinah Plain being identified as having the highest deficits in both studies. However, there are some differences which include slightly higher average rainfall, a reduced estimate of the evaporative losses and an increase in the total demands. As a result, the number of WAA which are considered to be in deficit is higher at 12 compared with eight in the previous study.

The comparison of estimates of rainfall, evaporative losses and demand between the 2000 study and this work are presented in Figure 5.7, Figure 5.8 and Figure 5.9 respectively.

Figure 5.7: Comparison of WAA rainfall

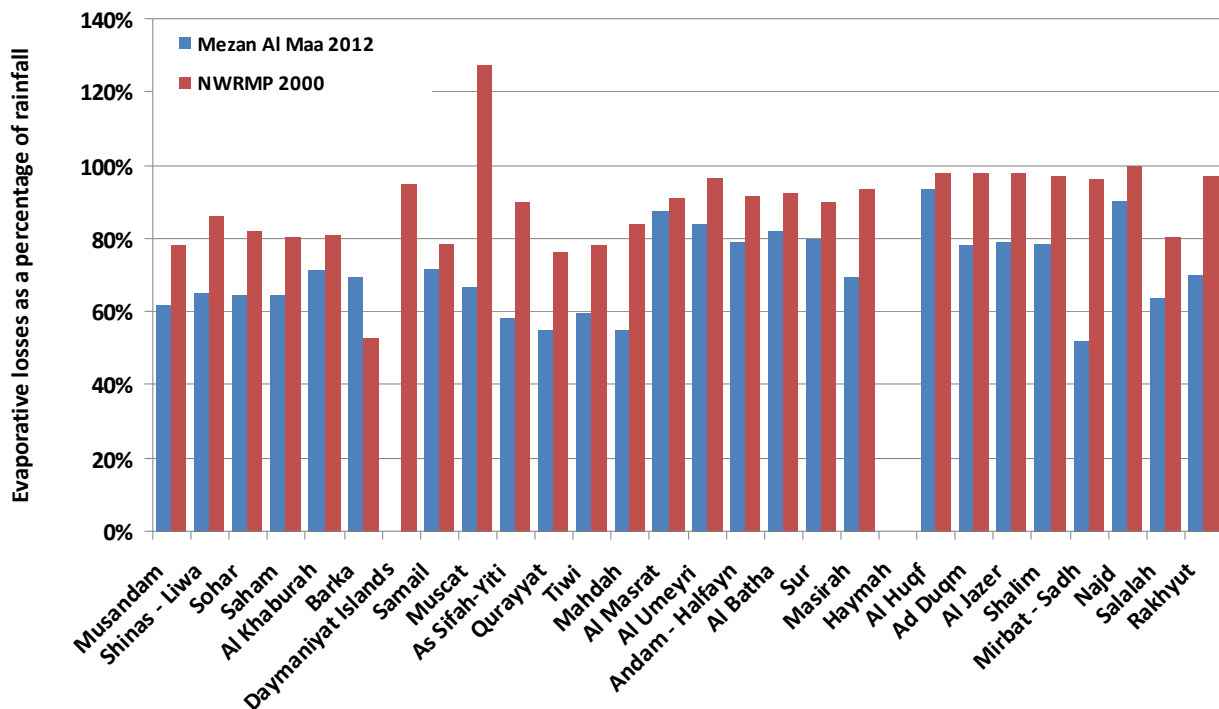


Source: NWRMP2000 and Mott MacDonald, 2012

Overall average rainfall for the country is lower in the current study, being 51 mm/year compared with 57 mm/year in the previous study. This difference in the average annual rainfall is in part linked to the period of analysis. Although high rainfall rates were recorded in the mid-1990s and during Gonu in June 2007 there was also a period of extremely low rainfall in the mid-1980s and the years before Gonu. Given the limited available data prior to 1985, the extension of the dataset back to 1976 undertaken in NWRMP 2000 is subject to significant uncertainty. Using the dataset over a longer period of time and covering a wider range of climatic conditions as done in this study allows a more accurate assessment of the long term average rainfall.

The results of the comparison of estimates for evaporation show that in all WAA apart from Barka, the percentage loss of rainfall to evaporation is higher in the NWRMP 2000 study (Figure 5.8). On average, there is a 36% decrease in calculated evaporative losses for the Sultanate of Oman in the 2012 study compared with the 2000 study. In both studies, there is a slight trend for higher evaporative losses as a percentage of rainfall in the south than in the north.

Figure 5.8: Comparison of evaporation losses



Source: NWRMP2000 and Mott MacDonald, 2012

The comparison of estimated demands (Figure 5.9) show that they are generally higher in the current study, which is broadly in agreement with expectation. The increase is 30% over the periods represented by the two studies.

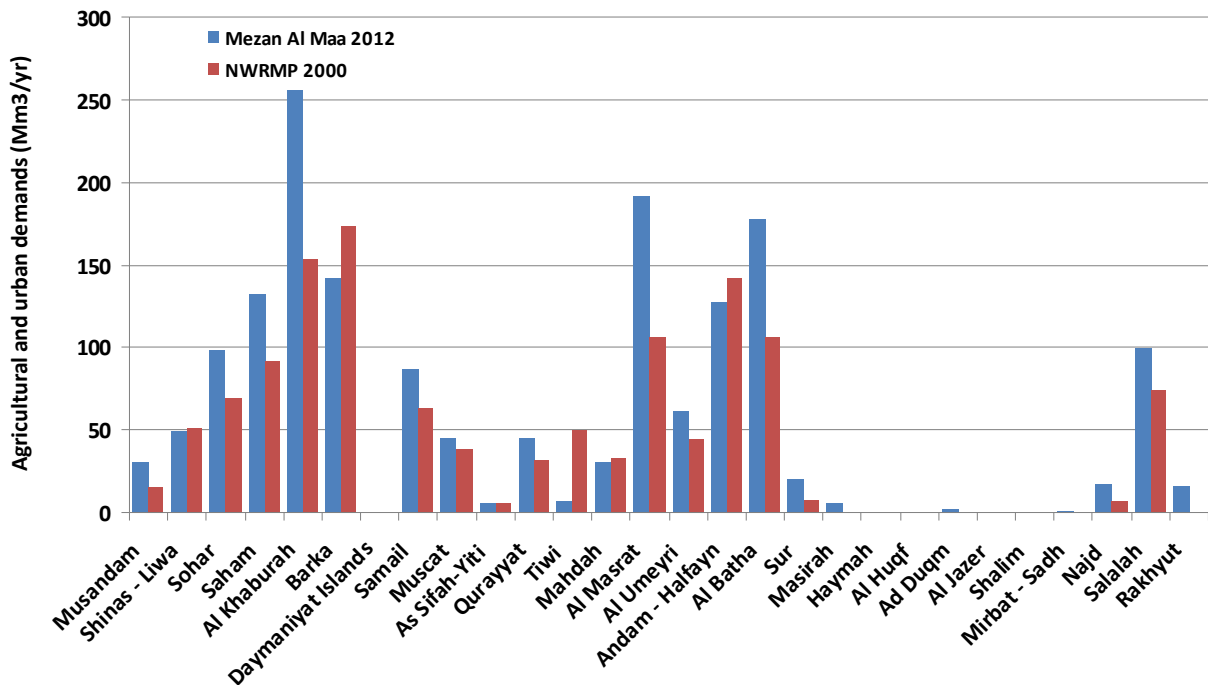
Overall, trends in the 2000 and 2012 water balance results are similar with the lowest demands in the centre of the country, for example, Haymah, Al Huqf and Al Jazer and the highest demands in the Al Batinah Plain in both studies.

The NWRMP 2000 study estimated the gross agricultural demand based upon the cropped areas determined through analysis of the National Well Inventory (MWR, 1996) and the National Falaj Inventory (MRMEWR, 2001). Gross groundwater abstractions were based upon these data. In the current study, the

estimation of groundwater abstractions is calculated on the basis of the net crop demand and crop areas are calculated using satellite imagery.

The more accurate satellite imagery available and the advanced techniques of image processing that have been used in the current study are considered to provide a more accurate estimation of crop areas than in the NWRMP 2000.

Figure 5.9: Comparison of total demands



Source: NWRMP2000 and Mott MacDonald, 2012

6. Conclusion and recommendations

6.1 Conclusions

A water balance provides the means for evaluating the availability and sustainability of water resources to supply different demands. For the Sultanate of Oman, this is of particular importance because water is such a scarce resource. High demands and over abstraction have led to saline intrusion along the Al Batinah coast and predicted population growth means that pressure on water resources is increasing. An understanding of the main sources and sinks of water and their spatial variability aids the management of water resources in Oman.

A preliminary data analysis was used to agree upon the modelling period of interest. Poor data availability meant that there was not sufficient detail to undertake the water balance studies prior to 1985. More recent datasets were still undergoing data processing by MRMWR. Therefore, the period of interest was agreed to be 1985 to 2007.

Based upon the characteristics of Oman, a modelling methodology was developed to account for the most important features of the water resources of the country. A bespoke modelling code was written which was designed to be flexible enough to model both those areas with a good quality of information and those where data is more sparsely distributed.

Following consultation with MRMWR, 18 water balance models were constructed, containing up to five WAA. Where the data availability was poor, for example in the Haymah region, a **Method 1** model was used. **Method 1** models provided a long term average water balance with no calibration to the observed data being undertaken. **Method 2** models were more complex than the **Method 1** models requiring more detailed datasets and calibration to the observed data where available. An annual average water balance is calculated based on the monthly outputs from the model.

Results from the calibrated water balance models indicate that 12 of the 28 WAA have a deficit in the water balance. These include all five WAA that make up the Al Batinah coast (Shinas-Liwa, Sohar, Saham, Al Khaburah and Barka), the area around the capital (Muscat, Samail and Qurayyat), Salalah, Haymah and the interior regions of Al Masrat, Al Umeyri, Al Batha and Andam-Halfayn. Areas with a high deficit are linked to those with high demands. Conversely, those areas which have a surplus of water have little or no demands.

Rainfall provides a volume of 15,841 Mm³/year to Oman with 12,553 Mm³/year lost due to evaporation and initial absorption. Agricultural abstraction is 1,546 Mm³/year, making up 95% of the total groundwater abstraction of the Sultanate of Oman with urban requirements (88 Mm³/year) comprising the other 5%. The total estimated recharge per year is 2,725 Mm³/year of which direct recharge from rainfall is 2,397 Mm³/year or 88% of the total with contributions from wadi recharge (240 Mm³/year, 8.8%), urban recharge (77 Mm³/year, 2.8%) and reservoir recharge (10 Mm³/year, 0.4%).

This water balance calculation represents a significant step forward from the 1991 and 2000 studies. It has used current data and an improved modelling approach that better represents the transient processes.

A high degree of confidence can be placed in the current study as the results are based upon or calibrated against observed data and the latest techniques in data processing have been used. However, gaps in the dataset lead to uncertainties in the central parts of Oman.

Capacity building was integral to the project at all stages. The training has provided MRMWR with a thorough understanding of the theory behind the water balance models and the techniques and processes which are required for their construction, calibration and results processing. Four of the Ministry's staff became conversant with the methodology and assumptions behind the construction and calibration of the models and three models were constructed with full participation of MRMWR staff.

6.2 Recommendations

Given improvements in the data used in the current study in comparison with NWRMP 2000 and an improved conceptual understanding of the groundwater system and its interaction with the surface environment, the models can be used with more confidence in general water resources management and planning. It is recommended that the models will remain a live tool that is subjected to improvements on a regular basis.

It is recommended that the modelling tools are used for water resources assessment on a more localised scale. Use at this scale may not only be useful for MRMWR, but also for external stakeholders involved with resource assessment at local scale, such as the work in progress in different parts of Oman for the million date palm project.

Water balance modelling is a data intensive procedure and there is a strong reliance upon the observation data. Unfortunately, this means that where data sources are scarce, there is greater uncertainty associated with the results. The full extent of the uncertainties in the modelling results is discussed and it is noted that for progress to be made in the future and so that greater confidence can be placed in the results, it is important to not only increase the quantity of the rain and wadi gauges but also to improve procedures of quality control.

It is therefore recommended that MRMWR undertake the tasks required to improve the data required for the models. This includes making best use of data available within the ministry and using data and information that can be obtained from ongoing study conducted by others, for example studies done for the million date palm project in different parts of Oman.

Improvement in conceptual understanding is closely related to the improvements in monitoring and the better definition of other data used by the model. Historic studies, proved a good starting point for improvement in conceptual understanding beyond what has been achieved during the water balance project. More important is to make use of the findings from ongoing projects that consider a variety of aspects of the groundwater systems.

Given improvements in the data used in the models and an improved conceptual understanding of modelled groundwater systems, there is scope for improvement of the models. Improvements could include refinement of the model grid to better represent the spatial variation in model data and aquifer system characteristics.

It is recommended that the models are considered as tools that serve the ministry for years to come and that uncertainty in model findings are reduced with time through continued upgrade and refinement of the models.